

Physicochemical and urban land-use characteristics associated with resistance to precipitation in estuaries vary across scales

Anna B. Turețcaia^{1,*}, Nicole G. Dix^{2,3}, Hannah Nicklay^{3,4}, Matthew C. Ferner^{5,4}, Emily B. Graham^{1,6,5,*}

¹ Pacific Northwest National Laboratory, Richland, WA 99352, USA
² Guana Tolomato Matanzas National Estuarine Research Reserve, Ponte Vedra Beach, FL 32082, USA
³ Biology Department, University of North Florida, Jacksonville, FL 32224, USA
⁴ Lake Superior National Estuarine Research Reserve, University of Wisconsin Madison, Division of Extension, Superior, WI 54880, USA
^{4,5} San Francisco State University, Estuary and Ocean Science Center, Tiburon, CA 94920, USA
^{5,6} School of Biological Sciences, Washington State University, Pullman, WA 99164, USA

Correspondence to: Anna B. Turețcaia (anna.turetciaia@pnnl.gov) and Emily B. Graham (emily.graham@pnnl.gov)

Formatted: Superscript

Formatted: Superscript

Abstract. Estuaries are subject to frequent stressors, including elevated nutrient loading and extreme hydrologic events, which impact water quality and disrupt ecosystem stability and health. 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 [worldclimate](#). However, generalizable patterns in factors related to estuarine responses to extreme precipitation remain unknown. [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.](#) We investigate [which](#) physicochemical ~~faetors~~ and land-use characteristics ~~that~~ are associated with ecological resistance to precipitation – ~~broadly~~ defined as the magnitude of ecosystem change induced by an event – in five disparate estuaries distributed across the continental United States. Using long-term meteorological and water quality data from the National Estuarine Research Reserve System along with land use/land cover and population data, we examine relationships between the resistance index – a proxy for ecosystem stability calculated using dissolved oxygen – and physicochemical and urban land use characteristics on local-to-continental scales. Contrary to our initial hypothesis, we found that more urbanized estuaries were more resistant to precipitation events, [possibly due to persistent disturbances on their baseline dissolved oxygen levels,](#) and that water temperature, water column depth, turbidity, nitrogen, and chlorophyll-*a* were related to resistance on a continental scale. However, these [continental-scale patterns were modulated by](#)~~trends interacted with~~ estuarine salinity and varied across individual estuaries, where ~~we found~~ additional relationships ~~betweenef~~ resistance ~~andwith~~ salinity, ~~turbidity,~~ phosphate concentrations, N:P, and tree cover [emerged.](#) [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.](#) Considering emerging stressors from new [environmentalelimatic](#) scenarios and from urbanization, these results are important for representing the impacts of disturbances in large-scale models and for informing management decisions regarding estuarine water quality.

1. Introduction

Estuaries are highly dynamic environments that often connect freshwater and saltwater systems, cycle organic matter and nutrients from land to oceans, and provide essential ecosystem services (Bianchi, 2007; He and Silliman, 2019). The function of estuarine ecosystems as unique sites for carbon and nutrient cycling, and habitats for macro- and micro-flora and fauna, relies on stability of a predictable range of dynamic processes like temperature fluctuations, hydrology and nutrient mixing. However, anthropogenic activities and extreme ~~precipitation~~~~climate~~ events threaten estuarine ecosystem stability and function (Kemp et al., 2009; Zhang et al., 2010). Predicted increases in urban population size and in the frequency and intensity of precipitation events highlight the urgency to understand the response of estuaries to ~~new~~ urbanization and ~~new~~ ~~precipitation patterns~~~~weather~~~~climate scenarios~~ (Kyzar et al., 2021; Li et al., 2019; Martínez et al., 2007; Pickett et al., 2011). Yet, the factors that impact ~~the response of~~ urban estuaries' ~~response~~ to precipitation are not fully understood.

When combined with intense precipitation, watershed urbanization and associated changes in land use/land cover (LULC) often result in increased ~~ds in~~ stream hydrological flashiness (Gannon et al., 2022; Grimm et al., 2008; Reisinger et al., 2017). Hydrological flashiness induces ~~high~~~~increased~~ flow rates that cause changes in channel morphology (Booth and Jackson, 1997; Gregory, 2011; Leopold, 1968; Vietz et al., 2016), habitat destruction (Walsh et al., 2005), and disruption of microbial metabolic processes (Reisinger et al., 2017; Uehlinger, 2000). Flashiness can also drastically affect primary production – a regulatory component of dissolved oxygen (DO) dynamics in aquatic environments – through increases in flow velocity, transport of phytoplankton, sediment migration, and light limitation through increased turbidity (Bernot et al., 2010; Fisher et al., 1982; McSweeney et al., 2017; Reisinger et al., 2017; Uehlinger, 2000).

While DO is dynamic and depends on ~~a~~ ~~myriad of~~ biological, chemical, and physical processes, it is essential for many estuarine functions and has been widely used as an indicator for overall ecosystem health (Abdul-Aziz et al., 2007; Abdul-Aziz and Gebreslase, 2023; Chapra, 2008; Cox, 2003; Kannel et al., 2007; Zhi et al., 2021). Dissolved oxygen is critical to maintaining the life cycles of macro- and micro-fauna, ~~for example,~~ and supports the biogeochemical cycling of carbon and nutrients by serving as a terminal electron acceptor (Bernhardt et al., 2018; Chapra, 2008; Zarnetske et al., 2012). ~~Urban~~~~Built~~ areas in particular have been ~~linked~~~~previously connected~~ to altered aquatic DO concentrations and other water quality parameters (Bernhardt et al., 2008;

Chang, 2005; Freeman et al., 2019; Vietz et al., 2016). Given the tight link between aquatic DO, land use, and diverse ecosystem functions, DO is an important indicator and holistic measure of estuarine health.

In addition to impacts on DO, extreme precipitation events ~~can cause are often associated with~~ excess nitrogen (N) delivery and ~~changes in~~ salinity ~~change~~, particularly ~~in for~~ waterways adjacent to urban-type LULC (Walsh et al., 2005). Nitrogen is central to mediating metabolic processes across a wide range of ecosystems and land covers (Mulholland et al., 2008; Schindler, 1977; Smith, 1984; Vitousek and Howarth, 1991). It is particularly important for primary production in aquatic ecosystems because many phytoplankton species are N-limited (Evans and Seemann, 1989; Howarth, 1988; Vitousek and Howarth, 1991). Further, extreme precipitation events ~~can cause drastic changes in estuarine salinity through are often associated with~~ influx of freshwater (i.e., runoff) and/or saltwater (i.e., storm surges) ~~into estuaries~~, which ~~changes salinity~~, can induce stratification and hypoxia, and impact ecosystem metabolic functions (Rabalais et al., 2010; Wetz and Yoskowitz, 2013; Zhang et al., 2010). However, depending on the temporal and spatial scales of evaluation, the reported trends of estuarine responses to precipitation and salinity changes can be conflicting.

~~Identifying c~~Commonalities ~~in~~ responses to major precipitation events across disparate estuaries can help ~~to~~ project long-term estuarine~~iney~~ health under ~~increasinged progressive~~ urbanization and more extreme ~~precipitationelimite~~ events. ~~Howeverbut they such commonalities~~ have been difficult to ~~discern and~~ decipher. ~~This is~~, in part, due to ~~variation in how~~ the complex and interconnected dynamics within ~~individual~~ estuaries ~~and their varied responses~~ to precipitation, ~~even at local scales~~. While Ombadi & Varadharajan (2022) report contrasting effects of urbanization on salinity during flood events when regional ~~dynamics areclimate is~~ considered, a continental-scale study by Kaushal et al. (2018) suggests that anthropogenic activity is associated with increasing salinity in waterways. However, ~~the later study~~ Kaushal et al. (2018) recognizes that regional, ~~weather-related-climate~~, LULC, and geologic variabilities also influence salinization patterns. Similarly, continental-scale evaluations showed that ~~waterways within~~ small watersheds appear consistently less flashy than ~~those in~~ large watersheds; and that there is a substantial amount of variability in these relationships at regional scale (Baker et al., 2004; Gannon et al., 2022; Hopkins et al., 2015; Poff et al., 2006). Such variation in relationships across scales may be particularly prevalent in ecosystems influenced by anthropogenic activities (Hopkins et al., 2015;

Poff et al., 2006), which demonstrates the importance of considering multiple spatial scales in understanding estuarine responses to changes in precipitation patterns and watershed land use.

We aim to uncover generalizable ~~responses~~ ~~patterns~~ ~~of responses~~ to large precipitation events across five estuaries ~~that spanspanning~~ a gradient of urbanization and physicochemical ~~characteristics~~ ~~properties~~. Using DO as an ~~indicator of~~ ecosystem health ~~indicator~~ (Abdul-Aziz and Gebreslase, 2023), we evaluate estuarine~~iney~~ resistance to precipitation – defined here as the ability of estuaries to maintain ~~stability in~~ DO ~~stability~~ (Isbell et al., 2015; Lake, 2013; McCluney et al., 2014; Pimm, 1984; Utz et al., 2016; Van Meerbeek et al., 2021). ~~In~~ the context of physicochemical ~~factors~~ and land-use ~~factorse~~ ~~characteristics~~, ~~we evaluate estuarine resistance~~ at: 1) the continental-scale (i.e., across all estuaries); 2) across estuaries grouped by salinity; and 3) within each estuary. We hypothesize that urbanization decreases estuarine resistance to precipitation, and ~~further~~ that relationships ~~between~~ ~~of~~ resistance ~~andwith~~ physicochemical and land-use factors will ~~vary with~~ ~~diverge onwith~~ spatial scale and ~~differences in~~ ambient salinity. This study helps ~~advance~~ understanding ~~of~~ how ongoing changes in ~~the Earth system~~ ~~climate and~~ ~~urbanization conditions~~ influence estuarine ecosystem health.

2. Methods

2.1 ~~Dataset description.~~ Estuaries and monitoring locations.

We used long-term water quality monitoring data from five estuaries in the National Estuarine Research Reserve System (NERRS, 2023) to understand factors associated with their resistance to precipitation events. Lake Superior (LKS), WI; Chesapeake Bay Maryland (CBM), MD (Jug Bay only); Guana Tolomato Matanzas (GTM), FL; Weeks Bay (WKB), AL; and San Francisco Bay (SFB), CA span ~~ecoregions~~ ~~climate zones~~, land uses, and salinity (0.1–35 ppt) (Fig. 1, Table 1). Across all estuaries, there were a total of 19 monitoring locations. ~~(3 at CBM, and 4 at LKS, GTM, WKB, and SFB).~~

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).

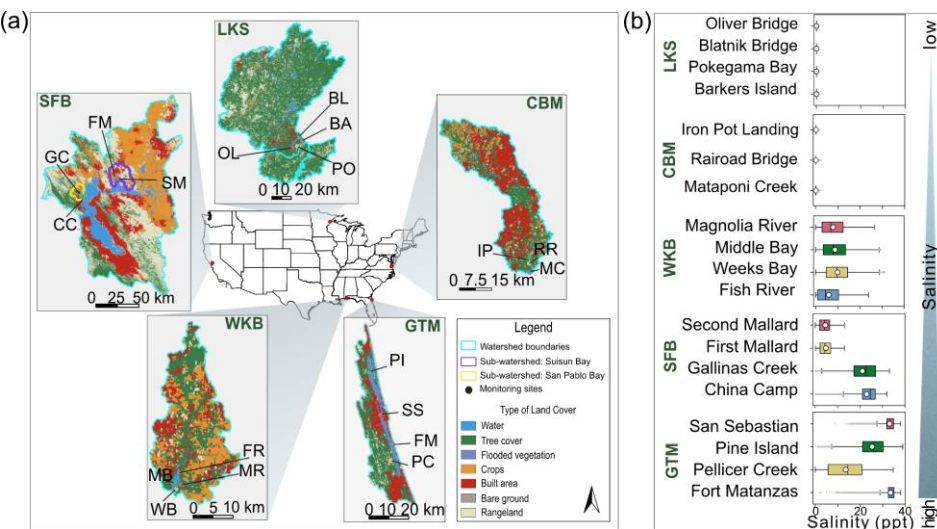


Figure 1. Selected National Estuarine Research Reserve (NERR) stations. a) Map of monitoring locations and land use/land cover within associated watersheds at Lake Superior (LKS) NERR, Chesapeake Bay, Maryland (CBM) NERR, Guana Tolomato Matanzas (GTM) NERR, Weeks Bay (WKB) NERR, and San Francisco Bay (SFB) NERR. b) Salinity from 2012 to 2022

for each monitoring location at each NERR (all n > 150,000). Boxes indicate interquartile range. Means are shown in white circles. Black lines inside the boxes indicate medians.

Table 1. Land use/land cover (LULC) and population density in ~~five~~ each National Estuarine Research Reserve System estuaries within 10-km to water quality and nutrient monitoring locations.

LULC class	Estuary and % LULC class within 10-km to monitoring locations (%)					
	<u>Lake Superior (LKS)</u>	<u>Chesapeake Bay (CBM-Jug Bay)</u>	<u>Guana Tolomato-Matanzas (GTM)</u>	<u>Weeks Bay (WKB)</u>	<u>San Francisco Bay (SFB)</u>	
					(San Pablo Bay) CC	(Suisun Bay) FM, SM
Water	10.43	2.30	8.58	4.85	5.04	3.59
Tree cover	58.78	53.72	45.11	38.52	26.91	1.16
Flooded vegetation	0.88	1.37	13.04	0.05	1.40	21.33
Crops	0.19	4.63	0.19	30.36	18.05	19.67
Built area	18.84	27.19	23.99	19.33	31.65	21.87
Bare ground	0.06	0.25	0.26	0.10	0.11	1.17
Rangeland	9.82	10.53	8.82	6.76	16.47	31.2
Surface area and population estimates						
Area (km ²)	4898.7	218.2	6465.6	213.0	105.01	2065.86
Estimated population	71,111	49,291	148,557	17,404	48,161	100,582

within the area (ppl)						
Population density (ppl km ⁻²)	145	225	230	81	458	488
LULC definitions per ESRI (Karra et al., 2021)						
<i>Water</i> – areas where water was present throughout the year. Excludes man-made structures like docks. <i>Tree cover</i> – vegetation with closed/dense canopy ≥ 15 meters. <i>Flooded vegetation</i> – areas with intermixing of water and vegetation flooded seasonally or predominantly throughout the year. <i>Crops</i> – human planted vegetation (cereals, grasses, and corps) that are not at tree height. <i>Built area</i> – human made structures like roads, railroad networks, parking spaces, industrial and residential buildings. <i>Bare ground</i> – areas dominated by rocks, soil, sand (i.e. desert) with sparse to no vegetation throughout the year <i>Rangeland</i> – homogeneous grasses, mixes of vegetation below tree-height with rocks and soil, clearings in the forests.						

2.2 Land use and land cover.

To assess the relationships between resistance and urbanization, we used LULC data at 10-meter resolution from ESRI (2017–2020) (Karra et al., 2021) and population density data at 100-meter resolution from World Population Hub (Bondarenko et al., 2020) ~~(Table 1)~~. The NERR watersheds shapefiles were obtained from NERRS, (2023). We analyzed LULC and population density using QGIS 3.30.3 (QGIS Geographic Information System, 2024) equipped with a semi-automatic classification plug-in, which generates percentages of each class within a given area based on the classification raster. The resulting breakdown of LULC and population density within watersheds is shown in Table S2.

Further, because the resistance index was calculated for precipitation events across short time-scales (i.e., days), ~~which underrepresents the draining time of some large watersheds 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. ~~we considered LULC and population density from a 10-km proximity zone surrounding monitoring locations (Table 1). For the SFB-NERR watershed, separate we used 10-km proximity zones were delineated for from San Pablo and Suisun embayments to account for quantify LULC and population density due to different hydrologic dynamics within each embayment.~~

All data were collected using NERRS standard operating procedures. Briefly, water column DO (mg L⁻¹, calculated from % air saturation, temperature, and salinity at the time of measurement; thereby accounting for the impacts of temperature and salinity fluctuations on DO concentration), temperature, turbidity, salinity, and depth were measured at 15-min intervals using synchronized YSI-EXO2 multiparameter sondes. Meteorological conditions, including precipitation, were also measured at 15-min intervals using NERRS standard weather station instrumentation. PO₄³⁻, NO₃⁻, NH₄⁺, NO₂⁻ and chlorophyll-*a* (Chl-*a*) were measured monthly from grab samples and analyzed in the lab (NERRS, 2023). Samples for nutrients were ~~filtered in the field through 0.7 µm glass fiber filters and~~ analyzed following the U.S. Environmental Protection Agency (EPA) methods (O'Dell, 1996b, a; U.S. EPA., 1993a). For Chl-*a* analysis, the samples were collected as whole water, then filtered onto 0.45 µm glass-filters and processed following APHA, (2001) and U.S. EPA., (1993b) methods. While Chl-*a* is also measured as Chlorophyll fluorescence using optical sensor with YSI sondes, NERRS recommends using laboratory-based measurements due to the confounding effects of various fluorescent species, organism type, light, temperature and more on sensor-based Chl-*a* measurements (sensor and lab-based measurements often do not correspond to each other). We omitted all data flagged as 'suspect' or 'out of range'.

Additionally, we calculated water column depth as the sum of measured water depth plus the distance between the sonde and sediment bed (Table S1). We also calculated the sum of NO₃⁻

Formatted: Superscript

, NO₂⁻, and NH₄⁺ to assess dissolved inorganic nitrogen (DIN) concentrations and the ratio of DIN to PO₄⁻³ (hereafter, N:P).

2.3.2 Determination of major precipitation events.

Because hydrologic dynamics and related estuarine functions can vary dramatically with annual weather conditions, we first- selected one ‘wet’ and one ‘dry’ year for each estuary using precipitation records from nearby airports. The purpose of selecting years with disparate rainfall patterns was to encompass the maximum range of variability in expected estuarine resistance-~~to~~ ~~precipitation~~. Following Murrell et al. (2018), we calculated the long-term interquartile range (IQR, 1990-2020) of total monthly precipitation for each estuary and then -selected relatively wet/dry years based on the number of months plotting above/below IQR and total annual precipitation. Possible wet and dry years were further filtered based on the- completeness of NERRS data available for each estuary (Fig. S1). Long-term precipitation records included: Duluth International, Washington Reagan International, Jacksonville International, Birmingham-Airport, and San Francisco International airports available from the National Center for Environmental Information.

Further, we selected major precipitation events within each wet and dry year by plotting daily precipitation using data from NERR meteorological stations (Fig. S2). 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. For example, at GTM we focused on tropical storms Colin, Julia, and Hermine, hurricanes Matthew and Irma, and two Nor'easters (Table S32). Data availability was a second consideration – we removed possible events for which there was a substantial amount of missing data. Lastly, because metabolic and hydrologic processes vary across seasons, we chose to focus on warm season events, with the exception of San Francisco Bay where most precipitation occurs in the cool season -but seasonal temperature fluctuations are generally lower than in other systems (Fig. S2 and S3, Table S32).

2.4.3 Calculation of resistance.

To investigate physicochemical and urban land-use characteristics associated with estuarine responses to precipitation events, we calculated the resistance index described in Orwin

& Wardle (2004). The resistance index is a normalized parameter (−1 to +1) describing the magnitude of shift in a response variable from an initial condition. It has been used across a wide variety of ecosystems and response variables, including aquatic ecosystems (Thayne et al., 2022, 2023; Tsai et al., 2011). The resistance index is calculated as:

$$Resistance = 1 - \frac{2|D_0|}{(C_0 + |D_0|)} \quad (\text{eq. 1})$$

where, C_0 = concentration of the response variable pre-disturbance, and D_0 = difference between the concentration of the response variable pre- and post-disturbance (P_0) (i.e., $D_0 = C_0 - P_0$). An index value of +1 indicates the highest possible resistance. Index values between 0 and 1 show that the magnitude of response variable shift is less than the magnitude of the baseline (i.e., $|D_0| \leq C_0$). A resistance index of 0 indicates that the shift in the response variable is equivalent to the magnitude of the baseline (i.e., $|D_0| = C_0$), whereas index values between < 0 and −1 reflect that change in the response variable is greater than the magnitude of the baseline (i.e., $|D_0| > C_0$). Overall, index values closer to 1 indicate more resistant systems (Orwin and Wardle, 2004).

While the resistance index is indicative of the ability of a system to maintain its pre-disturbance functions and ecological state (i.e., ecosystem stability), we emphasize that it is a normalized value that does not in itself convey information about overall estuarine health. Similarly, the resistance index in-itself alone cannot infer if a shift has a positive or a negative effect on the ecosystem health. ~~The resistance index can infer the ability of a system to maintain its pre-disturbance functions and/or ecological state (i.e., ecosystem stability).~~ ~~It~~ The resistance index enables the comparison of the amount of change induced by disturbance across vastly different estuaries.

In parallel, it is also useful to consider the absolute value of the response variable (in this case DO) pre- and post-disturbance, which conveys information on the ambient state of an estuary and the directionality of its response to the disturbance. We therefore present C_0 and P_0 (Fig. 2a–e, Table S43, Fig. S4) to define differences in DO within and across estuaries. ~~We also present, as well as~~ the resistance index, which pairs C_0 and P_0 values for the same event (Fig. 2f–j), to understand the ecosystem stability within and across estuaries after precipitation.

Because DO is critical to myriad functions that regulate the health of aquatic ecosystems (Abdul-Aziz et al., 2007; Abdul-Aziz & Gebreslase, 2023; Caffrey, 2004; Mulholland et al., 2001; Murrell et al., 2018; Odum, 1956) and because estuarine metabolism is virtually impossible to model due to bi-directional flow (Loken et al., 2021); we used temperature and salinity adjusted

DO (mg L^{-1}) to calculate the resistance index. Additionally, the resistance index is highly sensitive to the researcher-defined baseline and post-disturbance time periods that are used to calculate C_0 and D_0 . Therefore, we calculated C_0 as average DO during a manually-curated timespan preceding each precipitation event (~24 hours to 6 days, without precipitation) where DO dynamics looked unremarkable (Fig. S54, Table S32). The timespan for estimating P_0 was also manually selected in the context of each event, defined here as the maximum displacement from C_0 during and after the event (Fig. S54, Table S32).- We also verified that the resistance index calculated using DO (mg L^{-1}) versus DO (% sat.)- showed no notable differences (Fig. S65).

2.54 Statistical analysis.

To compare resistance, nutrient concentrations, and concentrations of DO pre- and post-precipitation within and among between estuaries, we used ANOVA with post-hoc Tukey HSD or Kruskal-Wallis test, as appropriate based on the Shapiro-Wilk normality test.

To test associations of specific physicochemical and land-use factor associations with estuarine resistance to precipitation, we used linear regressions at continental and local scales independently (i.e., all estuaries combined vs. within each individual estuary) and within salinity-based groups (i.e., using a threshold of average annual salinity less than or above 10 ppt calculated for wet and dry years separately). 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. The low-salinity group included all LKS and CBM locations, First Mallard and Second Mallard locations at SFB during wet and dry years, as well as Fish River, Middle Bay, Magnolia Bay, and Weeks Bay (Weeks Bay during dry year only) at WKB estuary. The high-salinity group included all monitoring locations at GTM, China Camp and Gallinas Creek at SFB estuary for wet and dry years, and Weeks Bay at WKB during the wet year.

We used annual mean values for continental-scale, local-scale, and salinity-based groups regressions involving nutrients and Chl-*a* because monthly sampling intervals of lab-based

Formatted: Subscript

Formatted: Superscript

Formatted: Font: Italic

measurements did not always correspond with selected precipitation events. This resulted in two data points per monitoring location for nutrients and Chl-*a* regressions. While not directly associated with any particular precipitation event, relationships of nutrients and Chl-*a* with resistance values analyzed on an annual basis carry valuable information about how the ambient conditions of the system can impact an estuary's response to precipitation. This knowledge is essential for deriving and testing hypotheses that describe why a certain estuary may respond to a storm event in a particular way.

For regressions involving sensor-based measurements, we attempted to provide as much resolution as possible into specific events. We therefore used values averaged over the event-specific baseline periods (Table S32) for sensor measurements across scales and salinity-based groupings. Values averaged over event-specific baseline periods were matched with corresponding event-specific resistance index resulting in one data point per precipitation event per each monitoring location. We did not include LULC and population density as predictors of resistance at individual estuaries because of the close proximity of some monitoring locations to one another (< 800 m).

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.

Statistical analyses and visualizations were performed in Python 3.10.11 using scipy.stats, statsmodels, stats.multicomp.pairwise_tukeyhsd, and seaborn, regplot, scikit-learn, and matplotlib libraries/packages.

3. Results

3.1 Land use/land cover and nutrient concentrations across estuaries.

Data describing LULC and population density within 10 km of the monitoring locations for all estuaries are shown in Table 1. The five study estuaries spanned strong gradients in LULC and nutrient concentrations. Both embayments of the SFB had higher percentages of urban-type

land-characteristics (e.g., built area) and population density than any other estuary, followed by CBM (Table 1). Agricultural land was more prevalent at WKB (30.36%) compared to other estuaries. GTM and LKS had more mixed LULC, with high proportions of tree cover. ~~With regard to nutrient concentrations,~~ SFB and CBM had high DIN concentrations compared to LKS and GTM ($p < 0.01$). Mean DIN values at all SFB and CBM monitoring locations were > 0.504 mg-N L⁻¹ versus < 0.16 mg-N L⁻¹ at LKS and GTM (Fig. S96). Phosphate concentrations were the highest at SFB (mean across all monitoring locations = 0.135 mg-P L⁻¹, SD = 0.08 ; means at all other estuaries < 0.03 mg-P L⁻¹, $p < 0.001$, Fig. S95). Overall, mean N:P across LKS, CBM, GTM, WKB, and SFB estuaries were 28.04 (SD = 28.08), 26.56 (SD = 10.75), 2.84 (SD = 0.91), 83.82 (SD = 55.27), and 5.10 (SD = 1.4), respectively (Fig. S107), with GTM and SFB indicating N limiting conditions based on a 16N:1P Redfield ratio (Redfield, 1934).

3.2 Changes in dissolved oxygen and resistance to precipitation across estuaries and monitoring locations.

DO concentrations pre- and post-precipitation differed across all estuaries, when evaluating the overall directionality-trends (pre- (C₀): $F = 45.6$, $p < 0.0001$; and post- (P₀): $F = 17.1$, $p < 0.0001$, Fig. 2a–e). Across all precipitation events (i.e., non-specific to an event), SFB had the highest pre-precipitation DO concentration of all estuaries. Generally, at SFB and CBM (more urban) and at WKB (more agricultural), DO declined following precipitation ($p < 0.01$). At LKS, precipitation events significantly increased DO concentration ($F = 5.1$, $p = 0.0327$). There was no significant difference between the overall pre- and post-precipitation DO concentrations at GTM ($F = 0.5$, $p = 0.48$).

Resistance also differed across estuaries ($F = 21.6$, $df1 = 4$, $df2 = 172$, $p < 0.0001$, Fig. 2). SFB monitoring locations had the highest mean resistance-to-precipitation (mean = 0.68), while monitoring locations at LKS were the least resistant-to-precipitation (mean = 0.47). Within individual estuaries, resistance varied across monitoring locations at LKS ($F = 13.9$, $df1 = 3$, $df2 = 24$, $p < 0.0001$), CBM ($F = 7.9$, $df1 = 2$, $df2 = 27$, $p < 0.01$), and SFB ($F = 10.2$, $df1 = 3$, $df2 = 27$, $p < 0.001$) but was not significantly different between monitoring locations within GTM ($F = 3.5$, $df = 3$, $p = 0.32$) and WKB ($F = 0.9$, $df = 3$, $p = 0.81$) (Fig. 2f–j). Resistance was most variable across monitoring locations at LKS (-0.26 to 0.89) and least variable across locations at WKB (0 to 0.73).

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: Italic

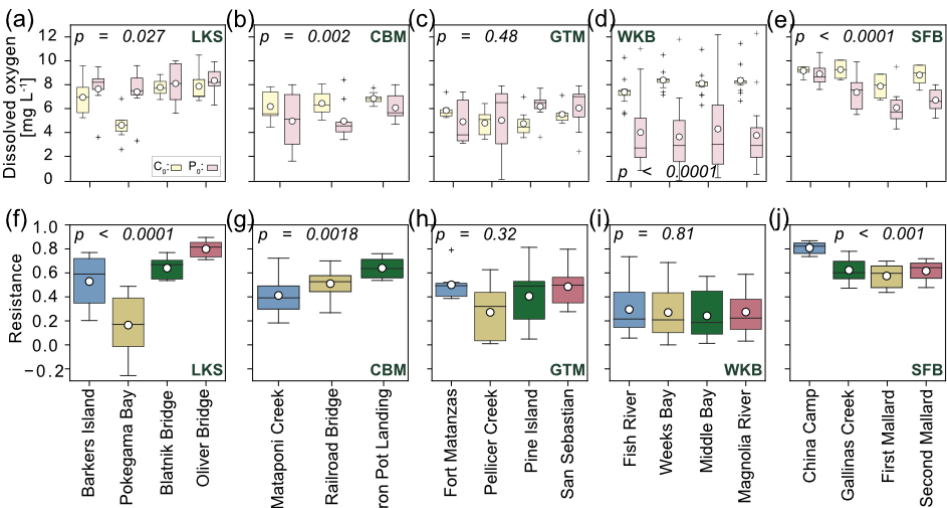


Figure 2: Variation in pre- and post-disturbance distribution of dissolved oxygen and resistance within individual estuaries. Boxes show the quartiles of the dataset and the whiskers show the rest of the distribution. Means are shown in white circles, and medians are shown in black solid lines. *P*-values are at the top of each panel. a-e) Distribution of dissolved oxygen concentrations prior to (C_0 , yellow solid boxes) and post (P_0 , pink dashed boxes) precipitation. f-j) Resistance index across monitoring locations at: Lake Superior (LKS) NERR (all $n = 7$), Chesapeake Bay, Maryland (CBM—Jug Bay) NERR (all $n = 10$), Guana Tolomato-Matanzas (GTM) NERR (all $n = 7$), Weeks Bay (WKB) NERR (all $n = 15$), San Francisco Bay (SFB) NERR ($n = 8$ except Second Mallard (SM) $n = 7$).

3.3 Continental, salinity-based, and local relationships between resistance and with physicochemical factors, land use/land cover, and population density.

When data from the five estuaries were considered together (i.e., continental-scale), we found significant positive relationships of between resistance and with water column depth ($p < 0.0001$; $R^2 = 0.10$), turbidity ($p = 0.0015$; $R^2 = 0.06$), log(DIN) ($p = 0.031$; $R^2 = 0.12$), percent built area ($p = 0.02$; $R^2 = 0.14$), and population density ($p = 0.001$; $R^2 = 0.27$), as well as significant negative relationships with water temperature ($p < 0.0001$; $R^2 = 0.39$) and Chl-*a* ($p < 0.0001$; $R^2 = 0.39$) (Fig. 3, Table S54).

When grouped by salinity, estuarine resistance ~~to precipitation~~ was more ~~strongly~~ tightly correlated to physicochemical and land-use factors (Fig. 3, Table S54). Within ‘low-salinity’ estuaries, resistance was positively related ~~to~~with depth of the water column ($p < 0.0001$; $R^2 = 0.10$), which is consistent with ~~continental-scale results~~ the trend observed on continental scale; and negatively related to salinity ($p < 0.0001$; $R^2 = 0.214$), a relationship not found on continental-scale. Within ‘high-salinity’ estuaries, mean resistance showed positive relationships ~~with~~to annual mean log(DIN) ($p = 0.004$; $R^2 = 0.55$) and ~~to~~ percent built area ($p \leq 0.00102$, $R^2 = 0.73$), ~~which also was~~ consistent with continental-scale results. Also, resistance in high-salinity estuaries was positively ~~related to~~associated with turbidity ($p < 0.0001$, $R^2 = 0.29$). Observations present in ‘high-salinity’ estuaries but absent from continental-scale evaluations included negative relationships ~~between~~of mean resistance ~~and~~with tree cover ($p = 0.011$; $R^2 = 0.46$), ~~as well as~~and negative relationships ~~with~~to N:P ($p < 0.0001$; $R^2 = 0.81$). Additionally, mean resistance in both low- and high-salinity groups was positively related to population density ($p = 0.051$; $R^2 = 0.16$, and $p \leq 0.00102$; $R^2 = 0.73$, respectively), and negatively related to water temperature ($p = 0.001$; $R^2 = 0.38$, and $p = 0.002$; $R^2 = 0.60$, respectively) and Chl-*a* ($p \leq 0.00102$, $R^2 = 0.46$, and $p = 0.044$; $R^2 = 0.32$, respectively). The temperature and Chl-*a* ~~relationships~~trends were consistent with continental-scale ~~result~~observations. Generally, ‘low-salinity’ estuaries ~~had~~showed fewer significant relationships ~~between~~of resistance ~~and~~ ~~with~~physicochemical factors, LULC, and population density compared to ‘high-salinity’ estuaries.

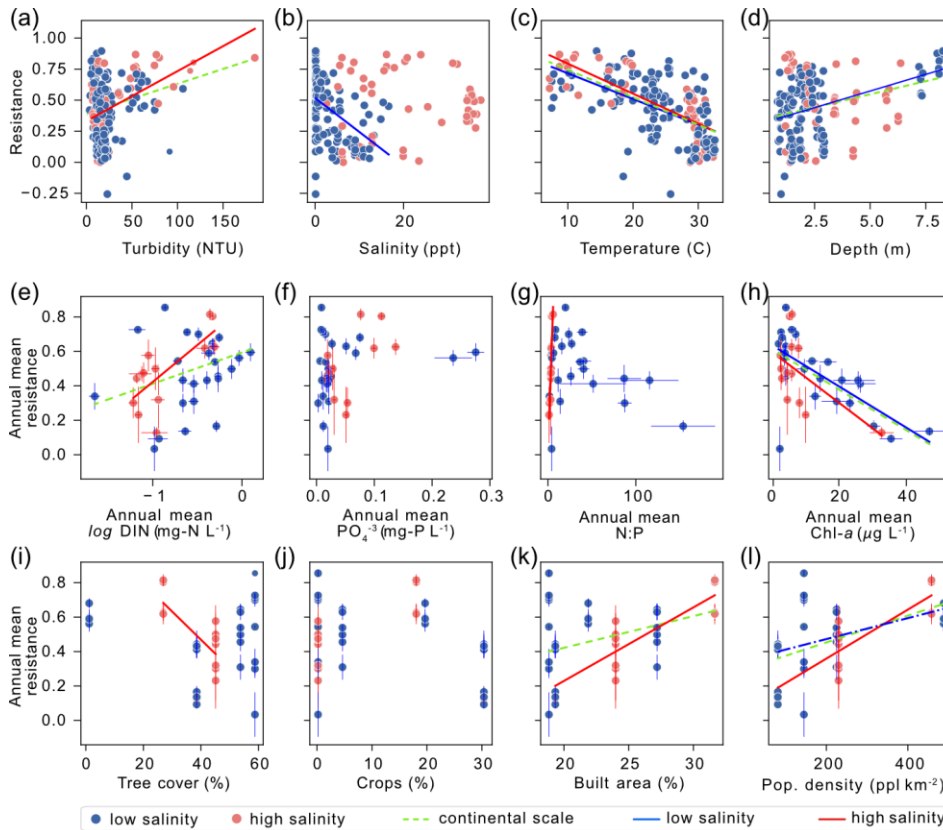
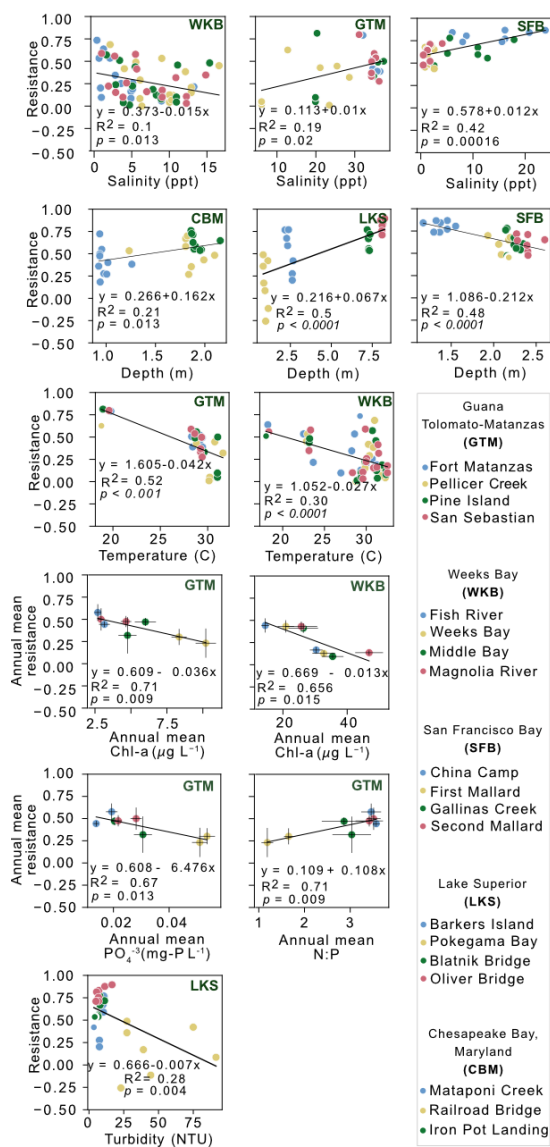


Figure 3. Relationships of continental-scale and salinity-based resistance with physicochemical factors, land use/land cover, and population density. Continental-scale regressions considered all monitoring locations across all estuaries. Significant relationships ($p < 0.05$) are shown in dotted green, solid red, and solid blue lines for continental-scale, high-salinity and low-salinity estuaries, respectively. Standard errors of the mean are shown in vertical and horizontal lines. The LULC parameters and population density were used from within the 10-km proximity zone radius adjoined to the monitoring locations. Please refer to Table S54 for resulting statistics and to Fig. S78 for information on covariance among predictor variables.

At local scales (i.e., within each estuary), resistance was related to some physicochemical factors not factors that were not observed in continental-scale or salinity-based groups

relationships. Moreover, the number, strength, and direction of relationships between local-scale resistance and physicochemical factors varied substantially across estuaries (Fig. 4, Figs. S119, Fig. S120). Resistance at GTM had the highest number of significant relationships between resistance and physicochemical factors. Resistance was negatively related to water temperature ($p < 0.001$; $R^2 = 0.52$), PO_4^{3-} ($p = 0.013$; $R^2 = 0.67$) and Chl-*a* concentrations ($p = 0.009$; $R^2 = 0.71$), as well as positively related to salinity and N:P ($p = 0.02$, $R^2 = 0.19$ and $p = 0.009$, $R^2 = 0.71$, respectively). In contrast, at CBM, resistance was related only to water column depth (positive, $p = 0.013$; $R^2 = 0.21$). At LKS, resistance was positively related to water column depth ($p < 0.0001$; $R^2 = 0.50$), and negatively related to turbidity ($p = 0.004$; $R^2 = 0.28$). At WKB, relationships between resistance and water temperature, salinity, and Chl-*a* concentrations were all negative ($p < 0.0001$, $R^2 = 0.30$; $p = 0.013$, $R^2 = 0.10$; and $p = 0.015$, $R^2 = 0.66$, respectively). At SFB, resistance was negatively related to water column depth ($p < 0.0001$; $R^2 = 0.48$), which opposed the general trend, and positively related to salinity ($p = 0.00016$; $R^2 = 0.42$). There was no overarching relationship between resistance and total precipitation amount of each event, except for a significant but weak negative relationship at GTM estuary ($p = 0.026$, $R^2 = 0.18$, Fig. S134).



424
 425 **Figure 4.** Relationships between resistance and physicochemical factors for each estuary. National
 426 Estuarine Reserve System (NERR) estuary abbreviations: Lake Superior (LKS) NERR,
 427 Chesapeake Bay, Maryland (CBM—Jug Bay) NERR, Guana Tolomato Matanzas (GTM) NERR,
 428 Weeks Bay (WKB) NERR, and San Francisco Bay (SFB) NERR. Significant correlations ($p <$

0.05) are shown with black lines. Standard errors of the mean are shown in vertical and horizontal black lines for relationships using annual means for chlorophyll-*a* (Chl-*a*), PO₄³⁻, and N:P. For additional results see Figs. S119, Fig. S120, and Fig. S142.

In summary, some relationships ~~between~~ estuarine resistance ~~and~~ physicochemical factors and urban land use appeared to be more universal while others varied across scales (Fig. 5). For instance, resistance was related to water temperature, water column depth, turbidity, and Chl-*a* across continental- and local-scales, and within salinity-based estuary groups. Dissolved inorganic N, percent built area, and population density were all related to resistance at the continental scale and in salinity-based groups. Both local and salinity-based evaluations revealed ~~correlations of that~~ N:P, salinity, and turbidity ~~were related to~~ resistance ~~to precipitation~~. Unique relationships included PO₄³⁻ at the local scale (GTM only) and tree cover in ‘high-salinity’ estuaries.

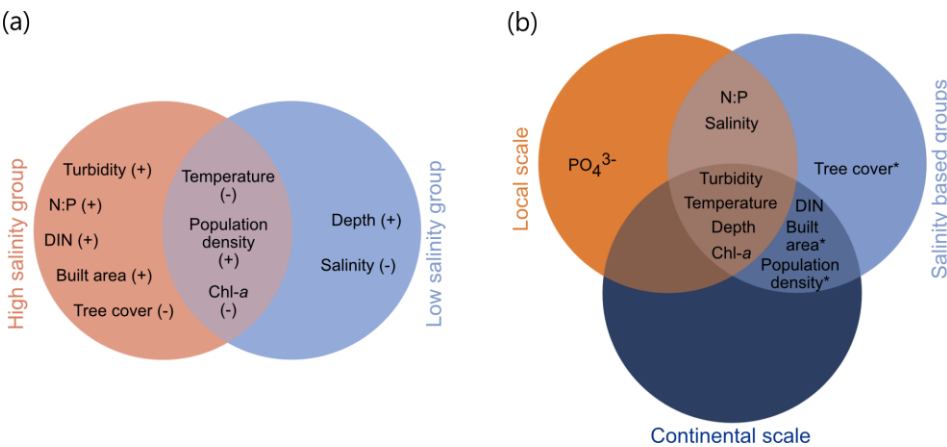


Figure 5. Cross-scale relationships ~~between~~ estuarine resistance ~~and~~ physicochemical factors and land-use ~~factor~~ characteristics. a) Venn diagram of resistance relationships ~~with~~ physicochemical ~~factors~~ and land-use ~~factor~~ characteristics in high- vs. low-salinity estuaries. Positive or negative relationships are indicated with ‘+’ and ‘-’ respectively. b) Venn diagram of ~~resistance~~ 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.

4. Discussion

~~Discerning Understanding patterns in~~ estuarine response ~~patternss following to~~ precipitation is important for predicting ~~futurethe~~ impacts of urbanization and ~~changing global weather patternselimate change~~ on estuarine ~~ecosystemses as a whole~~. Previous studies have shown that patterns identified at large scales may not be applicable across different ~~ecoregionselimatic conditions~~, ~~regional-geologiesy~~, and/or other ecosystem factors (Baker et al., 2004; Gannon et al., 2022; Hopkins et al., 2015; Kaushal et al., 2018; Ombadi and Varadharajan, 2022; Poff et al., 2006). Our results underscore the importance of cross-scale evaluations that can elucidate commonalities in estuarine response to precipitation, as well as variability in the factors associated with resistance ~~to precipitation~~ across individual estuaries.

We show that while relationships between estuarine resistance, urbanization, and DIN may ~~existprevail~~ at the continental-scale, they ~~domay~~ not ~~consistentlyalways apply within correspond~~ ~~to resistance in~~ individual estuaries. This is because ~~an estuary's local~~ resistance ~~dependsis associated with on~~ myriad specific factors in addition to many factors identified at larger scales. ~~IAlso,~~ in contrast to our overarching hypothesis, we find that urbanized estuaries tend to have higher resistance than more pristine estuaries. These results ~~could~~ suggest that the effects of watershed urbanization may impact estuarine stability by either providing some mechanism that allows estuaries responding to major precipitation events to dampen large shifts in DO; or by disturbing the baseline DO to an extent where even a major precipitation event would not produce a significant shift in DO, making the system appear highly resistant.

4.1 Dissolved oxygen dynamics differ ~~betweenin~~ estuaries ~~influenced bywith~~ urban or agricultural land use ~~land cover~~ and those with minimal urbanization.

There were vast differences in geometry, circulation, and hydrologic conditions among urbanized estuaries versus estuaries surrounded by agricultural land in this study. Yet, they exhibited similar patterns in DO response to precipitation. Precipitation generally reduced DO concentrations at WKB, SFB, and CBM (Fig. 2a–e). Simultaneously, the estuary with the least

amount of urbanized LULC—LKS—~~overall~~, experienced an overall increase in DO concentration following precipitation.

While a wide range of physical factors can impact DO in estuaries including channel geometry, ~~and river discharge, circulation, wind patterns, residence time, and upstream reservoirs~~ (Kemp and Boynton, 1980; Raimonet and Cloern, 2017; Raymond et al., 2012; Raymond and Cole, 2001; Scully, 2010; Zheng et al., 2024), ~~wind (Scully, 2010; Zheng et al., 2024), and circulation (Raimonet & Cloern, 2017), (Kemp and Boynton, 1980)~~ urban estuaries in particular are often impacted by a combination of these processes. Urban estuaries often serve as basins for wastewater treatment outflows, which can supply continued freshwater discharge and nutrients during baseflow ~~when river discharge is low~~. Both urban and agriculturally influenced estuaries are prone to increased nutrient loading during and shortly after precipitation events (Chapin et al., 2004; Costanzo et al., 2003; Mallin et al., 2009), which impacts primary production and microbial metabolism and may lead to declines in DO concentrations (e.g., algal blooms). 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).

Therefore, closely examining the directionality of change in DO response to precipitation is important for informing the environmental significance of storm events for a specific ~~estuary~~ estuary system. An ~~overall~~ increase in DO following precipitation could reduce hypoxia through ~~processes like water column~~ reaeration of the water column (Bianucci et al., 2018; Bohórquez-Bedoya et al., 2024), and have positive effects on nutrient cycling and growth ~~conditions for macro- and micro- fauna~~ (Harris et al., 2015) ~~and growth conditions for macro- and micro- fauna~~. A decrease in DO following precipitation may reflect the opposite effects (e.g., hypoxia), ~~leading to which are associated with~~ changes in microbial community structure, disruptions in nutrient cycles, and fish die-off (Diaz et al., 1992; Llansó, 1992). Further, the ~~extent degree~~ to which ecosystem health is ~~linked to~~ associated with DO changes is intertwined with its ~~ambient~~ original ecological state and ~~with~~ the magnitude of the DO ~~change in DO~~. An increase in DO following a storm may be less consequential for estuaries with DO-replete ambient conditions as compared to estuaries with chronically depleted DO. This implies that a ~~comprehensive to more fully assessment the effects~~ of storms impacts on estuarine ecosystem stability and health, ~~estuarine responses should~~ consider ~~be evaluated both through the lens of the~~

resistance index ~~alongside~~, historical DO conditions and ~~through~~ the magnitude and directionality of DO change.

For example, resistance index values for the more pristine and tree-cover dominated Pokegama Bay at LKS was comparable to most monitoring ~~locations~~stations at WKB, which were associated with agriculture. ~~However~~, Pokegama Bay and WKB experienced different patterns in DO change following precipitation (Figs. 2, ~~S4~~). While the full nature of the causes and impacts of DO change in each estuary is beyond the scope of this study, the differences in absolute DO change suggests that different underlying processes influence stability in estuarine dynamics in response to precipitation across different estuaries. Our goal ~~here~~ is to ~~identify~~unravel common ~~factors that are able to~~ predictors of estuarine resistance at the continental ~~_scale~~, despite ~~substantial~~this variabilityin in processes, ~~while also identifying as well as to reveal specific~~ salinity-dependent and estuary-specific predictors ~~in estuaries with contrasting salinity and in individual estuaries to that~~ help elucidate ~~certain~~ dynamics that may be ~~particularly influential~~more impactful in ~~individual systems~~one estuary relative to another.

4.2 Urbanization and inorganic nitrogen correspond with elevated resistance to precipitation at the continental-scale.

Higher resistance to precipitation in the most urbanized estuaries and overarching relationships ~~between~~of urban LULC ~~and with~~ resistance across all estuaries reflect that estuaries within urban watersheds typically experience relatively small shifts in DO following precipitation (Figs. 2, ~~Fig. 3~~). These results contradict our hypothesis that urban estuaries should show low resistance to precipitation because of greater physical and chemical disturbances ~~like~~ (flashiness, streambed scouring, N loading, ~~and~~ turbidity, ~~etc.~~) ~~that impact DO dynamics~~ (Bernhardt et al., 2008; Groffman et al., 2004; Hession et al., 2003; Hopkinson & Vallino, 1995; Walsh et al., 2005).

It is possible that watershed urbanization could equip estuaries with adaptations that help dampen precipitation impacts on shifts in DO. For instance, an increase in flashiness in waterways would increase flow velocity and ~~water column~~ reaeration ~~of the water column in estuaries~~ (Raymond et al., 2012; Raymond and Cole, 2001) and contribute to phytoplankton removal via transport or turbidity-driven light attenuation (Caffrey, 2004; Pennock and Sharp, 1986). This impact may be particularly important for estuaries whose baseline DO conditions are influenced by algal blooms, which induce large diel DO fluctuations by overproducing DO during the day

and severely depleting ~~it~~^{DO} at night (Chapin et al., 2004; Ni et al., 2020). ~~Managing such control for overgrowth of~~ phytoplankton ~~overgrowth could~~^{would} help maintain DO ~~closer to~~^{near} baseline conditions. Supporting this explanation, turbidity-driven limitations on phytoplankton were previously reported for the SFB estuary (Cloern, 1987). We also found ~~that positive and negative relationships of~~ turbidity ~~and~~^{was positively related to built area}. Chl-~~a~~^{was negatively related to,} ~~respectively, with built area and~~ population density (Fig. S13), and ~~PO₄⁻³ 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 PO₄⁻³ concentrations (Keller and Fox, 2019).~~

Relatively high levels of ambient N and low ambient DO in urban estuaries may also facilitate comparatively ~~small~~^{low} DO fluctuations in response to precipitation. ~~Watershed urbanization is often related to high N export to estuarine environments including in the San Francisco Bay area (Bettez et al., 2015; Dugdale et al., 2007; Hopkinson and Vallino, 1995; Parker et al., 2012; Reisinger et al., 2016).~~ Here, estuarine inorganic N concentrations were related to urbanization and also were a major predictor of resistance at the continental-scale (Figs. 3₂ ~~and Fig. S13~~³). 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~~^{including}, 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 Pehler, 2008). Relationships of resistance with N and urbanization were particularly evident in more coastal (high-salinity) estuaries where we found positive ~~relationships~~^{associations of} ~~between~~ resistance ~~with~~^{with} N:P₂ and built area (Fig. 3 ~~and S13~~³). 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 NH₄⁺ were previously suggested to regulate algal blooms in the San Francisco Bay estuary (Dugdale et al., 2007; Parker et al., 2012). Elevated NH₄⁺ concentrations~~

Formatted: Font: Not Italic

Formatted: Subscript

Formatted: Superscript

Formatted: Superscript

Formatted: Subscript

Formatted: Superscript

Formatted: Subscript

Formatted: Superscript

Formatted: Subscript

Formatted: Superscript

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.

Alternatively, we also consider if baseline DO concentrations in urban estuaries are already disturbed to such an extent that precipitation events cause minimal further disruption. Urbanization itself can promote large diel DO fluctuations, as suggested by (Gold et al., 2020), and if a precipitation event induces fluctuations that are similar in magnitude, the post-precipitation DO concentrations will not deviate significantly from baseline conditions. Under such a scenario, urban estuaries will appear more resistant to precipitation events compared to more pristine systems/natural estuaries.

4.3 Water column depth, temperature, turbidity, and Chl-*a* are related to resistance across all scales.

We found generalizable patterns (across all scales), in which resistance was mostly positively related to water column depth and turbidity, and negatively related to water temperature and Chl-*a* (Figs. 3–5). As discussed above, phytoplankton dynamics may be an important factor in regulating DO in response to disturbance due to their tight linkage with N loading, which is consistent with results previously reported by others (Thayne et al., 2023). This is further underscored by the existence of a relationship between Chl-*a* and resistance across continental, salinity-based, and local analyses. In parallel, the relationship between resistance and turbidity was positive at the continental scale and in the high-salinity group (Fig. 3), while at LKS resistance and turbidity correlated negatively (Figs. 3, Fig. 4). The positive relationship/associations of between resistance and with turbidity and simultaneous negative relationship with Chl-*a* can be attributed to turbidity-driven light attenuating conditions that restrict phytoplankton growth, which is further confirmed through negative correlation between turbidity and Chl-*a* (Fig. S78).

Water column depth can also influence estuarine the calculated resistance of estuaries to precipitation through physical and hydrologic impacts on DO. Through dilution, deeper estuaries may better/could have a greater capacity to resist hydrologic changes following/in response to precipitation, for instance by attenuating the effects/influx of oxygen-saturated rain-water, nutrient

Formatted: Subscript

Formatted: Superscript

loading, turbulence, and water-atmosphere gas exchange. Similarly, deep estuaries have longer equilibration time with environmental conditions and less diel variability in parameters like temperature (Caissie, 2006; Macan, 1958). These characteristics which also influence affects diel and seasonal DO dynamics, potentially possibly resulting in more stable DO baselines and more moderate responses to precipitation. Deeper estuaries can also be associated with urbanization, which also shows high resistance in this study, because shifts towards more urban and agricultural LULC generally deepen estuarine channels through increased runoff, sediment transport, hydrological flashiness, channel dredging, and/or other anthropogenic activities (O'Driscoll et al., 2010; Simon and Rinaldi, 2006; Walsh et al., 2005). Therefore, water column depth appears to be a significant critical factor in regulating the resistance to precipitation in estuaries.

Lastly, because temperature controls various chemical and biological processes that impact DO availability (e.g., microbial growth, oxygen solubility), many studies have focused on the impact of rising temperature on DO dynamics in estuaries (Apple et al., 2006; Caffrey, 2003; Caffrey et al., 2014). Highlighted results link changes in weather patterns climate change to thermal pollution of aquatic systems following rain events (Zahn et al., 2021) and link show connections of elevated global temperatures to with decreased primary production (Song et al., 2018). As such, estuaries with elevated ambient temperatures may have a decreased capacity to resist disturbances to DO dynamics relative to estuaries with more moderate temperatures.

4.4 High variability in factors associated with resistance at local scales.

The contrasting relationships and substantial differences in the 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 and conservation strategies (Fig. 5). Individual estuaries may require need to consideration of factors beyond water temperature, water column depth, turbidity, and Chl-*a*—identified here as generalizable at the (i.e., continental scale)—, and as well as be mindful of differences deviations in the directionality of relationships trends 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

~~related~~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 whole-system and/or in~~ individual factor levels, ~~is responses to stressors are not uncommon~~. Understanding how individual physicochemical factors respond to precipitation broadly and within each system provides insight into the observed relationships ~~between~~of those factors ~~and~~with resistance. For example, Chl-*a* and dissolved inorganic phosphorus have been shown to respond more strongly to storms in some estuaries ~~more~~than in others, due to differences in light ~~availability~~limitation, 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 in different~~ estuaries (Apple et al., 2008). ~~While there are myriad potential estuary-specific interactions that may result in different responses to stressors, our results highlight that system variability is important when identifying parameters involved in estuarine resistance to precipitation. We also acknowledge that other scales of investigation (e.g., regional) could introduce additional insight into the predictors of estuarine resistance. Moreover, S~~system dependencies on groundwater discharge ~~as a driver of nutrient inputs and a regulator of~~control on 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 of urban estuaries to precipitation.~~

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.,

Formatted: Space After: 0 pt

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.

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.

Formatted: Justified, Indent: First line: 0"

Formatted: Space After: 0 pt

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.

5. Conclusions.

In light of increasing urbanization and changing emerging rainfall patterns and climate scenarios, cross-scale evaluations of the responses of estuaries to precipitation events are imperative for developing effective management strategies. We find that urban estuaries appear to be more resistant to changes in DO in response to precipitation than more pristine estuaries; and that the depth of the water column, water temperature, turbidity, and Chl-*a* are generalizable cross-scale predictors for estuarine resistance. However, across different scales, we find that system variability results in additional factors that are important to consider when managing the responses to major precipitation events of individual estuaries. Based on our results, we suggest that investigations targeting N, nutrient delivery mechanisms, and microbial activity could help understand what makes urban estuaries more resistant to large shifts in DO following precipitation. We also highlight that high-resolution water quality and nutrient data surrounding precipitation events, along with careful considerations of local variabilities and models for system responses to precipitation, are needed to help elucidate the underlying mechanisms for high resistance of urban estuaries. This study serves as a platform for improvement of guidelines and predictive capabilities addressing system response to future weather and climate and urbanization scenarios.

Data availability: This study used publicly available datasets, which included: 1) Long-term estuarine water quality, nutrients and meteorological conditions and watershed boundaries for Lake Superior (LKS) NERR, Chesapeake Bay, Maryland (CBM) NERR, Guana Tolomato Matanzas (GTM) NERR, Weeks Bay (WKB) NERR, and San Francisco Bay (SFB) NERR stations from <https://cdmo.baruch.sc.edu>; 2) Long-term precipitation data from U.S. airports from

<https://www.ncei.noaa.gov/cdo-web/datasets>; 3) Land use/land cover maps from <https://livingatlas.arcgis.com/landcover/>; 4) U.S. population data from <https://www.worldpop.org/>. Data and ~~data~~ processing code are ~~also~~ available at <https://figshare.com/s/49d2f3dca084d885638a>.

Author Contribution: E.B.G. and A.B.T. developed the study and interpreted the results. A.B.T. performed data analysis and drafted the manuscript. - All authors contributed to manuscript editing.

Competing interest: The authors declare that they have no competing interest.

Acknowledgements:

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Biological and Environmental Research program Early Career award to EBG. The work was performed by Pacific Northwest National Laboratory, operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC05-76RL01830. We thank the National Estuarine Research Reserve System (NERRS), supported by awards from the Office for Coastal Management, National Oceanographic and Atmospheric Administration (NOAA), and Kyle Derby and Dr. Scott Phipps from Chesapeake Bay, Maryland NERR and Weeks Bay NERR, respectively, for maintaining water quality monitoring ~~locations~~~~stations~~ and providing publicly available data upon which this publication is based. We also thank Drs. Alexander J. Reisinger and Matthew H. Kaufman for the insight on metabolism models for aquatic environments.

References

- Abbott, K. M., Zaidel, P. A., Roy, A. H., Houle, K. M., and Nislow, K. H.: Investigating impacts of small dams and dam removal on dissolved oxygen in streams, PLOS ONE, 17, e0277647, <https://doi.org/10.1371/journal.pone.0277647>, 2022.
- Abdul-Aziz, O. I. and Gebreslase, A. K.: Emergent Scaling of Dissolved Oxygen (DO) in Freshwater Streams Across Contiguous USA, Water Resour. Res., 59, e2022WR032114, <https://doi.org/10.1029/2022WR032114>, 2023.
- Abdul-Aziz, O. I., Wilson, B. N., and Gulliver, J. S.: Calibration and Validation of an Empirical Dissolved Oxygen Model, J. Environ. Eng., 133, 698–710, [https://doi.org/10.1061/\(ASCE\)0733-9372\(2007\)133:7\(698\)](https://doi.org/10.1061/(ASCE)0733-9372(2007)133:7(698)), 2007.

743 APHA: Standard Methods for the Examination of Water and Wastewater, (SM10200H), 20th
744 ed., United Book Press, Inc., Baltimore, Maryland, 2001.

745 Apple, J. K., Giorgio, P. A. del, and Kemp, W. M.: Temperature regulation of bacterial
746 production, respiration, and growth efficiency in a temperate salt-marsh estuary, *Aquat. Microb.*
747 *Ecol.*, 43, 243–254, <https://doi.org/10.3354/ame043243>, 2006.

748 Apple, J. K., Smith, E. M., and Boyd, T. J.: Temperature, Salinity, Nutrients, and the Covariation
749 of Bacterial Production and Chlorophyll-a in Estuarine Ecosystems, *J. Coast. Res.*, 2008, 59–75,
750 <https://doi.org/10.2112/SI55-005.1>, 2008.

751 Baker, D. B., Richards, R. P., Loftus, T. T., and Kramer, J. W.: A New Flashiness Index:
752 Characteristics and Applications to Midwestern Rivers and Streams1, *JAWRA J. Am. Water*
753 *Resour. Assoc.*, 40, 503–522, <https://doi.org/10.1111/j.1752-1688.2004.tb01046.x>, 2004.

754 Beman, M. J., Arrigo, K. R., and Matson, P. A.: Agricultural runoff fuels large phytoplankton
755 blooms in vulnerable areas of the ocean, *Nature*, 434, 211–214,
756 <https://doi.org/10.1038/nature03370>, 2005.

757 Bernhardt, E. S., Band, L. E., Walsh, C. J., and Berke, P. E.: Understanding, Managing, and
758 Minimizing Urban Impacts on Surface Water Nitrogen Loading, *Ann. N. Y. Acad. Sci.*, 1134,
759 61–96, <https://doi.org/10.1196/annals.1439.014>, 2008.

760 Bernhardt, E. S., Heffernan, J. B., Grimm, N. B., Stanley, E. H., Harvey, J. W., Arroita, M.,
761 Appling, A. P., Cohen, M. J., McDowell, W. H., Hall Jr., R. O., Read, J. S., Roberts, B. J., Stets,
762 E. G., and Yackulic, C. B.: The metabolic regimes of flowing waters, *Limnol. Oceanogr.*, 63,
763 S99–S118, <https://doi.org/10.1002/lno.10726>, 2018.

764 Bernot, M. J., Sobota, D. J., Hall Jr, R. O., Mulholland, P. J., Dodds, W. K., Webster, J. R.,
765 Tank, J. L., Ashkenas, L. R., Cooper, L. W., Dahm, C. N., Gregory, S. V., Grimm, N. B.,
766 Hamilton, S. K., Johnson, S. L., McDowell, W. H., Meyer, J. L., Peterson, B., Poole, G. C.,
767 Valett, H. M., Arango, C., Beaulieu, J. J., Burgin, A. J., Crenshaw, C., Helton, A. M., Johnson,
768 L., Merriam, J., Niederlehner, B. R., O'brien, J. M., Potter, J. D., Sheibley, R. W., Thomas, S.
769 M., and Wilson, K.: Inter-regional comparison of land-use effects on stream metabolism,
770 *Freshw. Biol.*, 55, 1874–1890, <https://doi.org/10.1111/j.1365-2427.2010.02422.x>, 2010.

771 Bettez, N. D., Duncan, J. M., Groffman, P. M., Band, L. E., O'neil-dunne, J., Kaushal, S. S.,
772 Belt, K. T., and Law, N.: Climate Variation Overwhelms Efforts to Reduce Nitrogen Delivery to
773 Coastal Waters, *Ecosystems*, 18, 1319–1331, <https://doi.org/10.1007/s10021-015-9902-9>, 2015.

774 Bianchi, T. S.: *Biogeochemistry of Estuaries*, Oxford University Press, USA, 721 pp., 2007.

775 Bianucci, L., Balaguru, K., Smith, R. W., Leung, L. R., and Moriarty, J. M.: Contribution of
776 hurricane-induced sediment resuspension to coastal oxygen dynamics, *Sci. Rep.*, 8, 15740,
777 <https://doi.org/10.1038/s41598-018-33640-3>, 2018.

778 Black, R. W., Moran, P. W., and Frankforter, J. D.: Response of algal metrics to nutrients and
779 physical factors and identification of nutrient thresholds in agricultural streams, *Environ. Monit.*

780 Assess., 175, 397–417, <https://doi.org/10.1007/s10661-010-1539-8>, 2011.

781 Bohórquez-Bedoya, E., Rovelli, L., and Lorke, A.: Rainfall as a driver for near-surface
782 turbulence and air-water gas exchange in freshwater aquatic systems, *PLOS ONE*, 19, e0299998,
783 <https://doi.org/10.1371/journal.pone.0299998>, 2024.

784 Bondarenko, M., Kerr, D., Sorichetta, A., and Tatem, A.: Census/projection-disaggregated
785 gridded population datasets for 189 countries in 2020 using Built-Settlement Growth Model
786 (BSGM) outputs, <https://doi.org/10.5258/SOTON/WP00684>, 2020.

787 Booth, D. B. and Jackson, C. R.: Urbanization of Aquatic Systems: Degradation Thresholds,
788 Stormwater Detection, and the Limits of Mitigation1, *JAWRA J. Am. Water Resour. Assoc.*, 33,
789 1077–1090, <https://doi.org/10.1111/j.1752-1688.1997.tb04126.x>, 1997.

790 Brookfield, A. E., Hansen, A. T., Sullivan, P. L., Czuba, J. A., Kirk, M. F., Li, L., Newcomer, M.
791 E., and Wilkinson, G.: Predicting algal blooms: Are we overlooking groundwater?, *Sci. Total*
792 *Environ.*, 769, 144442, <https://doi.org/10.1016/j.scitotenv.2020.144442>, 2021.

793 Buelo, C. D., Besterman, A. F., Walter, J. A., Pace, M. L., Ha, D. T., and Tassone, S. J.:
794 Quantifying Disturbance and Recovery in Estuaries: Tropical Cyclones and High-Frequency
795 Measures of Oxygen and Salinity, *Estuaries Coasts*, [https://doi.org/10.1007/s12237-023-01255-](https://doi.org/10.1007/s12237-023-01255-1)
796 1, 2023.

797 Caffrey, J. M.: Production, Respiration and Net Ecosystem Metabolism in U.S. Estuaries, in:
798 Coastal Monitoring through Partnerships: Proceedings of the Fifth Symposium on the
799 Environmental Monitoring and Assessment Program (EMAP) Pensacola Beach, FL, U.S.A.,
800 April 24–27, 2001, edited by: Melzian, B. D., Engle, V., McAlister, M., Sandhu, S., and Eads, L.
801 K., Springer Netherlands, Dordrecht, 207–219, https://doi.org/10.1007/978-94-017-0299-7_19,
802 2003.

803 Caffrey, J. M.: Factors controlling net ecosystem metabolism in U.S. estuaries, *Estuaries*, 27, 90–
804 101, <https://doi.org/10.1007/BF02803563>, 2004.

805 Caffrey, J. M., Murrell, M. C., Amacker, K. S., Harper, J. W., Phipps, S., and Woodrey, M. S.:
806 Seasonal and Inter-annual Patterns in Primary Production, Respiration, and Net Ecosystem
807 Metabolism in Three Estuaries in the Northeast Gulf of Mexico, *Estuaries Coasts*, 37, 222–241,
808 <https://doi.org/10.1007/s12237-013-9701-5>, 2014.

809 Caissie, D.: The thermal regime of rivers: a review, *Freshw. Biol.*, 51, 1389–1406,
810 <https://doi.org/10.1111/j.1365-2427.2006.01597.x>, 2006.

811 Chang, H.: Spatial and Temporal Variations of Water Quality in the Han River and Its
812 Tributaries, Seoul, Korea, 1993–2002, *Water. Air. Soil Pollut.*, 161, 267–284,
813 <https://doi.org/10.1007/s11270-005-4286-7>, 2005.

814 Chapin, T. P., Caffrey, J. M., Jannasch, H. W., Coletti, L. J., Haskins, J. C., and Johnson, K. S.:
815 Nitrate sources and sinks in Elkhorn Slough, California: Results from long-term continuous in
816 situ nitrate analyzers, *Estuaries*, 27, 882–894, <https://doi.org/10.1007/BF02912049>, 2004.

817 Chapra, S. C.: Surface Water-Quality Modeling, Waveland Press, 865 pp., 2008.

818 Chen, N., Wu, Y., Chen, Z., and Hong, H.: Phosphorus export during storm events from a human
819 perturbed watershed, southeast China: Implications for coastal ecology, *Estuar. Coast. Shelf Sci.*,
820 166, 178–188, <https://doi.org/10.1016/j.ecss.2015.03.023>, 2015.

821 Cheng, Y., Bhoot, V. N., Kumbier, K., Sison-Mangus, M. P., Brown, J. B., Kudela, R., and
822 Newcomer, M. E.: A novel random forest approach to revealing interactions and controls on
823 chlorophyll concentration and bacterial communities during coastal phytoplankton blooms, *Sci.*
824 *Rep.*, 11, 19944, <https://doi.org/10.1038/s41598-021-98110-9>, 2021.

825 Cloern, J. E.: Turbidity as a control on phytoplankton biomass and productivity in estuaries,
826 *Cont. Shelf Res.*, 7, 1367–1381, [https://doi.org/10.1016/0278-4343\(87\)90042-2](https://doi.org/10.1016/0278-4343(87)90042-2), 1987.

827 Cloern, J. E.: Our evolving conceptual model of the coastal eutrophication problem, *Mar. Ecol.*
828 *Prog. Ser.*, 210, 223–253, <https://doi.org/10.3354/meps210223>, 2001.

829 Cloern, J. E. and Jassby, A. D.: Patterns and Scales of Phytoplankton Variability in Estuarine–
830 Coastal Ecosystems, *Estuaries Coasts*, 33, 230–241, <https://doi.org/10.1007/s12237-009-9195-3>,
831 2010.

832 Costanzo, S. D., O’Donohue, M. J., and Dennison, W. C.: Assessing the seasonal influence of
833 sewage and agricultural nutrient inputs in a subtropical river estuary, *Estuaries*, 26, 857–865,
834 <https://doi.org/10.1007/BF02803344>, 2003.

835 Cox, B.: A review of currently available in-stream water-quality models and their applicability
836 for simulating dissolved oxygen in lowland rivers, *Sci. Total Environ.*, 314–316, 335–377,
837 [https://doi.org/10.1016/S0048-9697\(03\)00063-9](https://doi.org/10.1016/S0048-9697(03)00063-9), 2003.

838 Diaz, R. J., Neubauer, R. J., Schaffner, L. C., Pihl, L., and Baden, S. P.: Continuous monitoring
839 of dissolved oxygen in an estuary experiencing periodic hypoxia and the effect of hypoxia on
840 macrobenthos and fish, in: *Marine Coastal Eutrophication*, edited by: Vollenweider, R. A.,
841 Marchetti, R., and Viviani, R., Elsevier, Amsterdam, 1055–1068, [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-0-444-89990-3.50091-2)
842 [0-444-89990-3.50091-2](https://doi.org/10.1016/B978-0-444-89990-3.50091-2), 1992.

843 Dix, N., Phlips, E., and Suscy, P.: Factors Controlling Phytoplankton Biomass in a Subtropical
844 Coastal Lagoon: Relative Scales of Influence, *Estuaries Coasts*, 36, 981–996,
845 <https://doi.org/10.1007/s12237-013-9613-4>, 2013.

846 Dix, N. G., Phlips, E. J., and Gleeson, R. A.: Water Quality Changes in the Guana Tolomato
847 Matanzas National Estuarine Research Reserve, Florida, Associated with Four Tropical Storms,
848 *J. Coast. Res.*, 2008, 26–37, <https://doi.org/10.2112/SI55-008.1>, 2008.

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

852 Elser, J. J., Bracken, M. E. S., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H.,

853 Ngai, J. T., Seabloom, E. W., Shurin, J. B., and Smith, J. E.: Global analysis of nitrogen and
854 phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems,
855 *Ecol. Lett.*, 10, 1135–1142, <https://doi.org/10.1111/j.1461-0248.2007.01113.x>, 2007.

856 Evans, J. R. and Seemann, J. R.: The allocation of protein nitrogen in the photosynthetic
857 apparatus: costs, consequences, and control., in: *Photosynthesis*, edited by: Briggs, W. R., Alan
858 R. Liss, New York, 183–205, 1989.

859 Ferencz, S. B., Cardenas, M. B., and Neilson, B. T.: Aerobic respiration in riparian exchange
860 zones of regulated river corridors, *Hydrol. Process.*, 35, e14386,
861 <https://doi.org/10.1002/hyp.14386>, 2021a.

862 Ferencz, S. B., Muñoz, S., Neilson, B. T., and Cardenas, M. B.: Riverbed Temperature and Heat
863 Transport in a Hydropeaked River, *Water Resour. Res.*, 57, e2021WR029609,
864 <https://doi.org/10.1029/2021WR029609>, 2021b.

865 Fisher, S. G., Gray, L. J., Grimm, N. B., and Busch, D. E.: Temporal Succession in a Desert
866 Stream Ecosystem Following Flash Flooding, *Ecol. Monogr.*, 52, 93–110,
867 <https://doi.org/10.2307/2937346>, 1982.

868 Freeman, L. A., Corbett, D. R., Fitzgerald, A. M., Lemley, D. A., Quigg, A., and Steppe, C. N.:
869 Impacts of Urbanization and Development on Estuarine Ecosystems and Water Quality,
870 *Estuaries Coasts*, 42, 1821–1838, <https://doi.org/10.1007/s12237-019-00597-z>, 2019.

871 Gannon, J. P., Kelleher, C., and Zimmer, M.: Controls on watershed flashiness across the
872 continental US, *J. Hydrol.*, 609, 127713, <https://doi.org/10.1016/j.jhydrol.2022.127713>, 2022.

873 Gold, A., Thompson, S., Magel, C., and Piehler, M.: Urbanization alters coastal plain stream
874 carbon export and dissolved oxygen dynamics, *Sci. Total Environ.*, 747, 141132,
875 <https://doi.org/10.1016/j.scitotenv.2020.141132>, 2020.

876 Gregory, K. J.: Wolman MG (1967) A cycle of sedimentation and erosion in urban river
877 channels. *Geografiska Annaler* 49A: 385-395., *Prog. Phys. Geogr.*, 35, 831–841,
878 <https://doi.org/10.1177/0309133311414527>, 2011.

879 Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., and Briggs, J.
880 M.: Global Change and the Ecology of Cities, *Science*, 319, 756–760, 2008.

881 Groffman, P. M., Law, N. L., Belt, K. T., Band, L. E., and Fisher, G. T.: Nitrogen Fluxes and
882 Retention in Urban Watershed Ecosystems, *Ecosystems*, 7, 393–403,
883 <https://doi.org/10.1007/s10021-003-0039-x>, 2004.

884 Guildford, S. J. and Hecky, R. E.: Total nitrogen, total phosphorus, and nutrient limitation in
885 lakes and oceans: Is there a common relationship?, *Limnol. Oceanogr.*, 45, 1213–1223,
886 <https://doi.org/10.4319/lo.2000.45.6.1213>, 2000.

887 Harris, L. A., Hodgkins, C. L. S., Day, M. C., Austin, D., Testa, J. M., Boynton, W., Van Der
888 Tak, L., and Chen, N. W.: Optimizing recovery of eutrophic estuaries: Impact of destratification

889 and re-aeration on nutrient and dissolved oxygen dynamics, *Ecol. Eng.*, 75, 470–483,
890 <https://doi.org/10.1016/j.ecoleng.2014.11.028>, 2015.

891 He, Q. and Silliman, B. R.: Climate Change, Human Impacts, and Coastal Ecosystems in the
892 Anthropocene, *Curr. Biol.*, 29, R1021–R1035, <https://doi.org/10.1016/j.cub.2019.08.042>, 2019.

893 Hession, W. C., Pizzuto, J. E., Johnson, T. E., and Horwitz, R. J.: Influence of bank vegetation
894 on channel morphology in rural and urban watersheds, *Geology*, 31, 147–150,
895 [https://doi.org/10.1130/0091-7613\(2003\)031<0147:IOBVOC>2.0.CO;2](https://doi.org/10.1130/0091-7613(2003)031<0147:IOBVOC>2.0.CO;2), 2003.

896 Hopkins, K. G., Morse, N. B., Bain, D. J., Bettez, N. D., Grimm, N. B., Morse, J. L., Palta, M.
897 M., Shuster, W. D., Bratt, A. R., and Suchy, A. K.: Assessment of Regional Variation in
898 Streamflow Responses to Urbanization and the Persistence of Physiography, *Environ. Sci.*
899 *Technol.*, 49, 2724–2732, <https://doi.org/10.1021/es505389y>, 2015.

900 Hopkinson, C. S. and Vallino, J. J.: The relationships among man’s activities in watersheds and
901 estuaries: A model of runoff effects on patterns of estuarine community metabolism, *Estuaries*,
902 18, 598–621, <https://doi.org/10.2307/1352380>, 1995.

903 Howarth, R. W.: Nutrient Limitation of Net Primary Production in Marine Ecosystems, *Annu.*
904 *Rev. Ecol. Syst.*, 19, 89–110, 1988.

905 Howarth, R. W. and Marino, R.: Nitrogen as the limiting nutrient for eutrophication in coastal
906 marine ecosystems: Evolving views over three decades, *Limnol. Oceanogr.*, 51, 364–376,
907 https://doi.org/10.4319/lo.2006.51.1_part_2.0364, 2006.

908 Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T. M.,
909 Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J. N., Guo, Q., Hautier, Y., Hector,
910 A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P., Meyer, S. T., Mori, A. S., Naeem, S.,
911 Niklaus, P. A., Polley, H. W., Reich, P. B., Roscher, C., Seabloom, E. W., Smith, M. D., Thakur,
912 M. P., Tilman, D., Tracy, B. F., van der Putten, W. H., van Ruijven, J., Weigelt, A., Weisser, W.
913 W., Wilsey, B., and Eisenhauer, N.: Biodiversity increases the resistance of ecosystem
914 productivity to climate extremes, *Nature*, 526, 574–577, <https://doi.org/10.1038/nature15374>,
915 2015.

916 Kannel, P. R., Lee, S., Lee, Y.-S., Kanel, S. R., and Khan, S. P.: Application of Water Quality
917 Indices and Dissolved Oxygen as Indicators for River Water Classification and Urban Impact
918 Assessment, *Environ. Monit. Assess.*, 132, 93–110, <https://doi.org/10.1007/s10661-006-9505-1>,
919 2007.

920 Karra, K., Kontgis, C., Statman-Weil, Z., Mazzariello, J. C., Mathis, M., and Brumby, S. P.:
921 Global land use / land cover with Sentinel 2 and deep learning, in: 2021 IEEE International
922 Geoscience and Remote Sensing Symposium IGARSS, IGARSS 2021 - 2021 IEEE International
923 Geoscience and Remote Sensing Symposium, Brussels, Belgium, 4704–4707,
924 <https://doi.org/10.1109/IGARSS47720.2021.9553499>, 2021.

925 Kaushal, S. S., Likens, G. E., Pace, M. L., Utz, R. M., Haq, S., Gorman, J., and Grese, M.:
926 Freshwater salinization syndrome on a continental scale, *Proc. Natl. Acad. Sci.*, 115, E574–

927 E583, <https://doi.org/10.1073/pnas.1711234115>, 2018.

928 Keller, A. A. and Fox, J.: Giving credit to reforestation for water quality benefits, PLOS ONE,
929 14, e0217756, <https://doi.org/10.1371/journal.pone.0217756>, 2019.

930 Kemp, W. M. and Boynton, W. R.: Influence of biological and physical processes on dissolved
931 oxygen dynamics in an estuarine system: Implications for measurement of community
932 metabolism, *Estuar. Coast. Mar. Sci.*, 11, 407–431, [https://doi.org/10.1016/S0302-](https://doi.org/10.1016/S0302-3524(80)80065-X)
933 3524(80)80065-X, 1980.

934 Kemp, W. M., Testa, J. M., Conley, D. J., Gilbert, D., and Hagy, J. D.: Temporal responses of
935 coastal hypoxia to nutrient loading and physical controls, *Biogeosciences*, 6, 2985–3008,
936 <https://doi.org/10.5194/bg-6-2985-2009>, 2009.

937 Kornelsen, K. C. and Coulibaly, P.: Synthesis review on groundwater discharge to surface water
938 in the Great Lakes Basin, *J. Gt. Lakes Res.*, 40, 247–256,
939 <https://doi.org/10.1016/j.jglr.2014.03.006>, 2014.

940 Kyzar, T., Safak, I., Cebrian, J., Clark, M. W., Dix, N., Dietz, K., Gittman, R. K., Jaeger, J.,
941 Radabaugh, K. R., Roddenberry, A., Smith, C. S., Sparks, E. L., Stone, B., Sundin, G., Taubler,
942 M., and Angelini, C.: Challenges and opportunities for sustaining coastal wetlands and oyster
943 reefs in the southeastern United States, *J. Environ. Manage.*, 296, 113178,
944 <https://doi.org/10.1016/j.jenvman.2021.113178>, 2021.

945 Lake, P. S.: Resistance, Resilience and Restoration, *Ecol. Manag. Restor.*, 14, 20–24,
946 <https://doi.org/10.1111/emr.12016>, 2013.

947 Leopold, L. B.: Hydrology for urban land planning - A guidebook on the hydrologic effects of
948 urban land use, Circular, U.S. Geological Survey, <https://doi.org/10.3133/cir554>, 1968.

949 Li, C., Zwiers, F., Zhang, X., Chen, G., Lu, J., Li, G., Norris, J., Tan, Y., Sun, Y., and Liu, M.:
950 Larger Increases in More Extreme Local Precipitation Events as Climate Warms, *Geophys. Res.*
951 *Let.*, 46, 6885–6891, <https://doi.org/10.1029/2019GL082908>, 2019.

952 Liao, A., Han, D., Song, X., and Yang, S.: Impacts of storm events on chlorophyll-a variations
953 and controlling factors for algal bloom in a river receiving reclaimed water, *J. Environ. Manage.*,
954 297, 113376, <https://doi.org/10.1016/j.jenvman.2021.113376>, 2021.

955 Llansó, R. J.: Effects of hypoxia on estuarine benthos: the lower Rappahannock River
956 (Chesapeake Bay), a case study, *Estuar. Coast. Shelf Sci.*, 35, 491–515,
957 [https://doi.org/10.1016/S0272-7714\(05\)80027-7](https://doi.org/10.1016/S0272-7714(05)80027-7), 1992.

958 Loken, L. C., Van Nieuwenhuysse, E. E., Dahlgren, R. A., Lenocho, L. E. K., Stumpner, P. R.,
959 Burau, J. R., and Sadro, S.: Assessment of multiple ecosystem metabolism methods in an
960 estuary, *Limnol. Oceanogr. Methods*, 19, 741–757, <https://doi.org/10.1002/lom3.10458>, 2021.

961 Macan, T. T.: The temperature of a small stony stream, *Hydrobiologia*, 12, 89–106,
962 <https://doi.org/10.1007/BF00034143>, 1958.

963 Mallin, M. A., Johnson, V. L., and Ensign, S. H.: Comparative impacts of stormwater runoff on
 964 water quality of an urban, a suburban, and a rural stream, *Environ. Monit. Assess.*, 159, 475–91,
 965 <https://doi.org/10.1007/s10661-008-0644-4>, 2009.

966 Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., and Landgrave, R.:
 967 The coasts of our world: Ecological, economic and social importance, *Ecol. Econ.*, 63, 254–272,
 968 <https://doi.org/10.1016/j.ecolecon.2006.10.022>, 2007.

969 McCluney, K. E., Poff, N. L., Palmer, M. A., Thorp, J. H., Poole, G. C., Williams, B. S.,
 970 Williams, M. R., and Baron, J. S.: Riverine macrosystems ecology: sensitivity, resistance, and
 971 resilience of whole river basins with human alterations, *Front. Ecol. Environ.*, 12, 48–58,
 972 <https://doi.org/10.1890/120367>, 2014.

973 McSweeney, J. M., Chant, R. J., Wilkin, J. L., and Sommerfield, C. K.: Suspended-Sediment
 974 Impacts on Light-Limited Productivity in the Delaware Estuary, *Estuaries Coasts*, 40, 977–993,
 975 <https://doi.org/10.1007/s12237-016-0200-3>, 2017.

976 Mulholland, P. J., Fellows, C. S., Tank, J. L., Grimm, N. B., Webster, J. R., Hamilton, S. K.,
 977 Martí, E., Ashkenas, L., Bowden, W. B., Dodds, W. K., McDowell, W. H., Paul, M. J., and
 978 Peterson, B. J.: Inter-biome comparison of factors controlling stream metabolism, *Freshw. Biol.*,
 979 46, 1503–1517, <https://doi.org/10.1046/j.1365-2427.2001.00773.x>, 2001.

980 Mulholland, P. J., Helton, A. M., Poole, G. C., Hall, R. O., Hamilton, S. K., Peterson, B. J.,
 981 Tank, J. L., Ashkenas, L. R., Cooper, L. W., Dahm, C. N., Dodds, W. K., Findlay, S. E. G.,
 982 Gregory, S. V., Grimm, N. B., Johnson, S. L., McDowell, W. H., Meyer, J. L., Valett, H. M.,
 983 Webster, J. R., Arango, C. P., Beaulieu, J. J., Bernot, M. J., Burgin, A. J., Crenshaw, C. L.,
 984 Johnson, L. T., Niederlehner, B. R., O'Brien, J. M., Potter, J. D., Sheibley, R. W., Sobota, D. J.,
 985 and Thomas, S. M.: Stream denitrification across biomes and its response to anthropogenic
 986 nitrate loading, *Nature*, 452, 202–205, <https://doi.org/10.1038/nature06686>, 2008.

987 Murrell, M. C., Caffrey, J. M., Marcovich, D. T., Beck, M. W., Jarvis, B. M., and Hagy, J. D.:
 988 Seasonal oxygen dynamics in a warm temperate estuary: effects of hydrologic variability on
 989 measurements of primary production, respiration, and net metabolism, *Estuaries Coasts J. Estuar.*
 990 *Res. Fed.*, 41, 690–707, <https://doi.org/10.1007/s12237-017-0328-9>, 2018.

991 NOAA National Estuarine Research Reserve System (NERRS): <https://cdmo.baruch.sc.edu/>, last
 992 access: 26 July 2023.

993 Ni, W., Li, M., and Testa, J. M.: Discerning effects of warming, sea level rise and nutrient
 994 management on long-term hypoxia trends in Chesapeake Bay, *Sci. Total Environ.*, 737, 139717,
 995 <https://doi.org/10.1016/j.scitotenv.2020.139717>, 2020.

996 O'Dell, J. W.: Determination Of Nitrate-Nitrite Nitrogen by Automated Colorimetry, in:
 997 *Methods for the Determination of Metals in Environmental Samples*, Elsevier, 464–478,
 998 <https://doi.org/10.1016/B978-0-8155-1398-8.50026-4>, 1996a.

999 O'Dell, J. W.: Determination of Phosphorus by Semi-Automated Colorimetry, in: *Methods for*
 1000 *the Determination of Metals in Environmental Samples*, Elsevier, 479–495,

1001 <https://doi.org/10.1016/B978-0-8155-1398-8.50027-6>, 1996b.

1002 O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., and McMillan, S.: Urbanization Effects on
 1003 Watershed Hydrology and In-Stream Processes in the Southern United States, *Water*, 2, 605–
 1004 648, <https://doi.org/10.3390/w2030605>, 2010.

1005 Odum, H. T.: Primary Production in Flowing Waters, *Limnol. Oceanogr.*, 1, 102–117,
 1006 <https://doi.org/10.4319/lo.1956.1.2.0102>, 1956.

1007 Ombadi, M. and Varadharajan, C.: Urbanization and aridity mediate distinct salinity response to
 1008 floods in rivers and streams across the contiguous United States, *Water Res.*, 220, 118664,
 1009 <https://doi.org/10.1016/j.watres.2022.118664>, 2022.

1010 Orwin, K. H. and Wardle, D. A.: New indices for quantifying the resistance and resilience of soil
 1011 biota to exogenous disturbances, *Soil Biol. Biochem.*, 36, 1907–1912,
 1012 <https://doi.org/10.1016/j.soilbio.2004.04.036>, 2004.

1013 Paerl, H. W.: Why does N-limitation persist in the world's marine waters?, *Mar. Chem.*, 206, 1–
 1014 6, <https://doi.org/10.1016/j.marchem.2018.09.001>, 2018.

1015 Paerl, H. W. and Piehler, M. F.: Chapter 11 - Nitrogen and Marine Eutrophication, in: *Nitrogen*
 1016 *in the Marine Environment (Second Edition)*, edited by: Capone, D. G., Bronk, D. A.,
 1017 Mulholland, M. R., and Carpenter, E. J., Academic Press, San Diego, 529–567,
 1018 <https://doi.org/10.1016/B978-0-12-372522-6.00011-6>, 2008.

1019 Parker, A. E., Hogue, V. E., Wilkerson, F. P., and Dugdale, R. C.: The effect of inorganic
 1020 nitrogen speciation on primary production in the San Francisco Estuary, *Estuar. Coast. Shelf*
 1021 *Sci.*, 104–105, 91–101, <https://doi.org/10.1016/j.ecss.2012.04.001>, 2012.

1022 Pennock, J. R. and Sharp, J. H.: Phytoplankton production in the Delaware Estuary: temporal and
 1023 spatial variability, *Mar. Ecol. Prog. Ser.*, 34, 143–155, 1986.

1024 Pickett, S. T. A., Cadenasso, M. L., Grove, J. M., Boone, C. G., Groffman, P. M., Irwin, E.,
 1025 Kaushal, S. S., Marshall, V., McGrath, B. P., Nilon, C. H., Pouyat, R. V., Szlavecz, K., Troy, A.,
 1026 and Warren, P.: Urban ecological systems: Scientific foundations and a decade of progress, *J.*
 1027 *Environ. Manage.*, 92, 331–362, <https://doi.org/10.1016/j.jenvman.2010.08.022>, 2011.

1028 Pimm, S. L.: The complexity and stability of ecosystems, *Nature*, 307, 321–326,
 1029 <https://doi.org/10.1038/307321a0>, 1984.

1030 Poff, N. L., Bledsoe, B. P., and Cuhaciyan, C. O.: Hydrologic variation with land use across the
 1031 contiguous United States: Geomorphic and ecological consequences for stream ecosystems,
 1032 *Geomorphology*, 79, 264–285, <https://doi.org/10.1016/j.geomorph.2006.06.032>, 2006.

1033 QGIS Geographic Information System: <https://www.qgis.org/en/site/>, last access: 30 January
 1034 2024.

1035 Rabalais, N. N., Díaz, R. J., Levin, L. A., Turner, R. E., Gilbert, D., and Zhang, J.: Dynamics and

1036 distribution of natural and human-caused hypoxia, *Biogeosciences*, 7, 585–619,
1037 <https://doi.org/10.5194/bg-7-585-2010>, 2010.

1038 Raimonet, M. and Cloern, J. E.: Estuary–ocean connectivity: fast physics, slow biology, *Glob.*
1039 *Change Biol.*, 23, 2345–2357, <https://doi.org/10.1111/gcb.13546>, 2017.

1040 Raymond, P. A. and Cole, J. J.: Gas exchange in rivers and estuaries: Choosing a gas transfer
1041 velocity, *Estuaries*, 24, 312–317, <https://doi.org/10.2307/1352954>, 2001.

1042 Raymond, P. A., Zappa, C. J., Butman, D., Bott, T. L., Potter, J., Mulholland, P., Laursen, A. E.,
1043 McDowell, W. H., and Newbold, D.: Scaling the gas transfer velocity and hydraulic geometry in
1044 streams and small rivers: Gas transfer velocity and hydraulic geometry, *Limnol. Oceanogr.*
1045 *Fluids Environ.*, 2, 41–53, <https://doi.org/10.1215/21573689-1597669>, 2012.

1046 Redfield, A. C.: On the Properties of Organic Derivatives in Sea Water and Their Relation to
1047 Composition of the Phytoplankton, in: James Johnstone Memorial Volume, University Press of
1048 Liverpool, 176–192, 1934.

1049 Reisinger, A. J., Groffman, P. M., and Rosi-Marshall, E. J.: Nitrogen-cycling process rates across
1050 urban ecosystems, *FEMS Microbiol. Ecol.*, 92, fiw198, <https://doi.org/10.1093/femsec/fiw198>,
1051 2016.

1052 Reisinger, A. J., Rosi, E. J., Bechtold, H. A., Doody, T. R., Kaushal, S. S., and Groffman, P. M.:
1053 Recovery and resilience of urban stream metabolism following Superstorm Sandy and other
1054 floods, *Ecosphere*, 8, e01776, <https://doi.org/10.1002/ecs2.1776>, 2017.

1055 Schindler, D. W.: Evolution of Phosphorus Limitation in Lakes, *Science*, 195, 260–262,
1056 <https://doi.org/10.1126/science.195.4275.260>, 1977.

1057 Scully, M. E.: Wind Modulation of Dissolved Oxygen in Chesapeake Bay, *Estuaries Coasts*, 33,
1058 1164–1175, <https://doi.org/10.1007/s12237-010-9319-9>, 2010.

1059 Simon, A. and Rinaldi, M.: Disturbance, stream incision, and channel evolution: The roles of
1060 excess transport capacity and boundary materials in controlling channel response,
1061 *Geomorphology*, 79, 361–383, <https://doi.org/10.1016/j.geomorph.2006.06.037>, 2006.

1062 Smith, S. V.: Phosphorus versus nitrogen limitation in the marine environment, *Limnol.*
1063 *Oceanogr.*, 29, 1149–1160, <https://doi.org/10.4319/lo.1984.29.6.1149>, 1984.

1064 Song, C., Dodds, W. K., Rüegg, J., Argerich, A., Baker, C. L., Bowden, W. B., Douglas, M. M.,
1065 Farrell, K. J., Flinn, M. B., Garcia, E. A., Helton, A. M., Harms, T. K., Jia, S., Jones, J. B.,
1066 Koenig, L. E., Kominoski, J. S., McDowell, W. H., McMaster, D., Parker, S. P., Rosemond, A.
1067 D., Ruffing, C. M., Sheehan, K. R., Trentman, M. T., Whiles, M. R., Wollheim, W. M., and
1068 Ballantyne, F.: Continental-scale decrease in net primary productivity in streams due to climate
1069 warming, *Nat. Geosci.*, 11, 415–420, <https://doi.org/10.1038/s41561-018-0125-5>, 2018.

1070 Thayne, M. W., Kraemer, B. M., Mesman, J. P., Ibelings, B. W., and Adrian, R.: Antecedent lake
1071 conditions shape resistance and resilience of a shallow lake ecosystem following extreme wind

1072 storms, *Limnol. Oceanogr.*, 67, S101–S120, <https://doi.org/10.1002/lno.11859>, 2022.

1073 Thayne, M. W., Kraemer, B. M., Mesman, J. P., Pierson, D., Laas, A., de Eyto, E., Ibelings, B.
 1074 W., and Adrian, R.: Lake surface water temperature and oxygen saturation resistance and
 1075 resilience following extreme storms: chlorophyll a shapes resistance to storms, *Inland Waters*,
 1076 13, 339–361, <https://doi.org/10.1080/20442041.2023.2242081>, 2023.

1077 Tsai, J.-W., Kratz, T. K., Hanson, P. C., Kimura, N., Liu, W.-C., Lin, F.-P., Chou, H.-M., Wu, J.-
 1078 T., and Chiu, C.-Y.: Metabolic changes and the resistance and resilience of a subtropical
 1079 heterotrophic lake to typhoon disturbance, *Can. J. Fish. Aquat. Sci.*, 68, 768–780,
 1080 <https://doi.org/10.1139/f2011-024>, 2011.

1081 Uehlinger, U.: Resistance and resilience of ecosystem metabolism in a flood-prone river system,
 1082 *Freshw. Biol.*, 45, 319–332, <https://doi.org/10.1111/j.1365-2427.2000.00620.x>, 2000.

1083 U.S. EPA.: Method 350.1: Nitrogen, Ammonia (Calorimetric, Automated Phenate), 1993a.

1084 U.S. EPA.: Method 446.0: In Vitro Determination of Chlorophylls a, b, c1+c2 and Pheopigments
 1085 in Marine and Freshwater Algae by Visible Spectrophotometry, 1993b.

1086 Utz, R. M., Hopkins, K. G., Beesley, L., Booth, D. B., Hawley, R. J., Baker, M. E., Freeman, M.
 1087 C., and L. Jones, K.: Ecological resistance in urban streams: the role of natural and legacy
 1088 attributes, *Freshw. Sci.*, 35, 380–397, <https://doi.org/10.1086/684839>, 2016.

1089 Van Meerbeek, K., Jucker, T., and Svenning, J.-C.: Unifying the concepts of stability and
 1090 resilience in ecology, *J. Ecol.*, 109, 3114–3132, <https://doi.org/10.1111/1365-2745.13651>, 2021.

1091 Vietz, G. J., Walsh, C. J., and Fletcher, T. D.: Urban hydrogeomorphology and the urban stream
 1092 syndrome: Treating the symptoms and causes of geomorphic change, *Prog. Phys. Geogr. Earth*
 1093 *Environ.*, 40, 480–492, <https://doi.org/10.1177/0309133315605048>, 2016.

1094 Vitousek, P. M. and Howarth, R. W.: Nitrogen limitation on land and in the sea: How can it
 1095 occur?, *Biogeochemistry*, 13, 87–115, <https://doi.org/10.1007/BF00002772>, 1991.

1096 Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., and Morgan, R.
 1097 P.: The urban stream syndrome: current knowledge and the search for a cure, *J. North Am.*
 1098 *Benthol. Soc.*, 24, 706–723, <https://doi.org/10.1899/04-028.1>, 2005.

1099 Wetz, M. S. and Yoskowitz, D. W.: An ‘extreme’ future for estuaries? Effects of extreme
 1100 climatic events on estuarine water quality and ecology, *Mar. Pollut. Bull.*, 69, 7–18,
 1101 <https://doi.org/10.1016/j.marpolbul.2013.01.020>, 2013.

1102 Zahn, E., Welty, C., Smith, J. A., Kemp, S. J., Baeck, M.-L., and Bou-Zeid, E.: The Hydrological
 1103 Urban Heat Island: Determinants of Acute and Chronic Heat Stress in Urban Streams, *JAWRA J.*
 1104 *Am. Water Resour. Assoc.*, 57, 941–955, <https://doi.org/10.1111/1752-1688.12963>, 2021.

1105 Zarnetske, J. P., Haggerty, R., Wondzell, S. M., Bokil, V. A., and González-Pinzón, R.: Coupled
 1106 transport and reaction kinetics control the nitrate source-sink function of hyporheic zones, *Water*

1107 Resour. Res., 48, <https://doi.org/10.1029/2012WR011894>, 2012.

1108 Zhang, J., Gilbert, D., Gooday, A. J., Levin, L., Naqvi, S. W. A., Middelburg, J. J., Scranton, M.,
 1109 Ekau, W., Peña, A., Dewitte, B., Oguz, T., Monteiro, P. M. S., Urban, E., Rabalais, N. N.,
 1110 Ittekkot, V., Kemp, W. M., Ulloa, O., Elmgren, R., Escobar-Briones, E., and Van der Plas, A. K.:
 1111 Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future
 1112 development, *Biogeosciences*, 7, 1443–1467, <https://doi.org/10.5194/bg-7-1443-2010>, 2010.

1113 Zhang, M., Krom, M. D., Lin, J., Cheng, P., and Chen, N.: Effects of a Storm on the
 1114 Transformation and Export of Phosphorus Through a Subtropical River-Turbid Estuary
 1115 Continuum Revealed by Continuous Observation, *J. Geophys. Res. Biogeosciences*, 127,
 1116 e2022JG006786, <https://doi.org/10.1029/2022JG006786>, 2022.

1117 Zhang, Q., Fisher, T. R., Trentacoste, E. M., Buchanan, C., Gustafson, A. B., Karrh, R., Murphy,
 1118 R. R., Keisman, J., Wu, C., Tian, R., Testa, J. M., and Tango, P. J.: Nutrient limitation of
 1119 phytoplankton in Chesapeake Bay: Development of an empirical approach for water-quality
 1120 management, *Water Res.*, 188, 116407, <https://doi.org/10.1016/j.watres.2020.116407>, 2021.

1121 Zheng, Y., Huang, J., Feng, Y., Xue, H., Xie, X., Tian, H., Yao, Y., Luo, L., Guo, X., and Liu,
 1122 Y.: The Effects of Seasonal Wind Regimes on the Evolution of Hypoxia in Chesapeake Bay:
 1123 Results from A Terrestrial-Estuarine-Ocean Biogeochemical Modeling System, *Prog. Oceanogr.*,
 1124 103207, <https://doi.org/10.1016/j.pocan.2024.103207>, 2024.

1125 Zhi, W., Feng, D., Tsai, W.-P., Sterle, G., Harpold, A., Shen, C., and Li, L.: From
 1126 Hydrometeorology to River Water Quality: Can a Deep Learning Model Predict Dissolved
 1127 Oxygen at the Continental Scale?, *Environ. Sci. Technol.*, 55, 2357–2368,
 1128 <https://doi.org/10.1021/acs.est.0c06783>, 2021.

1129