Increased Utilization of Storm Surge Barriers
A Research Agenda on Estuary Impacts

Orton, Philip; Ralston, David; van Prooijen, Bram; Secor, David; Ganju, Neil; Chen, Ziyu; Fernald, Sarah; Brooks, Bennett; Marcell, Kristin

DOI
10.1029/2022EF002991

Publication date
2023

Document Version
Final published version

Published in
Earth's Future

Citation (APA)
Orton, P., Ralston, D., van Prooijen, B., Secor, D., Ganju, N., Chen, Z., Fernald, S., Brooks, B., & Marcell, K. (2023). Increased Utilization of Storm Surge Barriers: A Research Agenda on Estuary Impacts. *Earth's Future*, *11*(3), Article e2022EF002991. https://doi.org/10.1029/2022EF002991

AGU ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

COMMENTARY
10.1029/2022EF002991

Increased Utilization of Storm Surge Barriers: A Research Agenda on Estuary Impacts

Philip Orton[1], David Ralston[2], Bram van Prooijen[3], David Secor[4], Neil Ganju[5], Ziyu Chen[1], Sarah Fernald[6], Bennett Brooks[7], and Kristin Marcell[7]

[1]Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ, USA, [2]Woods Hole Oceanographic Institution, Woods Hole, MA, USA, [3]Delft University of Technology, Delft, The Netherlands, [4]Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD, USA, [5]U.S. Geological Survey, Woods Hole, MA, USA, [6]Hudson River National Estuarine Research Reserve and New York State Department of Environmental Conservation (NYSDEC), Albany, NY, USA, [7]Consensus Building Institute, Cambridge, MA, USA

Key Points:

- Gated storm surge barriers represent a fundamental change to our coastlines and potentially to ocean-estuary exchanges
- They are increasingly being built for coastal protection and closure frequency of existing barriers is increasing with sea level rise
- Funding of interdisciplinary basic and applied science research is critical to inform billion-dollar decisions on coastal engineering

Correspondence to:
P. Orton,
porton@stevens.edu

Citation:
Orton, P., Ralston, D., van Prooijen, B., Secor, D., Ganju, N., Chen, Z., et al. (2023). Increased utilization of storm surge barriers: A research agenda on estuary impacts. *Earth's Future*, *11*, e2022EF002991. https://doi.org/10.1029/2022EF002991

Received 23 JUN 2022
Accepted 17 FEB 2023

Abstract Rising coastal flood risk and recent disasters are driving interest in the construction of gated storm surge barriers worldwide, with current studies recommending barriers for at least 11 estuaries in the United States alone. Surge barriers partially block estuary-ocean exchange with infrastructure across an estuary or its inlet and include gated areas that are closed only during flood events. They can alter the stratification and salt intrusion, change sedimentary systems, and curtail animal migration and ecosystem connectivity, with impacts growing larger with increasing gate closures. Existing barriers are being used with increasing frequency due to sea level rise. New barrier proposals typically come with maximum closure frequency recommendations, yet the future adherence to them is uncertain. Given that the broader environmental effects and coupled-human dynamics of surge barriers are not well-understood, we present an interdisciplinary research agenda for this increasingly prevalent modification to our coastal zone.

1. Introduction

Increasing coastal flood risk worldwide is driving greater interest in the construction of storm surge barriers for coastal flood risk reduction. Storm surge barriers or tide gates cross an estuary's entrance and include gated areas that are closed only during coastal floods (e.g., Figure 1). Surge barriers can effectively minimize flooding, property damage, and loss of life during large storms, and can be a relatively cost-effective approach to mitigate coastal flood hazards (e.g., Deltacommissie, 2009; NRC, 2014). More surge barrier projects were completed worldwide in the 2010s than any prior decade, including flood risk reduction projects for St. Petersburg (Russia) and New Orleans (Mooyaart & Jonkman, 2017). The MOSE Barrier project is nearly completed and mostly operational on the Venice Lagoon, Italy (Mel et al., 2021). Surge barriers have recently been tentatively selected for flood risk reduction in Coastal Storm Risk Management studies by the United States Army Corps of Engineers (USACE) for 11 estuaries, including Jamaica Bay (New York), Hackensack River (New Jersey), Barnegat Bay (New Jersey), and Galveston Bay (Texas), among others (USACE, 2018, 2020, 2021a, 2021b, 2022a).

The rapid increase in coastal flood disasters in recent decades has primarily been driven by increases in population and property exposure, and increasingly chronic flooding at many locations is being driven by sea level rise (NRC, 2014). Yet, storm surge barriers are not a long-term solution to rising sea levels unless their gates are closed at an exponentially increasing frequency (Chen et al., 2020). Typically, management of barrier closures requires closures when a pre-defined water level threshold (the "trigger") is forecast to be exceeded. Recently, surge barrier plans have proposed 2-year or 5-year return period water levels (USACE, 2021b) as the trigger for closure. Additional shorefront risk reduction features (e.g., nature-based features or seawalls) must be built to address any flooding that occurs when higher-frequency events are coupled with rising sea levels (Chen et al., 2020). Thus, there is also potential that surge barriers, once in place, will have their gates closed more frequently than planned in the initial environmental impact assessment.

Storm surge barriers represent a fundamental change to the geometry of our coastlines and potentially to ocean-estuary exchanges (Figure 2). There is a strong consensus that further study of their estuary impacts is needed, with participation from a broad range of scientific disciplines (e.g., Brand et al., 2016; Swanson et al., 2013). Direct impacts of the barriers (e.g., on water levels) can be predicted and observed relatively easily. More complex consequences with longer time scales (e.g., for sediment dynamics, tidal marshes, migrating

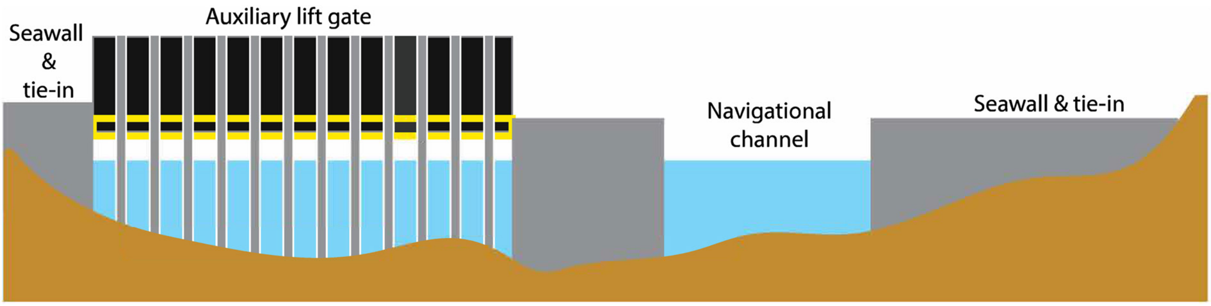

Figure 1. Schematic cross-section of a storm surge barrier system for an estuary with a wide ocean entrance. It includes auxiliary gates intended to reduce flow obstruction during non-storm periods and a wide navigation channel (which also has large gates, not pictured). A similar barrier is proposed for Jamaica Bay, New York City (USACE, 2022a).

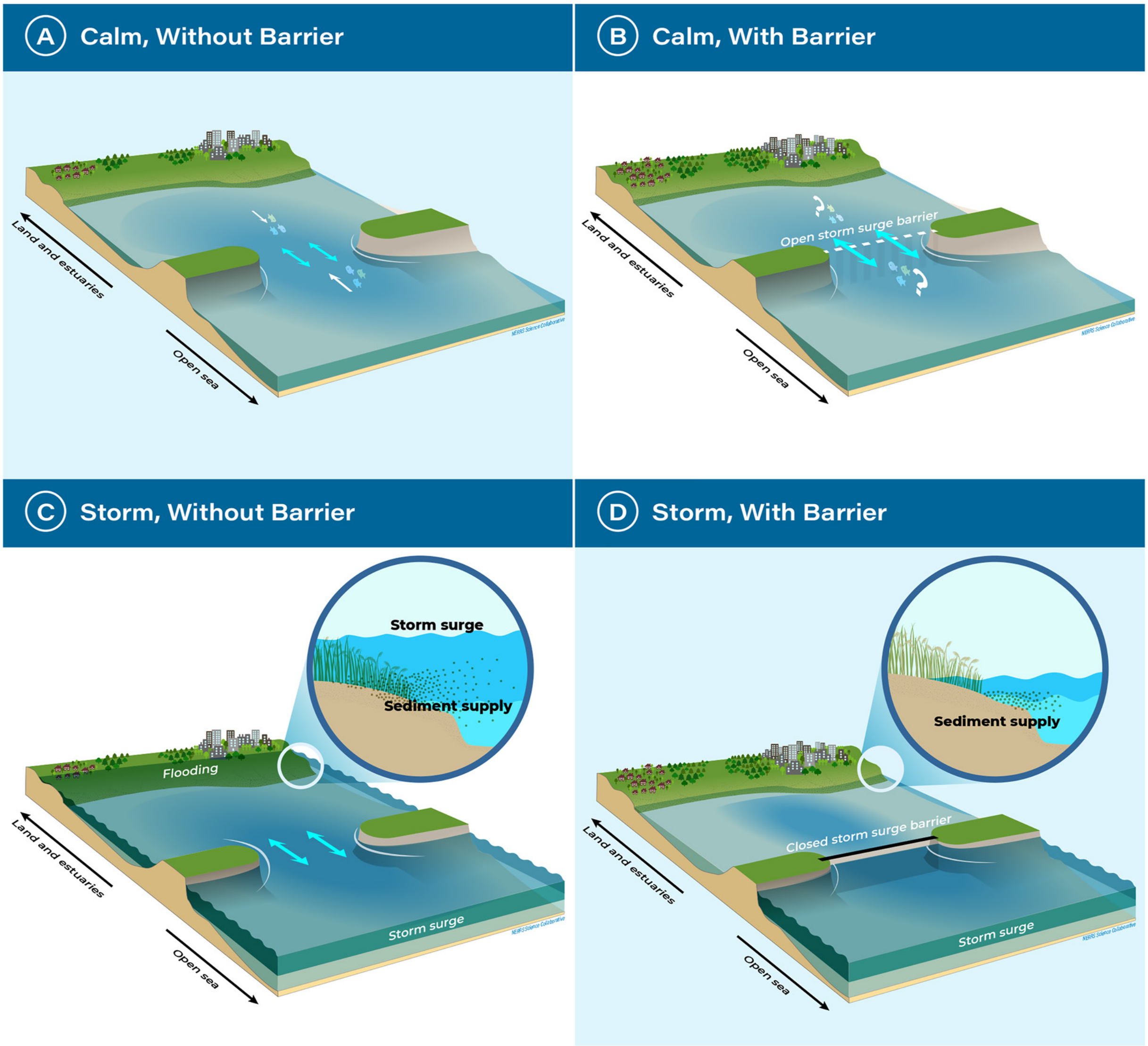

Figure 2. Conceptual diagram showing cases (a, c) without a surge barrier, (b, d) with one, and during (a, b) calm weather, and (c, d) a severe storm surge event. Selected known effects of surge barriers are to increase water speed (blue arrows) through open gates during calm weather (comparing a to b) and reduce flooding of wetlands and populated areas during storms (comparing c to d). Some of the topics for which further research is needed are sedimentation on marshes during flooding (c, d inset circles), induced development in floodplains (increasing buildings from a to b), and effects on migrating organisms (comparing a to b).

fishes; Figure 2) are more difficult to predict and require long term data sets (e.g., De Vet et al., 2017; Troost & Ysebaert, 2011). The proposed widespread deployment of surge barriers should be matched with an equivalent research agenda to improve our understanding of both the natural systems effects and the coupled human systems that will manage the barriers, once built.

The goal of this commentary is to catalyze a broad, interdisciplinary global research effort to study surge barrier estuary physical, chemical, sedimentary and ecological effects. We proceed with (Section 2) background on the known estuary impacts of surge barriers, (Section 3) a proposed research agenda to better understand their effects, and (Section 4) an outline of a pathway forward to address the research agenda.

2. Background

2.1. Open Surge Barrier Physical Effects due to Fixed Infrastructure

The fixed infrastructure of a storm surge barrier system when gates are open typically causes several long-term physical effects. These include locally enhanced water velocities around the open gates (Figure 2; Ralston, 2022), and reductions in velocities and tide amplitudes inside an estuary. For example, after construction of the surge barrier for the Eastern Scheldt estuary in the Netherlands, tidal range in the estuary decreased by 12% on average and tidal velocities decreased by 20–30% (Louters et al., 1998). These reductions in tidal amplitude were associated with reduced vertical mixing, increased salinity stratification (Bakker et al., 1990), and increased residence times (Nienhuis & Smaal, 1994). Modeling studies of hypothetical surge barriers for two "drowned river valley" type estuaries, Chesapeake Bay and the Hudson River estuary, found that open barriers would constrict and accelerate the flow, thereby increasing the total drag and turbulent mixing. This in turn would reduce the tidal amplitude inside these long river-estuaries, widely reducing vertical mixing, increasing stratification, and increasing saltwater intrusion (Du et al., 2017; Ralston, 2022). The amplitude of these changes scales with the degree of obstruction of tidal flows (Orton & Ralston, 2018). Past experience from constructed barriers and modeling of hypothetical barriers both suggest that adding auxiliary flow gates (Figure 1) can reduce flow obstruction and associated impacts but increase overall barrier cost (Mooyaart & Jonkman, 2017).

2.2. Closed Barrier Effects and Assessment Challenges

Barrier closure during a storm can have potentially positive estuary environmental impacts, such as by preventing flood-induced contaminant release/pollution, including wastewater, fuels, and contaminated sediments. Also, the prevention of storm erosion impacts at marsh edges or developed shorelines can be viewed as a positive ecosystem service, though it has ambiguous estuary-wide environmental effects given that erosion at one location often leads to sedimentation and accretion at another (Hu et al., 2018; Tognin et al., 2021).

Short-term effects from gate closures have similar effects on estuary salinity and stratification as the long-term effect of open barriers, but more immediate and amplified, and these are relieved gradually after the gates reopen. In some cases (e.g., smaller surge barriers) closure can be limited to a few hours during high water. However, in other cases multi-day gate closures may be necessary and have the potential to increase saltwater intrusion and stratification past historical maxima. Recovery time to normal conditions after re-opening depends on closure duration, streamflow and estuary length, with dry conditions slowing recovery (Chen & Orton, 2023). Barrier closures trap river water and rain and could cause flooding inside the protected area, particularly during long-duration events. Thus, an important precondition to building or closing barriers is to understand the probability of trapped water flooding (Chen et al., 2020).

Given the large but short-lived estuary effects of barrier closures, and the potential complexity of societal management of closures, assessing the impact of future barrier closures is more challenging. As mentioned in Section 1 (Introduction), there is potential that storm surge barriers, once built, will be closed more frequently in response to sea level rise, essentially using them as "sea level rise barriers". This has already occurred with some constructed surge barriers (e.g., Thames Barrier in Britain, Hall et al., 2019). Existing surge barriers in the northeastern United States are typically referred to as "hurricane barriers" (Morang, 2016; USACE, 2022b), but have a relatively low trigger water level that occurs frequently (Morang, 2007). Public data on the New Bedford Hurricane Barrier show that the closure frequency has generally increased through time and far exceeds the frequency of tropical cyclones of any intensity (Figure 3). The barrier is now used to prevent the increasingly frequent

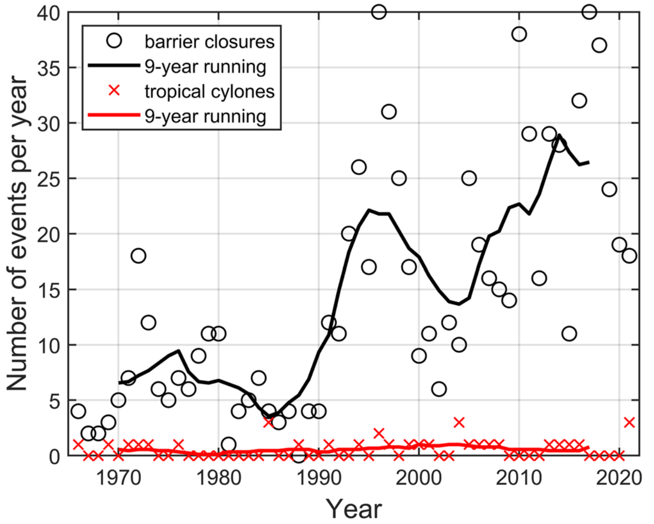

Figure 3. Annual frequency of New Bedford Hurricane Barrier closures (USACE, 2022b) and tropical cyclones (TCs) passing within 200 km from 1966 to 2021 (Landsea & Franklin, 2013), along with 9-year running averages.

flooding that is arising due to sea level rise. Variation in closure frequency over time, such as a local maximum in the 1990s and minimum in the 2000s, may be due to reductions in forecast uncertainty (Chen et al., 2020) or other governance factors such as a management decision to increase the trigger water level.

2.3. Surge Barrier Effects on Migrating Organisms

Flow obstructions of varying sorts can cause changes in faunal assemblages, phenology, and migration behaviors. Keystone fish species migrate from coastal waters to estuaries and freshwater for the purpose of spawning (Limburg & Waldman, 2009). For other species of fishes, cetaceans and turtles, nursery, overwintering, and spawning habitats straddle estuaries and immediately adjacent coastal shelf regions (Woodland et al., 2012). Increasingly, evidence is calling into question the concept of "estuarine-dependent" nektonic fauna (Able, 2005; Brown et al., 2019). Storm surge barriers could curtail reproductive migrations and bisect key habitats that straddle the estuarine-coastal interface where barriers are likely to occur (Figure 2). Specific studies on surge barrier impacts remain rare in the literature. The Geum Estuary Barrage in South Korea was built to intentionally reduce the tide prism and protect freshwater supply. After construction, downstream fish assemblage became more marine and the upstream assemblage more freshwater (Yoon et al., 2017). After the Eastern Scheldt Barrier was built in the Netherlands, there was increased residency by harbor porpoises, suggesting an ecological trap (Jansen et al., 2013). The barrier was also linked to a shift in the phytoplankton assemblage in the Eastern Scheldt due to increased water clarity with the reduction in tidal amplitude and sediment resuspension (Bakker et al., 1990). After construction of the Tawe Barrier Barrage in the United Kingdom, upstream and downstream migrations by adult and juvenile salmon were delayed (Russell et al., 1998).

2.4. Surge Barrier Effects on Sedimentary Systems and Tidal Marshes

Surge barrier projects can cause major changes to estuary sedimentary systems, leading to fundamental morphological changes including for tidal marshes. In the Eastern Scheldt (Section 2.1), the surge barrier reduced tidal energy and sediment resuspension and substantially reduced the sediment flux from the sea into the estuary. Tidal asymmetries in the flow through the barrier openings cause a divergence in sediment transport, reducing the landward transport of sediment from outside the barrier and the seaward transport of sediment sourced from inside. The sedimentary system shifted out of equilibrium, as the channels were too deep for the limited tidal energy. This led to erosion of the intertidal flats and filling of the channels (De Vet et al., 2017). Reductions in tidal resuspension and marsh inundation also led to a 63% loss of tidal marshes (Brand et al., 2016). Similarly, recent studies of Venice Lagoon have demonstrated how surge barriers can reduce coastal storm-driven sedimentation on tidal marshes and therefore their resilience to sea level rise (Tognin et al., 2021, Figure 2). This can in turn reduce the lagoon's geomorphic diversity (Tognin et al., 2022). Long-term morphological and vegetation changes can in turn feed-back on system hydrodynamics (e.g., Donatelli et al., 2018).

3. Research Agenda for Estuary Effects of Storm Surge Barriers

In this section, we identify the estuary science knowledge gaps that could be filled to improve decision-making around building or planning the operation of storm surge barriers. Interdisciplinary research addressing these gaps begins with studying a wider range of estuaries with observation and modeling as described in Section 3.1 below. The most direct effect of a surge barrier on an estuary is to change its hydrodynamics. The estuarine fluid dynamics community, both through observations and numerical models, have appropriate tools to build conceptual and deterministic models of these effects and guide research on topics that depend on the hydrodynamic impacts (e.g., Kirshen et al., 2020; Ralston, 2022). Hydrodynamic changes will cascade to sediment transport and associated geomorphic changes (Section 3.3), but modeling of hydrodynamics and sediment transport both have

10.1029/2022EF002991

remaining uncertainties (Section 3.2). Impacts on biota have seen little prior research and are subject to complex feedback processes (Section 3.4). Surge barriers will exist in the context of other long-term drivers of change such as dredging and climate change (Section 3.5). As described in Section 2.2, coastal flood risk and adaptation using storm surge barriers is a challenging coupled human-geophysical subject, suggesting that social science research is also needed (Section 3.6).

3.1. Data Collection and Research on a Wider Variety of Estuaries

Globally, very little physical and biological data are available to describe the pre-construction condition of riverine and estuarine systems where surge barriers have been constructed. This makes it difficult to comprehensively assess the effects of barriers on these systems or to know how the ecological systems have changed. The case with the most published literature and data is the Eastern Scheldt, an estuary with mean depth of 9 m and limited river input because its river was diverted in the mid-1800s (Louters et al., 1998). Considering proposals for surge barriers on drowned river valley estuaries or lagoonal estuaries (e.g., USACE, 2021a, 2022a), relatively little before-and-after data exists, even though these barriers have been built in the past (e.g., Neva River, Thames River; Mooyaart & Jonkman, 2017). The transport processes affecting salinity, sediment, and other material (e.g., nutrients, pollutants) vary greatly depending on the physical characteristics of an estuary, including geometry, depth, tidal amplitude, degree of stratification and freshwater inflow (e.g., Geyer & MacCready, 2014). Potential impacts of a surge barrier on estuary conditions vary with these same factors. An expanded range of estuaries and physical and ecological measurements, both before and for decades after surge barriers are built, can greatly improve our understanding of their environmental effects.

3.2. Near-Field/Far-Field Coupling and Modeling Sensitivities

Numerical hydrodynamic and sediment transport models are typically deployed for site and regional scale assessments of response to structures (e.g., McAlpin & Emiren, 2022; Warner et al., 2010). Although these models are appealing for their capacity to compare pre- and post-barrier installation scenarios, there are large uncertainties in the models related to spatial resolution and sediment properties, among other factors. The barrier and their openings lead to sharp contraction (upstream) and expansion (downstream) of tidal flow over relatively short distances (10–100s of m). The direct physical effects of this flow obstruction on tides, stratification and salinity can extend throughout the estuary landward of the barrier (10–100s of km). Simulating flows over this range of scales remains a challenge for numerical models, and modeling sensitivity studies would be valuable (e.g., resolution, horizontal eddy parameterizations). The flow through barrier openings can result in flow separation and shedding of vortices that results in form drag felt by the tidal flow at larger scales (Ralston, 2022). The vortices have length scales similar to the pier widths and at times greater than the water depth, so have characteristics of 2D (two-dimensional) turbulence in shallow flows that are not represented in estuary-scale models (Broekema et al., 2018; Uijttewaal & Jirka, 2003). Higher resolution modeling is needed to characterize interactions between the 2D vortices and 3D bottom boundary layer turbulence in the vicinity of the barriers, and to link the localized flow properties to larger-scale impacts on tidal energy flux and transport processes.

Similar modeling challenges apply to sediment transport and morphological evolution, where additional uncertainties are compounded by the range of scales, sharp gradients, and high velocities (e.g., Fringer et al., 2019). Model development and uncertainty assessment should be applied to bed sediment scour in the vicinity of barriers and farther into the estuary where decreased tidal velocities may reduce sediment resuspension or change locations of sediment deposition. Lastly, uncertainties in modeling pollution and biogeochemical impacts will be worsened by these hydrodynamic and sedimentary uncertainties.

3.3. Effects on Sedimentary Systems and Tidal Wetlands

Surge barriers can modify both local and estuary-scale sedimentary processes, and the range of these effects and potential feedback processes for different estuary types should be assessed. The Eastern Scheldt's estuary-wide reduction of intertidal shoals (Section 2.4) may exemplify the effect of surge barriers in reducing tidal amplitudes for an estuary that imports offshore sediments. However, in estuaries where the primary sediment source is from the rivers, barriers may have the opposite effect, increasing sediment retention and leading to enhanced sediment accumulation. Correspondingly, tidal flats and marshes located seaward of a barrier on a river-dominated estuary could experience reduced sediment delivery from the river and be prone to increased erosion. The location of an estuarine turbidity maximum may shift along with any shift in the salinity intrusion (landward or seaward) (Burchard et al., 2018). Potential feedback mechanisms range from relatively straightforward impacts of morphodynamic changes on hydrodynamics, to more complex biogeomorphological feedback mechanisms discussed in Section 3.4. Potential remobilization of contaminated sediment in urbanized estuaries provides additional motivation to better understand these processes.

Storms and associated high water levels are important but relatively understudied mechanisms for sediment supply to salt marshes (Leonardi et al., 2018). Post-event sampling campaigns have shown contrasting effects depending on local sediment supply and mobilization processes (Elsey-Quirk, 2016; FitzGerald et al., 2020); reduction of episodic high-water events will likely reduce storm-associated deposition on wetland platforms (Figure 2). Wave-induced erosion of marsh edges is often maximum near inlets where oceanic swell propagates unimpeded (Tommasini et al., 2019), therefore surge barriers may reduce edge erosion (even when open, if ocean swell waves are dissipated). On the landward marsh edge, migration is controlled by sea-level rise and storm surge that increase soil salinity at the forest-marsh transition (Fagherazzi et al., 2019); whether surge barriers influence migration by limiting the storm surge contribution to soil salinity can be investigated by comparing historical rates of migration with modern rates in natural and barriered systems. The Fagherazzi et al. (2019) "ecological ratchet" model of marsh migration assumes that storms and associated saltwater intrusion initiate forest dieback and control the lower boundary where forest may persist; sea-level rise controls the upper boundary of where forest can regenerate after episodic events. Therefore, the operation of surge barriers could largely eliminate the ecological ratchet and limit the migration of marsh into coastal forest. Salinity also plays a large role in the spread of invasive species at the landward margin, including Phragmites australis (Shaw et al., 2022). Eliminating the effect of episodic salinity fluctuations during storms may influence colonization by invasive species in the forest understory. Detailed field, remote-sensing, and modeling investigations into these coupled biogeomorphic processes across the estuary-wetland continuum could facilitate understanding the effects of barriers on wetland function and trajectory.

In urban estuary systems, the monetary benefits of surge barrier construction may greatly exceed the costs, and so an important research question is whether sedimentary mitigation can be effective and its costs manageable. For example, with the Eastern Scheldt, tidal flats are now nourished to mitigate the tidal flat erosion (Van der Werf et al., 2019). In cases where riverine sediment sources have been interrupted, they could be restored to mitigate loss of storm-driven sediment supply to marshes (Tognin et al., 2021). Similarly, sediments can be pumped onto marshes as thin layer placements, to mitigate any reductions in natural sedimentation. Research should also assess the long-term capacity and costs for managing sedimentary systems in these ways.

3.4. Effects on Migrating and Resident Organisms

A likely starting point for impact research pertinent to nektonic fauna (NF: crustaceans, fishes, turtles, and cetaceans) are the dams and other barriers that segment freshwater fluvial environments. Estuarine and coastal storm surge barriers will allow much greater organismal flux than freshwater dams but are expected to alter migrations and connectivity through their operations (frequency of closure; Figure 3), changed hydrology, and presence of artificial structures. As with dams, a focus on NF passage rates can aid in predictions of how storm surge barriers and their operation might affect key ecological functions such as reproduction, growth, and overwintering of populations; and production, resilience and stability in metapopulations and communities (Secor, 2015). Here, two baseline elements are important: (a) Understanding how spatial structure upstream and downstream of the imminent barrier contributes to ecological function (McKay et al., 2017) and, (b) estimating passage rates of NF with observations and models prior to barrier construction to support Before-After-Control-Impact (also Before-After-Gradient) studies (Algera et al., 2020; Bellmore et al., 2017; Ellis & Schneider, 1997).

Science that informs riverine barrier construction, design, and removal relies on passage rates of key biota and includes a range of empirical and modeling approaches. Here, the integration of empirical estimates and modeling provides an advantage in leveraging field designs and data in prediction and simulations (McKay et al., 2017). In comparison to upstream dams, estuarine and coastal barriers and adjacent regions will receive oceanographic forcing. Here numerical models that utilize observing system data (wind, temperature, tide, salinity) and derived hydraulic models can be coupled with empirical measures of passage rates (Burke et al., 2016; Hidalgo et al., 2016). Biotelemetry arrays are a particularly powerful means to synchronize fine scale (meters and seconds) three-dimensional movements of NF to coastal forcing, supporting flexible predictive models (e.g., nonlinear General Additive Mixed models; e.g., Breece et al., 2018; Rothermel et al., 2020). An alternative approach is to model passage as emergent behaviors related to simple and more complex simulations of movement ecology through agent-based models. The most abstract model might consider NF as passive particles, arguably an unreasonable assumption, but a valuable null model to evaluate how well passage is predicted under the simplest of assumptions. Such models are conducive in evaluating, a priori, not only impacts but aspects of barrier design and operation that might mitigate impacts (Goodwin et al., 2006; Morrice et al., 2020). Finally, e-DNA could support coarser assessments to evaluate impacts to NF communities and rare species (Consuegra et al., 2021; Pfleger et al., 2016).

Intertidal flats and marshes host a range of benthic species, influencing the flow, sediment transport and morphodynamics. Complex biogeomorphological feedback mechanisms can occur between biostabilizers/bioturbators, morphodynamics and hydrodynamics (Le Hir et al., 2007; Volkenborn et al., 2007; Weerman et al., 2012; Widdows & Brinsley, 2002). The robustness of these interactions determines how the system will react to a modification like a barrier. Biostabilizers reduce the erosion, while biodestabilizers or bioturbators can lead to more resuspension of sediment. These organisms strongly depend on immersion times and hydrodynamic stresses, but also on sediment composition and predation and food availability. Relatively small changes could lead to tipping the system to another equilibrium, with changes in bed level, bed composition and benthic community as consequence. Further research is needed on how robust these biogemorphological feedback mechanisms are and whether they can be changed by the presence of barriers.

3.5. Combined Effects of Surge Barriers, Dredging and Climate Change

Surge barrier driven increases in estuary salinity, stratification and bottom-water residence time could lead to reductions in dissolved oxygen concentrations (Du et al., 2017; Kirshen et al., 2020). These are similar changes to those expected from sea level rise and climate warming (e.g., Najjar et al., 2010), as well as dredging (Ralston & Geyer, 2019) in estuaries. For example, the projected landward shift in the Hudson River's salinity intrusion from modeling of the potential New York/New Jersey Harbor barrier was similar to that from the most recent harbor deepening project (from 13.7 to 15.2 m, in 2016; Ralston, 2022). Therefore, an important additional area of future research is the combination of climate change, dredging and surge barrier effects on estuaries.

3.6. Coupled Human-Natural System Dynamics of Surge Barrier Management

Surge barrier estuary impacts are highly sensitive to human management of gate closures (Section 2.2) and understanding and predicting future closure management and evolving societal vulnerability in barrier-protected floodplains is a grand research challenge. Two choices are available as flooding becomes more frequent due to sea level rise (Chen et al., 2020): (a) Close the barrier at an increasing frequency, or (b) raise the trigger water level for closures and pre-emptively apply shorefront or non-structural measures inside an estuary to prevent flooding. However, the record of society in pre-emptive flood risk reduction is poor (NRC, 2014), and increasing closures of surge barrier systems (e.g., Figure 3) are evidence that closing barriers more frequently may be a more common response to sea level rise. Moreover, it is common for governmental institutions, households and businesses to increase development in floodplains behind coastal risk reduction projects (Figure 2), a phenomenon called induced development (NRC, 2014). Given the NRC (2014) conclusion that the primary factor in our recent increases in flood risk has been increased development in floodplains, the potential for induced development requires further study, including the case where protective structures are located far from sight (Ludy & Kondolf, 2012).

4. A Path Forward

The research agenda above is interdisciplinary and ranges from fundamental to applied research questions. A joint effort including universities, government engineers, NGOs and scientific agencies is needed to tackle this societally important and rapidly growing topic. This likely requires new funding sources and strategies, and open science is key. New baseline science, such as before-after-control-impact study designs, is also critical. The recent US Engineering with Nature initiative provides an example of this broad collaboration (Bridges et al., 2015) as does the Dutch EcoShape consortium (De Vriend & Van Koningsveld, 2012). The broader challenge will be to better understand the long-term tradeoffs of investing in barriers versus other alternatives to address multiple hazards from an economic, social, and environmental perspective.

Data Availability Statement

The only data used in this commentary are publicly available data that were used in creating Figure 3. These are: (a) HURDAT2 (Landsea & Franklin, 2013) from https://www.nhc.noaa.gov/data/#hurdat. https://www.nhc.noaa.gov/data/#hurdat and (b) New Bedford Hurricane Barrier closures (USACE, 2022b), from https://reservoircontrol.usace.army.mil/nae_ords/cwmsweb/cwms_web.other_html.BulletinPage.

Acknowledgments

The authors draw on discussions during a series of 2019–2020 scientist and stakeholder workshops held under the project Assessing the Effects of Storm Surge Barriers on the Hudson River Estuary, https://nerrssciencecollaborative.org/project/Orton18. The lead author was supported by the National Estuarine Research Reserve Science Collaborative (Award NA14NOS4190145, Subaward SUBK00009741), the Environmental Defense Fund and NOAA's Climate Adaptation Partnerships (CAP) program (Award NA21OAR4310313).

References

Able, K. W. (2005). A re-examination of fish estuarine dependence: Evidence for connectivity between estuarine and ocean habitats. *Estuarine, Coastal and Shelf Science*, *64*(1), 5–17. https://doi.org/10.1016/j.ecss.2005.02.002

Algera, D., Rytwinski, T., Taylor, J., Bennett, J., Smokorowski, K., Harrison, P., et al. (2020). What are the relative risks of mortality and injury for fish during downstream passage at hydroelectric dams in temperate regions? A systematic review. *Environmental Evidence*, *9*(1), 3. https://doi.org/10.1186/s13750-020-0184-0

Bakker, C., Herman, P., & Vink, M. (1990). Changes in seasonal succession of phytoplankton induced by the storm-surge barrier in the Oosterschelde (SW Netherlands). *Journal of Plankton Research*, *12*(5), 947–972. https://doi.org/10.1093/plankt/12.5.947

Bellmore, J., Duda, J. J., Craig, L., Greene, S. L., Torgersen, C. E., Collins, M. J., & Vittum, K. (2017). Status and trends of dam removal research in the United States. *WIREs Water*, *4*(2), e1164. https://doi.org/10.1002/wat2.1164 Retrieved from http://pubs.er.usgs.gov/publication/70181792

Brand, N., Kothuis, B., & Van Prooijen, B. (2016). The Eastern Scheldt Survey: A concise overview of the estuary pre- and post barrier - Part 1: MEMO, urban Integrity-Naarden/B business EnergyAmsterdam. Retrieved from http://pure.tudelft.nl/ws/files/4682712/2016_The_Eastern_Scheldt_Survey_Brand_Kothuis_Prooijen_final.pdf

Breece, M. W., Fox, D. A., & Oliver, M. J. (2018). Environmental drivers of adult Atlantic sturgeon movement and residency in the Delaware Bay. *Marine and Coastal Fisheries*, *10*(2), 269–280. https://doi.org/10.1002/mcf2.10025

Bridges, T. S., Wagner, P. W., Burks-Copes, K. A., Bates, M. E., Collier, Z. A., Fischenich, C. J., et al. (2015). Use of natural and nature-based features (NNBF) for coastal resilience. Retrieved from Vicksburg, Mississippi, USA.

Broekema, Y., Labeur, R., & Uijttewaal, W. (2018). Observations and analysis of the horizontal structure of a tidal jet at deep scour holes. *Journal of Geophysical Research: Earth Surface*, *123*(12), 3162–3189. https://doi.org/10.1029/2018jf004754

Brown, D. M., Sieswerda, P. L., & Parsons, E. (2019). Potential encounters between humpback whales (*Megaptera novaeangliae*) and vessels in the New York Bight apex, USA. *Marine Policy*, *106*, 103527. https://doi.org/10.1016/j.marpol.2019.103527

Burchard, H., Schuttelaars, H. M., & Ralston, D. (2018). Sediment trapping in estuaries. *Annual Review of Marine Science*, *10*(1), 371–395. https://doi.org/10.1146/annurev-marine-010816-060535

Burke, B. J., Anderson, J. J., Miller, J. A., Tomaro, L., Teel, D. J., Banas, N. S., & Baptista, A. M. (2016). Estimating behavior in a black box: How coastal oceanographic dynamics influence yearling Chinook salmon marine growth and migration behaviors. *Environmental Biology of Fishes*, *99*(8), 671–686. https://doi.org/10.1007/s10641-016-0508-7

Chen, Z., & Orton, P. M. (2023). Effects of storm surge barrier closures on estuary saltwater intrusion and stratification. *Water Resources Research*, *59*(3), e2022WR032317. https://doi.org/10.1029/2022WR032317

Chen, Z., Orton, P. M., & Wahl, T. (2020). Storm surge barrier protection in an era of accelerating sea level rise: Quantifying closure frequency, duration and trapped river flooding. *Journal of Marine Science and Engineering*, *8*(9), 725. https://doi.org/10.3390/jmse8090725

Consuegra, S., O'Rorke, R., Rodriguez-Barreto, D., Fernandez, S., Jones, J., & Garcia de Leaniz, C. (2021). Impacts of large and small barriers on fish assemblage composition assessed using environmental DNA metabarcoding. *Science of the Total Environment*, *790*, 148054. https://doi.org/10.1016/j.scitotenv.2021.148054

Deltacommissie (2009). *Working together with water: A living land builds for its future. Findings of the Deltacommissie 2008, summary and conclusions*. Hollandia Printing.

De Vet, P., Van Prooijen, B., & Wang, Z. (2017). The differences in morphological development between the intertidal flats of the Eastern and Western Scheldt. *Geomorphology*, *281*, 31–42. https://doi.org/10.1016/j.geomorph.2016.12.031

De Vriend, H., & Van Koningsveld, M. (2012). Building with nature. Thinking, acting and interacting differently. Ecoshape Building With Nature, Dordrecht, The Netherlands.

Donatelli, C., Ganju, N. K., Zhang, X., Fagherazzi, S., & Leonardi, N. (2018). Salt marsh loss affects tides and the sediment budget in shallow bays. *Journal of Geophysical Research: Earth Surface*, *123*(10), 2647–2662. https://doi.org/10.1029/2018jf004617

Du, J., Shen, J., Bilkovic, D. M., Hershner, C. H., & Sisson, M. (2017). A numerical modeling approach to predict the effect of a storm surge barrier on hydrodynamics and long-term transport processes in a partially mixed estuary. *Estuaries and Coasts*, *40*(2), 387–403. https://doi.org/10.1007/s12237-016-0175-0

Ellis, J. I., & Schneider, D. C. (1997). Evaluation of a gradient sampling design for environmental impact assessment. *Environmental Monitoring and Assessment*, *48*(2), 157–172. https://doi.org/10.1023/A:1005752603707

Elsey-Quirk, T. (2016). Impact of hurricane Sandy on salt marshes of New Jersey. *Estuarine, Coastal and Shelf Science*, *183*, 235–248. https://doi.org/10.1016/j.ecss.2016.09.006

Fagherazzi, S., Anisfeld, S. C., Blum, L. K., Long, E. V., Feagin, R. A., Fernandes, A., et al. (2019). Sea level rise and the dynamics of the marsh-upland boundary. *Frontiers in Environmental Science*, *7*. https://doi.org/10.3389/fenvs.2019.00025

FitzGerald, D. M., Hughes, Z. J., Georgiou, I. Y., Black, S., & Novak, A. (2020). Enhanced, climate-driven sedimentation on salt marshes. *Geophysical Research Letters*, *47*(10), e2019GL086737. https://doi.org/10.1029/2019GL086737

Fringer, O. B., Dawson, C. N., He, R., Ralston, D. K., & Zhang, Y. J. (2019). The future of coastal and estuarine modeling: Findings from a workshop. *Ocean modelling*, *143*, 101458. https://doi.org/10.1016/j.ocemod.2019.101458. https://www.sciencedirect.com/science/article/pii/S1463500319301015

Geyer, W. R., & MacCready, P. (2014). The estuarine circulation. *Annual Review of Fluid Mechanics*, *46*(1), 175–197. https://doi.org/10.1146/annurev-fluid-010313-141302

Goodwin, R. A., Nestler, J. M., Anderson, J. J., Weber, L. J., & Loucks, D. P. (2006). Forecasting 3-D fish movement behavior using a Eulerian–Lagrangian–agent method (ELAM). *Ecological Modelling*, *192*(1), 197–223. https://doi.org/10.1016/j.ecolmodel.2005.08.004. https://www.sciencedirect.com/science/article/pii/S0304380005003327

Hall, J. W., Harvey, H., & Manning, L. J. (2019). Adaptation thresholds and pathways for tidal flood risk management in London. *Climate Risk Management*, *24*, 42–58. https://doi.org/10.1016/j.crm.2019.04.001. https://www.sciencedirect.com/science/article/pii/S2212096318301487

Hidalgo, M., Secor, D. H., & Browman, H. I. (2016). Observing and managing seascapes: Linking synoptic oceanography, ecological processes, and geospatial modelling. *ICES Journal of Marine Science*, *73*(7), 1825–1830. https://doi.org/10.1093/icesjms/fsw079

Hu, K., Chen, Q., Wang, H., Hartig, E. K., & Orton, P. M. (2018). Numerical modeling of salt marsh morphological change induced by Hurricane Sandy. *Coastal Engineering*, *132*, 63–81. https://doi.org/10.1016/j.coastaleng.2017.11.001

Jansen, O. E., Aarts, G. M., & Reijnders, P. J. (2013). Harbour porpoises Phocoena phocoena in the eastern Scheldt: A resident stock or trapped by a storm surge barrier? *PLoS One*, *8*(3), e56932. https://doi.org/10.1371/journal.pone.0056932

Kirshen, P., Borrelli, M., Byrnes, J., Chen, R., Lockwood, L., Watson, C., et al. (2020). Integrated assessment of storm surge barrier systems under present and future climates and comparison to alternatives: A case study of Boston, USA. *Climatic Change*, *162*(2), 445–464. https://doi.org/10.1007/s10584-020-02781-8

Landsea, C. W., & Franklin, J. L. (2013). Atlantic hurricane database uncertainty and presentation of a new database format. *Monthly Weather Review*, *141*(10), 3576–3592. https://doi.org/10.1175/mwr-d-12-00254.1. https://journals.ametsoc.org/view/journals/mwre/141/10/mwr-d-12-00254.1.xml

Le Hir, P., Monbet, Y., & Orvain, F. (2007). Sediment erodability in sediment transport modelling: Can we account for biota effects? *Continental Shelf Research*, *27*(8), 1116–1142. https://doi.org/10.1016/j.csr.2005.11.016

Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N. K., Plater, A. J., Schuerch, M., & Temmerman, S. (2018). Dynamic interactions between coastal storms and salt marshes: A review. *Geomorphology*, *301*, 92–107. https://doi.org/10.1016/j.geomorph.2017.11.001. https://www.sciencedirect.com/science/article/pii/S0169555X17304579

Limburg, K. E., & Waldman, J. R. (2009). Dramatic declines in North Atlantic diadromous fishes. *BioScience*, *59*(11), 955–965. https://doi.org/10.1525/bio.2009.59.11.7

Louters, T., Berg, J. H., & Mulder, J. P. M. (1998). Geomorphological changes of the Oosterschelde tidal system during and after the implementation of the Delta project. *Journal of Coastal Research*, *14*, 1134–1151.

Ludy, J., & Kondolf, G. M. (2012). Flood risk perception in lands "protected" by 100-year levees. *Natural Hazards*, *61*(2), 829–842. https://doi.org/10.1007/s11069-011-0072-6

McAlpin, T. O., & Emiren, A. G. (2022). Analysis of potential storm surge barrier impacts during normal tidal conditions. Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center. Vicksburg, Mississippi.

McKay, S. K., Cooper, A. R., Diebel, M. W., Elkins, D., Oldford, G., Roghair, C., & Wieferich, D. (2017). Informing watershed connectivity barrier prioritization decisions: A synthesis. *River Research and Applications*, *33*(6), 847–862. https://onlinelibrary.wiley.com/doi/abs/10.1002/rra.3021

Mel, R. A., Viero, D. P., Carniello, L., Defina, A., & D'Alpaos, L. (2021). The first operations of Mo.S.E. System to prevent the flooding of Venice: Insights on the hydrodynamics of a regulated lagoon. *Estuarine, Coastal and Shelf Science*, *261*, 107547. https://doi.org/10.1016/j.ecss.2021.107547. https://www.sciencedirect.com/science/article/pii/S0272771421003978

Mooyaart, L., & Jonkman, S. N. (2017). Overview and design considerations of storm surge barriers. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *143*(4), 06017001. https://doi.org/10.1061/(asce)ww.1943-5460.0000383

Morang, A. (2007). Hurricane barriers in New England and New Jersey - History and status after four decades. *Journal of Coastal Research*, *317*, 116. https://doi.org/10.21236/ada473784

Morang, A. (2016). Hurricane barriers in New England and New Jersey: History and status after five decades. *Journal of Coastal Research*, *32*(1), 181–205. https://doi.org/10.2112/JCOASTRES-D-14-00074.1

Morrice, K. J., Baptista, A. M., & Burke, B. J. (2020). Environmental and behavioral controls on juvenile Chinook salmon migration pathways in the Columbia River estuary. *Ecological Modelling*, *427*, 109003. https://doi.org/10.1016/j.ecolmodel.2020.109003. https://www.sciencedirect.com/science/article/pii/S0304380020300752

Najjar, R. G., Pyke, C. R., Adams, M. B., Breitburg, D., Hershner, C., Kemp, M., et al. (2010). Potential climate-change impacts on the Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *86*(1), 1–20. https://doi.org/10.1016/j.ecss.2009.09.026

Nienhuis, P. H., & Smaal, A. C. (1994). The Oosterschelde estuary, a case-study of a changing ecosystem: An introduction. *Hydrobiologia*, *282*(1), 1–14. https://doi.org/10.1007/BF00024616

NRC. (2014). National Research Council. Reducing coastal risk on the east and Gulf Coasts, committee on U.S. army corps of engineers water resources science, engineering, and planning: Coastal risk reduction; water science and technology board; ocean studies board; division on Earth and life studies

Orton, P., & Ralston, D. (2018). *Preliminary evaluation of the physical influences of storm surge barriers on the Hudson River estuary* (p. 81pp). Report to the Hudson River Foundation.

Pfleger, M. O., Rider, S. J., Johnston, C. E., & Janosik, A. M. (2016). Saving the doomed: Using eDNA to aid in detection of rare sturgeon for conservation (Acipenseridae). *Global Ecology and Conservation*, *8*, 99–107. https://doi.org/10.1016/j.gecco.2016.08.008. https://www.sciencedirect.com/science/article/pii/S2351989416300725

Ralston, D. K. (2022). Impacts of storm surge barriers on drag, mixing, and exchange flow in a partially mixed estuary. *Journal of Geophysical Research: Oceans*, *127*(4), e2021JC018246. https://doi.org/10.1029/2021JC018246

Ralston, D. K., & Geyer, W. R. (2019). Response to channel deepening of the salinity intrusion, estuarine circulation, and stratification in an urbanized estuary. *Journal of Geophysical Research: Oceans*, *124*(7), 4784–4802. https://doi.org/10.1029/2019JC015006

Rothermel, E. R., Balazik, M. T., Best, J. E., Breece, M. W., Fox, D. A., Gahagan, B. I., et al. (2020). Comparative migration ecology of striped bass and Atlantic sturgeon in the US Southern mid-Atlantic bight flyway. *PLoS One*, *15*(6), e0234442. https://doi.org/10.1371/journal.pone.0234442

Russell, I., Moore, A., Ives, S., Kell, L., Ives, M., & Stonehewer, R. (1998). The migratory behaviour of juvenile and adult salmonids in relation to an estuarine barrage. *Hydrobiologia*, *371*, 321–333. https://doi.org/10.1007/978-94-011-5090-3_36

Secor, D. H. P. (2015). *Migration ecology of marine fishes*. Johns Hopkins University Press. https://doi.org/10.1353/book.39942

Shaw, P., Jobe, J., & Gedan, K. B. (2022). Environmental limits on the spread of invasive *Phragmites australis* into upland forests with marine transgression. *Estuaries and Coasts*, *45*(2), 539–550. https://doi.org/10.1007/s12237-021-00980-9

Swanson, R., O'Connell, C., & Wilson, R. (2013). *Storm surge barriers: Ecological and special concerns. Paper presented at the storm surge barriers to protect New York city: Against the deluge*. New York University. 30-31 March 2009.

Tognin, D., D'Alpaos, A., Marani, M., & Carniello, L. (2021). Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. *Nature Geoscience*, *14*(12), 906–911. https://doi.org/10.1038/s41561-021-00853-7

Tognin, D., Finotello, A., D'Alpaos, A., Viero, D. P., Pivato, M., Mel, R. A., et al. (2022). Loss of geomorphic diversity in shallow tidal embayments promoted by storm-surge barriers. *Science Advances*, *8*(13), eabm8446. https://www.science.org/doi/abs/10.1126/sciadv.abm8446

Tommasini, L., Carniello, L., Ghinassi, M., Roner, M., & D'Alpaos, A. (2019). Changes in the wind-wave field and related salt-marsh lateral erosion: Inferences from the evolution of the Venice lagoon in the last four centuries. *Earth Surface Processes and Landforms*, *44*(8), 1633–1646. https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4599

Troost, K., & Ysebaert, T. (2011). *ANT oosterschelde: Long-term trends of waders and their dependence on intertidal foraging grounds*. IMARES Wageningen UR.

Uijttewaal, W. S. J., & Jirka, G. H. (2003). Grid turbulence in shallow flows. *Journal of Fluid Mechanics*, *489*, 325–344. https://doi.org/10.1017/s0022112003005020

USACE. (2018). *Final integrated city of Norfolk coastal storm risk management feasibility study/environmental impact statement: Feasibility study* (p. 493). United States Army Corps of Engineers Norfolk District.

USACE. (2020). *Collier County, Florida coastal storm risk management; draft integrated feasibility study and environmental impact statement* (p. 446). United States Army Corps of Engineers Norfolk District.

USACE. (2021a). *Coastal Texas protection and restoration feasibility study: Final environmental impact statement* (p. 645). United States Army Corps of Engineers Galveston District.

USACE. (2021b). *New Jersey back bays coastal storm risk management draft integrated feasibility report and tier 1 Environmental Impact Statement* (p. 514). United States Army Corps of Engineers Philadelphia District.

USACE. (2022a). New York-New Jersey harbor and tributaries coastal storm risk management feasibility study. United States Army Corps of Engineers New York District.

USACE. (2022b). *Reservoir regulation section annual report fiscal year 2021* (p. 72). Department of the Army New England District Corps of Engineers.

Van der Werf, J., De Vet, P., Boersema, M., Bouma, T., Nolte, A., Schrijvershof, R., et al. (2019). An integral approach to design the Roggenplaat intertidal shoal nourishment. *Ocean & Coastal Management*, *172*, 30–40. https://doi.org/10.1016/j.ocecoaman.2019.01.023

Volkenborn, N., Hedtkamp, S., Van Beusekom, J., & Reise, K. (2007). Effects of bioturbation and bioirrigation by lugworms (*Arenicola marina*) on physical and chemical sediment properties and implications for intertidal habitat succession. *Estuarine, Coastal and Shelf Science*, *74*(1–2), 331–343. https://doi.org/10.1016/j.ecss.2007.05.001

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a coupled ocean-atmosphere-wave-sediment transport (COAWST) Modeling System. *Ocean modelling*, *35*(3), 230–244. https://doi.org/10.1016/j.ocemod.2010.07.010

Weerman, E. J., Van Belzen, J., Rietkerk, M., Temmerman, S., Kéfi, S., Herman, P. M., & Van de Koppel, J. (2012). Changes in diatom patch-size distribution and degradation in a spatially self-organized intertidal mudflat ecosystem. *Ecology*, *93*(3), 608–618. https://doi.org/10.1890/11-0625.1

Widdows, J., & Brinsley, M. (2002). Impact of biotic and abiotic processes on sediment dynamics and the consequences to the structure and functioning of the intertidal zone. *Journal of Sea Research*, *48*(2), 143–156. https://doi.org/10.1016/s1385-1101(02)00148-x

Woodland, R. J., Secor, D. H., Fabrizio, M. C., & Wilberg, M. J. (2012). Comparing the nursery role of inner continental shelf and estuarine habitats for temperate marine fishes. *Estuarine, Coastal and Shelf Science*, *99*, 61–73. https://doi.org/10.1016/j.ecss.2011.12.019

Yoon, S. J., Hong, S., Kwon, B.-O., Ryu, J., Lee, C.-H., Nam, J., & Khim, J. S. (2017). Distributions of persistent organic contaminants in sediments and their potential impact on macrobenthic faunal community of the Geum River Estuary and Saemangeum Coast, Korea. *Chemosphere*, *173*, 216–226. https://doi.org/10.1016/j.chemosphere.2017.01.031