Effects of Storm Surge Barrier Closures on Estuary Saltwater Intrusion and Stratification

Ziyu Chen[1*], Philip M. Orton[1*]

[1]Department of Civil, Environmental and Ocean Engineering, Stevens Institute of Technology, Hoboken, NJ, 07030, USA

Corresponding author: Philip M. Orton (porton@stevens.edu) , Ziyu Chen (zchen44@stevens.edu)

Key Points:

- Multi-day gate closures can increase saltwater intrusion and stratification past historical maxima
- Recovery time to normal conditions after re-opening depends on closure duration, streamflow and estuary length
- Closure frequency should be limited in order to prevent durable estuary physical changes from inadequate recovery time

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Abstract

Gated storm surge barriers have been constructed or proposed in many estuaries worldwide for coastal flood risk reduction. Past studies have shown that, even when open, a barrier system's fixed infrastructure can increase estuary stratification and salt intrusion, potentially affecting water quality and ecological processes. However, surge barrier closures could have a much stronger influence on estuary conditions by temporarily blocking the tidal exchange. In this project, we use an existing regional three-dimensional hydrodynamic model, with modifications to simulate surge barrier closure and re-opening, to study the effects on estuarine salt intrusion and stratification of the Hudson River. Across a range of modeled scenarios of gate closure frequencies, durations and river streamflows, we evaluate the changes caused by gate closures, as well as the recovery time to normal conditions. Our results for the Hudson show long-duration gate closures (three or more days) with low streamflows temporarily lead to salt intrusion and stratification beyond recent historical extremes. Moreover, monthly frequency closures, which could occur as soon as 2070 under realistic scenarios of sea-level rise and barrier management, do not allow for recovery under low streamflow conditions and could lead to durable changes to estuary physical conditions. As a result, long duration closures and high frequency closures both constitute a threat to municipal water supplies. This study demonstrates a framework for understanding the potential impacts of any proposed surge barrier system and can help improve our understanding of corresponding ecological impacts.

Keywords: storm surge barrier; saltwater intrusion; stratification; estuary; freshwater resources; Hudson River

1 Introduction

Storm surge is one of the most catastrophic events among all natural disasters. It can cause a large number of fatalities as well as enormous economic losses in a single event. Moreover, coastal flood events are predicted to be more frequent and intense under sea-level rise (SLR) and climate driven changes in storm characteristics (Lin et al., 2012; Marsooli et al., 2019). Repeated record-setting years for hurricane damages are accelerating interest to investigate diverse engineering approaches for coastal flood risk reduction, including shoreline-based measures, natural and nature-based features and closable storm surge barriers or tide gates. Storm surge barriers or tide gates can effectively protect harbors and minimize flooding, property damage, and loss of life during large storms. They can be one of the most cost-effective approaches to mitigate the effects of flood hazards (Deltacommissie, 2009; National Research Council, 2014). An increasing number of storm surge barriers has been constructed and applied for flood protection worldwide (Mooyaart & Jonkman, 2017). Recently, storm surge barriers have been proposed for construction on many U.S. estuaries, including New York (NY)/New Jersey (NJ) Harbor (USACE, 2019), Boston Harbor (Kirshen et al., 2018), Galveston Bay/Houston (USACE, 2020b), coastal New Jersey (USACE, 2021a), Miami (USACE, 2020c) and Norfolk (USACE, 2017).

Surge barriers typically span the opening to a harbor or river mouth with gates in the barriers left open under normal conditions to allow exchange of water due to the tides. Past studies have shown that when the surge barriers are left open, due to their fixed infrastructure obstructing a portion of the estuary cross-section, they can reduce tidal exchange and cause increases to stratification and salt intrusion length (e.g., Du et al., 2017; Orton & Ralston, 2018; Ralston, 2022). These physical changes can affect water quality, ecological processes, sediment transport and other environmental aspects of an estuary (e.g., Bakker et al., 1990; Swanson et al., 2013). Gate closures may have a stronger impact on estuary conditions by completely stopping the tidal currents during the period of closure. Moreover, SLR can cause increased frequency of surge barrier closures and closure duration to prevent flooding, which will intensify the gate closure impacts (Chen et al., 2020). Already this has occurred with some constructed surge barriers (e.g., Thames Barrier in Britain, Lavery & Donovan, 2005; New Bedford Barrier in Massachusetts, Orton et al., 2022; Stamford barrier in Connecticut, USACE, 2021b). However, there have been no prior academic studies focused on modeling surge barrier closure effects.

Municipal water supplies in tidal rivers are increasingly threatened by salt intrusion due to climate change and dredging, which both can shift the salt front landward (e.g., Leuven et al., 2019; Yuan & Zhu, 2015). The historical records of abnormal estuarine salt intrusion and contamination of drinking water supplies typically show correlation with severe drought events (e.g., Bowen & Geyer, 2003). For some estuaries, increased salt intrusion also results from declining runoff due to climate change (e.g., Akter et al., 2019; Cloern et al., 2011). These effects could gradually increase the risk of salt contamination of upstream municipal water intakes. Surge barrier systems could further threaten upriver freshwater resources from both their open barrier effects and the gate closure operations for flood protection.

Similarly, evidence shows that climate change is worsening hypoxia in some estuaries due to rising sea levels, warming water temperatures and changes in streamflow, precipitation and/or wind patterns (e.g., Cottingham et al., 2018; Du et al., 2018; Ni et al., 2019). Surge barrier systems could worsen this trend by increasing the stratification and reducing and temporarily terminating the estuary vertical mixing. There is uncertainty how these combined effects could affect the estuary water quality.

Storm surge barriers are being evaluated by the US Army Corps of Engineers in its Harbor and Tributaries (HAT) Study for coastal storm risk management for the NY metropolitan area (USACE, 2019). The USACE estimates that coastal flood risk is very high in the region, at $5.1 billion average annual damages per year in 2030, leading to high benefit-cost ratios ranging from 2.1-4.6 for various surge barrier plans (USACE, 2020a). Two specific risk reduction alternatives being studied (Alternatives 2 and 3A) include surge barriers systems that would affect the Hudson River estuary and its many sub-estuaries. We recently held a series of stakeholder workshops that identified several specific concerns around prospective surge barriers, including excessive salt intrusion that could affect freshwater intakes that are normally only affected during drought conditions, and the potential for increased stratification of the eutrophic waters contributing to hypoxia in the Hudson or its adjoining estuaries (e.g., Orton et al., 2020).

In this paper, we study the effect of closed surge barriers on estuary physical conditions and use the hypothetical NY/NJ Harbor barriers and Hudson River estuary as a case study. The goals of this research are:

1. Quantifying the influences of storm surge barrier closures on estuary saltwater intrusion and stratification
2. Assessing the recovery time after the gates reopen, with application to understanding the maximum closure frequency

3. Identifying any extreme physical conditions induced by episodic operations of surge barriers that could cause new unexpected environmental issues
4. Recommending model experiments and metrics for evaluating other constructed/proposed barriers

Below, Section 2 introduces the study site and methods of the surge barriers closure modeling, Section 3 shows the results of closed surge barrier effects on the Hudson River estuary, and Section 4 discusses the generality of the surge barriers closure analysis with respect to different types of estuaries and the barrier management implications from this research. In Section 5 we summarize the primary conclusions of this research.

2 Study site and Methods

2.1 Hudson River Estuary and NY/NJ Harbor

The Hudson River Estuary and several other sub-estuaries and tide straits branch out from NY/NJ Harbor (Panel a in Figure 1). The Hudson, a 245 km long estuary and tidal river, is one of the most well-studied estuaries in the world regarding salt intrusion, salt stratification, estuary adjustment time, sediment transport and a wide range of other topics (Levinton et al., 2006). It is a relatively simple channelized estuary with limited wind effects and typical variations in salinity and stratification being predominantly controlled by river streamflow and fortnightly (spring-neap) and monthly (perigee-apogee) modulations in tidal forcing (e.g., Ralston et al., 2008). Resulting character varies between partially-mixed, strongly stratified and salt-wedge estuary types (e.g., Geyer & MacCready, 2014). Observations at the Battery tide gauge (southern Manhattan, New York City) show the tide is principally semi-diurnal and the mean tidal range is 1.4 m (Ralston & Geyer, 2017), varying from about 1 to 2 m (Orton & Visbeck, 2009). The Hudson is tidal from Manhattan to the Green Island dam at Troy, NY, and receives fresh water mainly from north of Troy (e.g., the Mohawk River) plus multiple smaller tributaries along the Hudson (Orton et al., 2012). Future climate change is expected to alter streamflow conditions by increasing the mean streamflow but also reducing the streamflow during the dry season (Schulte et al., 2017). Also, estuary temperatures will be warmed by regionally warming atmospheric temperatures.

Communities surrounding NY/NJ Harbor are vulnerable to coastal flooding due to storm surge and high tides and sometimes compound coastal-pluvial flooding (e.g., Hurricane Irene; Wahl et al. 2015). This estuary area also suffers from a high relative SLR rate due to subsidence (Kopp et al., 2014), which causes more severe and frequent flood hazards (e.g., Orton et al., 2019).

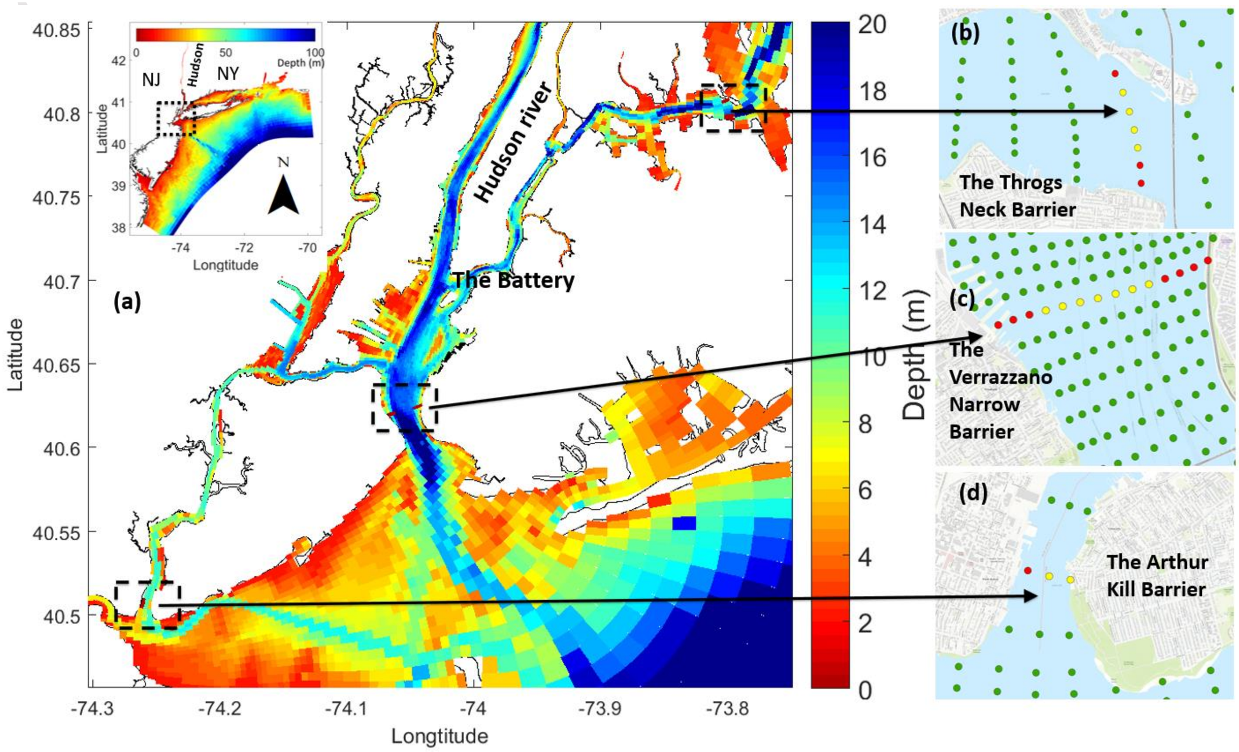

Figure 1. (Panel a) The NY-NJ Harbor-Estuary is shown with the proposed locations of the Alternative 3A storm surge barriers (Verrazzano barrier, Arthur Kill barrier, Throgs Neck barrier); (Panel a top left) The NYHOPS model domain stretches from Maryland to Cape Cod and is centered on the NJ and NY coastal zone and estuaries. Color shading represents model bathymetry with modified model grids for fixed barriers in Panel a. Panel b-d are the maps for the 3 proposed storm surge barriers; Green dots show grid cell centers, red dots represent fixed surge barrier components and yellow dots represent gates (or the aggregate area of several open gates).

2.2 Three-dimensional hydrodynamic model with closable gates

Computational modeling of estuary physical conditions is performed using the three-dimensional Stevens Estuarine and Coastal Ocean Model (sECOM) (Georgas & Blumberg, 2010). The model is applied on the New York Harbor Observing and Prediction System (NYHOPS) domain/grid including the Mid-Atlantic and Northeastern U.S. coastline from Maryland to Rhode Island . This model and domain have been applied in a forecast system since 2007 to provide accurate real-time water property forecasts (http://stevens.edu/NYHOPS) and probabilistic coastal-fluvial flood forecasts (Jordi et al., 2019). Streamflow is incorporated into the model including all tributaries of the region's waterways. For those tributaries without observations, freshwater inputs are also taken into account by scaling from nearby streamflow gauge data and the relative watershed area ratios (Georgas & Blumberg, 2010; Orton et al., 2012).The sECOM-NYHOPS model is well-validated in forecast (Georgas & Blumberg, 2010) and hindcast modes with typical hindcast RMSEs of 0.10 m, 1.2 °C and 2.3 psu for total water levels, temperature and salinity, respectively (Georgas, Yin, et al., 2016). Also, the model provides accurate estimates of the Hudson River salt front location (r^2 = 0.83; Georgas & Blumberg, 2011).

One of the storm surge barrier system scenarios being studied in the HAT Study (Figure 1) (Alternative 3A; USACE, 2019) is represented in the model as a combination of fixed immobile ("fixed") flow-obstructing barriers and closable gates. Grid cells are chosen to represent these features, with bathymetry data at blockages being altered to raise it high above sea level, blocking water flow. We revised the model code to enable scheduled gate closures and openings during a model simulation. The representations of the barriers and their gates are simplified, given our model's ~140 m across-channel resolution only typically has about 10-15 cells across the Verrazzano Narrows and Hudson River estuary channels. As a result, we only model open gates as wide-open spaces, and we do not resolve separate navigation gates (2) and auxiliary flow gates (several) that exist in the USACE designs, the latter of which at 46 m width (Ralston, 2022) would require resolutions of about 5-10 m to accurately capture. The potential approaches for closing and opening these different types of gates is later discussed in Section 4. Two prior studies have modeled open surge barrier effects on the Hudson. One preliminary study of surge barriers evaluated effects of a barrier at a different location further offshore but with similar coarse representations (Orton & Ralston, 2018). The other modeled the potential Verrazzano barrier using a nested grid with refined resolution of 20 m (Ralston, 2022).

For the Verrazzano barrier (Figure 1, Inset C), we capture the aggregate open cross-sectional area reasonably with 7 neighboring cells. This is the dominant water pathway for flow into Upper New York Bay and the Hudson. The modified surge barrier model digital elevation model (DEM) with fixed barriers and open gates is shown Figure 1. This model DEM has an approximate 58.7% gated flow area (GFA; cross-sectional area open to flow, as a percentage of that of the unobstructed natural system) at the Verrazzano barrier, to approximately match the USACE design's value of 59% at that location (USACE, 2019).

We more coarsely represent the two other barriers and their gates (Figure 1, Insets B and D respectively), although these have a much smaller effect on the Hudson, the focus of our study. Our barriers have a 4-cell wide 57.4% GFA at Throgs Neck (USACE: 62%) and a 2-cell wide 62.7% GFA at Arthur Kill (USACE: 47%). These two locations have smaller cross-sectional areas than the Verrazzano (Throgs Neck <50%, Arthur Kill <15%), and their flows do not enter directly into the Hudson.

We did not mimic the "concrete sill design" (a normal component of a surge barrier system under the gates; e.g., Mooyaart & Jonkman, 2017; USACE, 2019) in our model DEM at the open gate locations because the model's relatively coarse grid resolution of the gated flow areas already has smooth bathymetry that is similar to the concrete sill.

2.3 Model experiments and forcings

We simulate estuary physical conditions under 21 different scenarios summarized in Table 1 and described in detail below. To create the most realistic simulations, model initial conditions and boundary conditions are taken from the NYHOPS operational forecasts, typically from the hindcast period (24 hours at the start of each forecast period). This includes realistic tidal forcing with 9 constituents (K1, O1, Q1, M2, S2, N2, K2, M4, M6) to capture both the spring-neap and perigee-apogee variabilities. The experiments include cases that utilize idealized constant forcings or realistic historic events. These detailed spatiotemporal data are briefly summarized below and made available in the Supplementary Materials (SM). Additional experiments to quantify sensitivity to factors such as SLR and dredging are also summarized below (Section 2.5) and presented in detail in the SM.

When the barriers are open, the fixed barrier components can reduce the tidal amplitude of the estuary, which will in turn increase salt stratification and intrusion length (Orton & Ralston, 2018; Ralston, 2022). So, we run both “Without-Barrier” (NYHOPS DEM) and “Open-Barrier” (with fixed barriers DEM) scenarios to investigate the physical impact of the fixed barriers, and the latter is the “Control” simulation for comparison with gate closure conditions. Also, to study the gate closure effects, we use a range of tide- and storm-driven flood simulations with various gate closure frequencies, gate closure durations and streamflow conditions.

We model 1, 3 and 5-day long gate closures because this represents the range of durations for likely present and future high-tide flooding and storm surge events based on data from prior studies (e.g., Orton et al., 2016; Orton et al., 2019). In cases where there are successive flood threshold exceedances at high tides, even if the water level exceeds a flood datum briefly and then drops below it, the large navigation gates for cross-harbor barriers cannot be opened and closed within less than one tidal cycle (B. Wisemiller, USACE, pers. comm., 2021). An example of a multi-day surge event is the 1992 Nor’easter and if a similar event were to occur with 50 cm of SLR it would have 8 tide cycles exceeding moderate flood datum at Manhattan (Chen et al., 2020). A prior USACE-directed study of surge barriers for a nearby area similarly included a 4-day closure scenario for surge barrier closure experiments (NYC-DEP, 2016). We discuss management approaches proposed by the USACE to reduce these durations in Section 4.

Two types of flood scenarios are characterized in the model experiments. “Coastal-Flood” scenarios are simulated with tides only and no storm surge, representing both spring tide flooding events and storm surge flooding events with low or moderate rainfall. Both scenarios are captured in the same set of simulations because (a) local winds have only a minor effect on the Hudson, which is narrow and relatively sheltered from wind, and (b) any storm surge would be blocked by the surge barriers and have no effect on the Hudson conditions. Moreover, typical storm surges only have a minor effect on Hudson salinity and salt intrusion, as tides comprise an equal or larger component of total water level variability. Tidal flooding is presently only a factor at perigean (“King”) tides in a few neighborhoods of the harbor-estuary region (Orton et al., 2015), but will become more frequent and widespread with SLR (Orton et al., 2019). In these simulations, we consider the spring-neap-king tide variations at the open boundary conditions to capture realistic conditions in a broad sense.

A “Compound-Flood” scenario with storm surge, high streamflow and heavy rain-on-water was also studied, using the realistic scenario of tropical storm Irene (2011). While our recent research showed that such compound events have a very low probability of causing trapped water flooding (Chen et al., 2020), here we quantify and study the role of simultaneous rain on the surge barrier closure effects on the estuary saltwater intrusion and stratification. Irene modeling methods are explained in detail in Orton et al. (2012).

Streamflows for the Coastal-Flood scenarios are characterized by using a temporally-constant “Mean-Streamflow” case to represent average conditions, and a “Low-Streamflow” case to represent typical dry season conditions. The Mean-Streamflow case of 404 m^3/s (Table 1) is approximately equal to the USGS observed daily average streamflow at Green Island gauge

(USGS 01358000) from 1947 to 2019 (409 m^3/s). The Low-Streamflow case at the Green Island (150 m^3/s) is also close to the median of observed daily average streamflow during dry season (July to September) from 1947 to 2019 (156 m^3/s). Other Hudson tributaries are similarly characterized by mean and low streamflow estimates in the simulations. For comparison, the time-varying streamflow during Irene was 2800 m^3/s over a three-day period and 1200 m^3/s over a 30-day period (Figure S1). For further discussion of historical streamflow data supporting these choices, see Section SM Text S3.

The idealized Coastal-Flood scenario gate closures are centered on the peak of spring tide. For the NY/NJ Harbor-Estuary region, extratropical cyclones cause small-to-moderate but often long-duration storm surges that are relatively reliant on high tides to cause flooding. As a result, coastal flooding during extratropical cyclones predominantly occurs at spring tides and can occur for several consecutive tidal cycles (Orton et al., 2015). This pattern could be worsened by SLR, for example with a long-duration storm surge (e.g., December 1992 nor'easter, Chen et al., 2020). The effects on our results of this spring tide assumption are evaluated in SM Text S2.2.

To mimic the realistic gate closure operation for 1/3/5-day flood events, we close the Verrazzanno, Arthur Kill and Throgs Neck gates at slack tide before flood tide and reopen close to slack tide before ebb tide. We use initial simulations where the barrier is closed but not re-opened to learn the water rise rate for Low- and Mean Streamflow cases, then use that information to tune the timing of reopening to occur close to slack but when water levels are almost identical inside and outside the barriers. For the "Compound-Flood" scenarios, water inside the barrier system rises more significantly and there is a water level gradient present at the moment of opening the gates, as discussed below in Section 3.3.2.

Annual closure frequency is represented with the single-closure simulations, whereas a period of monthly closures is represented with the three-closure simulations (e.g., gates closed at spring tide in three consecutive months). For the sake of computational efficiency, we only run simulations for 150 days, which we find is enough to investigate the recovery of estuary physical conditions after closures for this system.

Table 1. Flood simulation scenarios with different closure duration, closure frequency, streamflow

Flood Event	*Streamflow (m^3/s)*	*Surge barriers operation*	*Closure Duration*	*Closure Frequency*
Coastal Flood	404	Without-Barrier	None	None
Coastal Flood	404	Open-Barrier (Control)	None	None
Coastal Flood	404	Gate-Closure	1/3/5 Days	Annual
Coastal Flood	404	Gate-Closure	1/3/5 Days	Monthly
Coastal Flood	150	Without-Barrier	None	None
Coastal Flood	150	Open-Barrier (Control)	None	None

Coastal Flood	150	Gate-Closure	1/3/5 Days	Annual
Coastal Flood	150	Gate-Closure	1/3/5 Days	Monthly
Compound Flood (Irene)	2800[a]	Without-Barrier	None	None
Compound Flood (Irene)	2800[a]	Open-Barrier (Control)	None	None
Compound Flood (Irene)	2800[a]	Gate-Closure	1/3/5 Days	Annual

[a] The compound flood event scenario Irene utilized realistic time-varying streamflows, for which the 3-day average was 2800 m^3/s

All simulations use appropriate initial conditions for periods with similar streamflows and salinity from our operational forecast system (Georgas, Blumberg, et al., 2016). For the Hurricane Irene (Compound Flood) simulation, we use initial conditions created from the operational simulation of that event, which requires only 2 days of spin-up time (Orton et al., 2012). For the idealized Coastal-Flood scenarios, we use the initial conditions from operational system simulations with similar conditions (for Mean- and Low- Streamflow scenarios) and include a 20-day spin-up time.

2.4 Post processing of salt intrusion and stratification

A summary diagram of the scientific methods for open and closed surge barrier effects on estuary conditions is shown below in Figure 2.

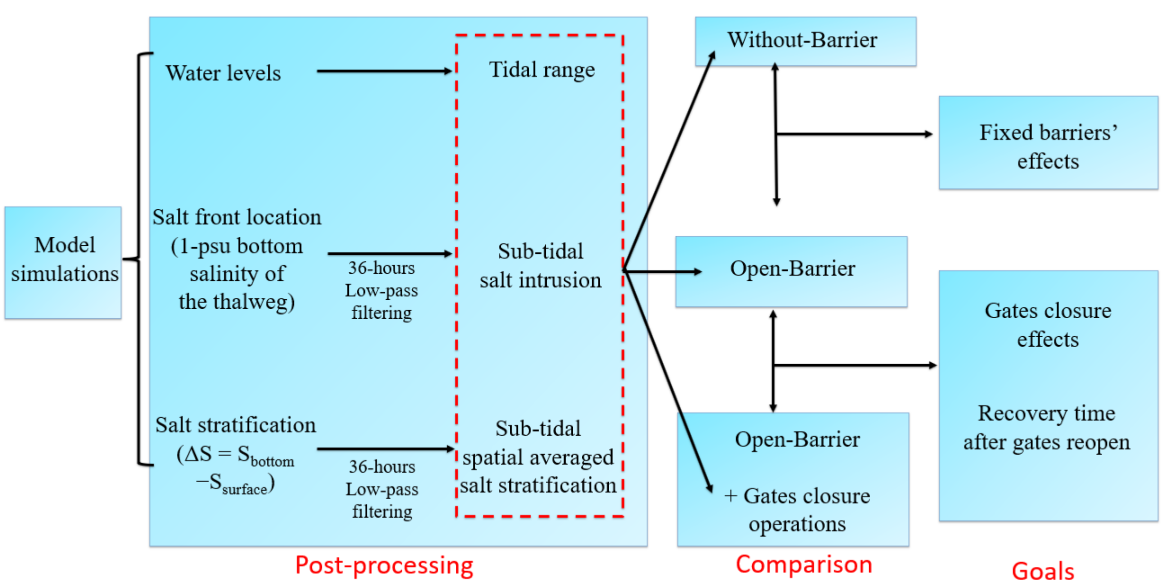

Figure 2. Diagram of the scientific analysis approach

The salt front is identified as the location of the 1-psu bottom isohaline in the Hudson's thalweg. We used a 36-hour low-pass running-average filter on the modeled salt intrusion length to remove the tidal signals and obtain the sub-tidal salt intrusion variation along the thalweg. Recovery time is defined as the period of time required after gate reopening for the sub-tidal salt intrusion length from a "Gate-Closure" scenario to be less than 3% to that in the Control scenario.

We quantify stratification and its changes in three ways: (1) the spatial average salinity difference between the bottom and surface layers ($\Delta S = S_{bottom} - S_{surface}$), (2) the spatial average salinity vertical gradient [$(S_{bottom} - S_{surface})$/depth] computed on all saltwater grid cells behind the barriers, and (3) the stratification at mid-estuary, defined as the thalweg location having a vertically average salinity of 15 psu. However, hereafter we only refer to approach #1 in our assessment of stratification changes because the other two approaches give similar results in this estuary. This is because for estuaries with relatively constant water depths like the Hudson, estuary-mean ΔS and ΔS/depth have very similar fractional variations. We define an "excess stratification recovery time" for the estuary stratification as the period of time required after gate reopening for the excess stratification in the Gate-Closure scenario to disappear compared with the stratification in the Control scenario. After the gates are reopened, this is defined as being the first time when the difference of sub-tidal spatial average stratification between the Gate-Closure scenario and Control scenario is less than 0.

We compute the maximum stratification conditions along the thalweg from single gate closure scenarios. Also, we compare these with the maximum stratification variation range during 1979-2013 from a hindcast based on the NYHOPS model (Georgas, Yin, et al., 2016). The salt stratification and intrusion increments (positive anomalies relative to the state before closing the gates) by various durations of gate closures are also evaluated, which can be compared with natural variability.

2.5 Sensitivity analyses

Several sensitivity tests were conducted, quantifying the effects of SLR, dredging, wind, horizontal diffusion parameterization settings, and neap-spring phasing of closures on our results. These methods and results are presented in detail in SM sections (Text S1-S2), and briefly discussed in Section 4.

3 Results

An example case of the influence of a surge barrier's open infrastructure, as well as the chain of events surrounding a closure, are shown in Figure 3. Spatiotemporal salinity shade plots showing full-duration simulation results for Control scenarios and all experiments given in Table 1 are presented in order (from panel a to u) in Figure S2. Below, we present the baseline change between Without-Barrier and Open-Barrier simulations (Section 3.1). We then contrast spatiotemporal shade-plots of results for Open-Barrier sample versus Closed-Barrier results from single 3-day gate closures and their recovery process (Section 3.2). We present detailed analyses of single (annual) closure effects on saltwater intrusion and stratification and its recovery time (Section 3.3). The monthly closure scenarios indicate more severe estuary effects, as there is likely inadequate recovery time between the high frequent closures. These results are discussed below but are only displayed in Figure S2 because they do not add to the demonstration already shown with single-closure cases below.

3.1 Fixed (open) storm surge barrier impacts

The model simulations indicate the Open-Barrier system (Alternative 3A) causes 0.1% to 4% (median is 3.2%) salt intrusion length extension and -1.4% to 7% (median is 1.3%) changes of salinity stratification compared with Without-Barrier system with constant Mean-Streamflow during a spring neap cycle. Also, there is about 3.0% average tide range reduction at the Battery in one lunar cycle, a similar reduction to that found in the modeling results from the HAT Study (USACE, 2020a). These results serve as our primary baseline or Control scenario, against which closures are compared.

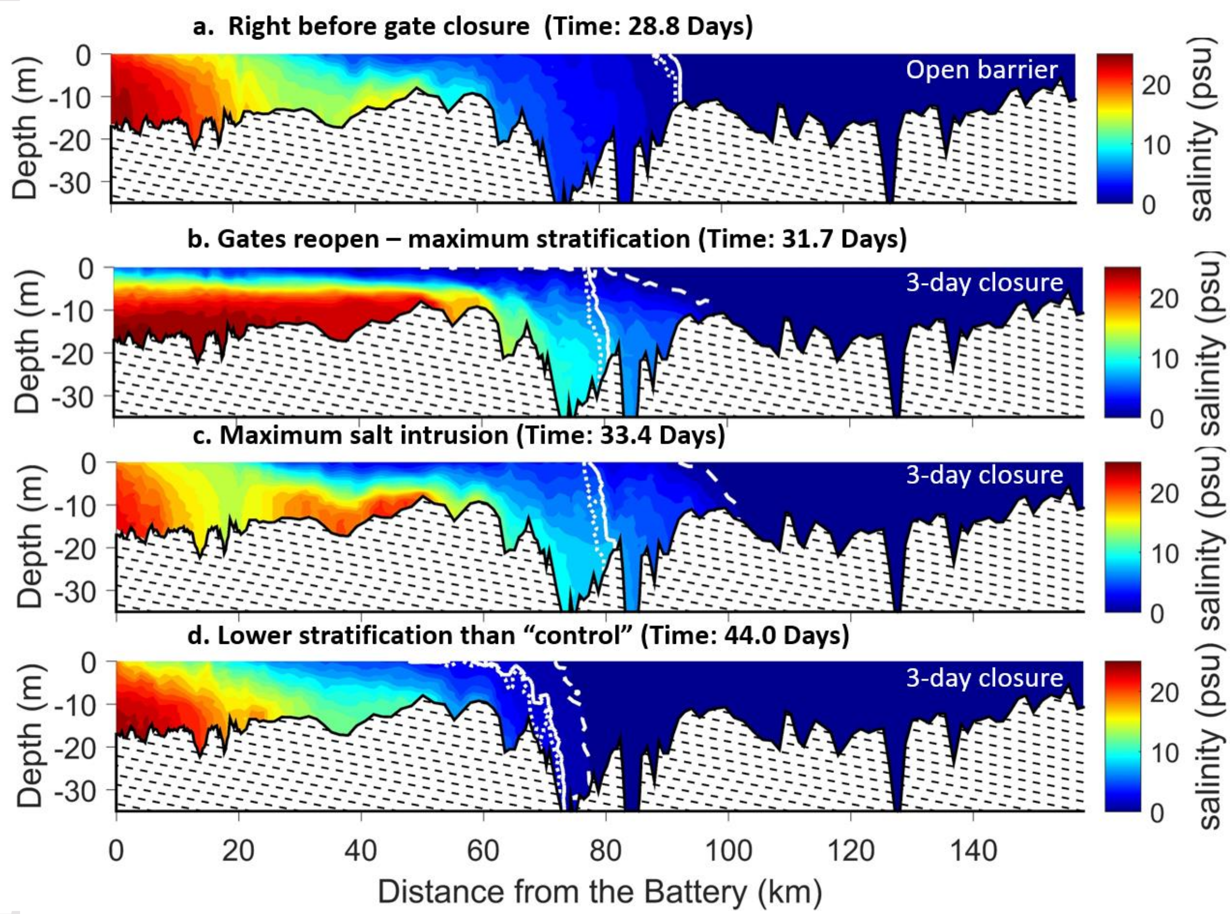

Figure 3. Salinity profiles along the Hudson River thalweg during mean streamflow conditions from (a) the Alternative 3A Open-Barrier simulation and (b,c,d) 3-day Gate-Closure simulation at different simulation times. White lines in each figure are the 1 psu isohalines from simultaneous Without-Barrier simulation (dotted), Open-Barrier simulation (dashed) and Gate-Closure simulation (solid).

3.2 Spatiotemporal view of closed barrier impacts

3.2.1 Coastal flood events

Gate closures intended to prevent flooding have an intensified but temporary impact on estuary conditions (e.g., Figure 3 for Mean-Streamflow conditions). The barrier closure stops the tidal currents and associated vertical water column mixing throughout the estuarine areas behind the barrier. The salt intrusion responds to its along-estuary density-gradient (baroclinic) forcing and this lack of vertical mixing by propagating rapidly up-estuary (Figure 3b). A salt wedge slides below fresher surface water with relatively little mixing, enhancing stratification relative to the Open-Barrier case (compare horizontal and vertical 1 psu contour lines). After the gates are reopened, tidal currents are re-instated but there remain high levels of stratification, so the salt intrusion continues moving upstream for a brief period until it reaches its maximum (Figure 3c). After continued vertical mixing and seaward advection, the salinity stratification and intrusion gradually return toward their normal values (Figure 3d).

Figure 4 left-side panels (a,c,e) give a continuous spatiotemporal perspective on the modeled salinity stratification and gate closure effects for Mean-Streamflow conditions. The Open-Barrier (Control) scenario (panel a) shows the common pattern of periodic variations of salt intrusion length and stratification with modulation of tides by the spring-neap cycle and lunar orbital (perigee-apogee) phasing (e.g., Orton & Visbeck, 2009; Ralston et al., 2008). The barrier gate closure (panel c, day 28.9) leads to increased stratification and migration of the salt front up-estuary, and the re-opening of the gates (day 31.7) enables a gradual recovery. Shade plots of the difference between Control and the Gate-Closure experiment show positive (yellow) and negative (blue) anomalies and a recovery back to normal conditions (green for zero difference) within about three weeks.

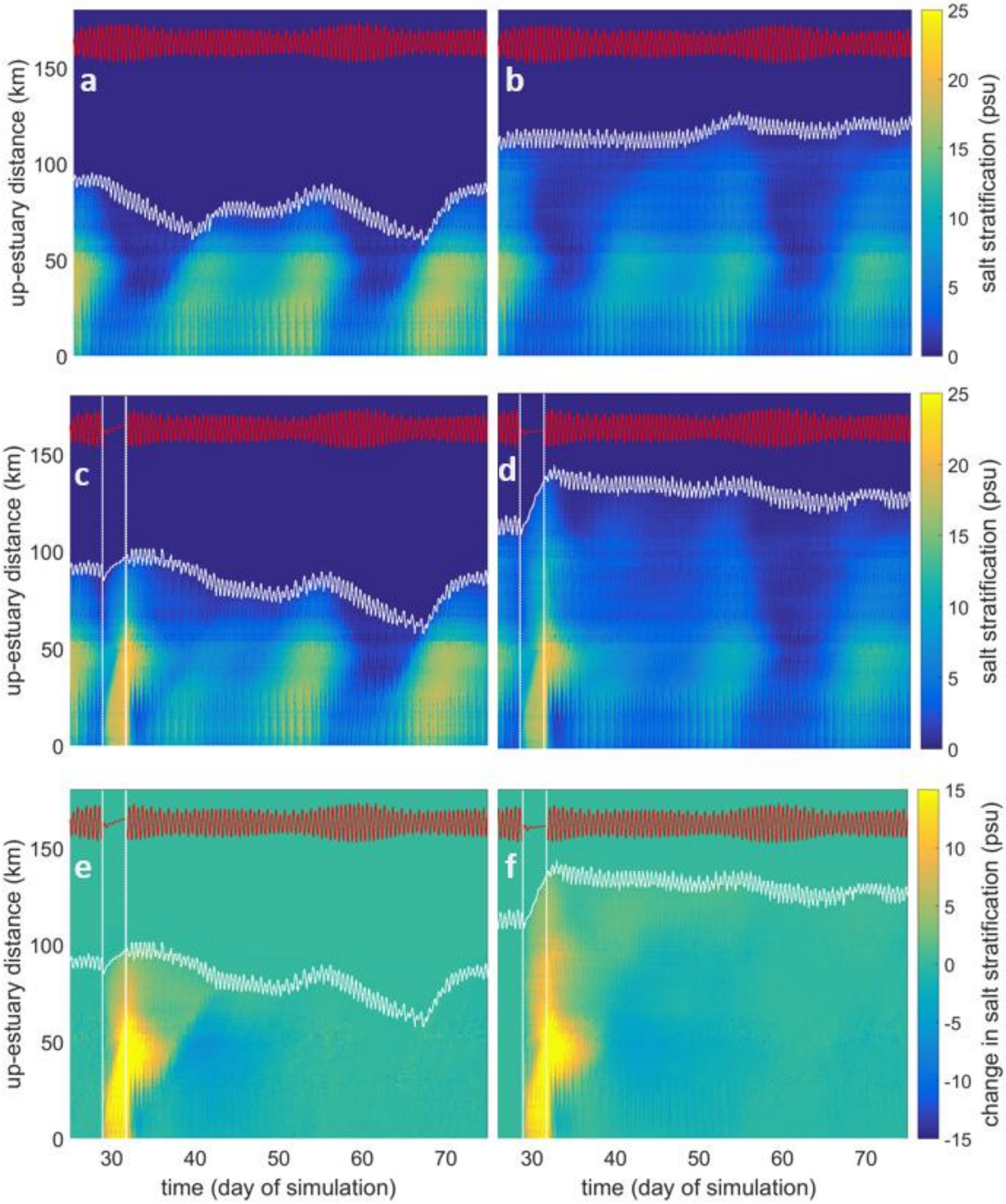

Figure 4. Spatio-temporal stratification and stratification change for the Hudson, with distance up-estuary from the Battery. The left column panels (a,c,e) show results for the Mean-Streamflow simulations, right column panels (b,d,f) show results for Low-Streamflow simulations. Color shading in the top row panels (a,b) shows modeled salinity stratification ($\Delta S = S_{bottom} - S_{surface}$) for the Open-Barrier (Control) scenario and middle row panels (c,d) show

results for the single (annual) 3-day Gate-Closure scenario. Bottom row color shading represents the corresponding changes in salinity stratification (Gate-Closure scenario minus Open-Barrier scenario). White lines show the salt intrusion length, and red lines show the water level at the Battery with an arbitrary scaling. The vertical dashed lines show the time of gate closure or reopening.

The gate closure impacts have potential to overlap with the negative effects from possible low streamflow conditions during a dry-weather coastal flood event, which would lead to more extreme salt intrusion and stratification conditions. Contrasting mean (panels a,c of Figure 4) and low river discharge conditions (panels b,d), lower streamflow leads to a greater salt intrusion distance, a typical pattern for a river-estuary. When gate closure occurs under low streamflow conditions, it results in relatively slow recovery of the stratification and salt intrusion length (panel f). Historically, drought conditions with low streamflow can enable the salt intrusion to reach 120 km from the Battery, contaminating municipal freshwater intakes at Poughkeepsie (Bowen & Geyer, 2003). Gate closure could aggravate this salt intrusion problem – Figure 4 shows an example that salt intrusion length could extend to about 140 km from the Battery.

3.2.2 Compound flood events

Gate closures during periods of high streamflow further illustrate a clear trend toward lesser salinity impacts and more rapid recovery times. As with Mean- or Low- Streamflow, the salt intrusion moves up-estuary during the period of closure. However, once the gates are opened, the barotropic-forced depth-averaged outflow (with some modulation by the tides) quickly advects the salinity anomalies seaward (Figure 5). Hurricane Irene is an extreme case, with the highest river discharge at this area in the past 70 years washing salt almost entirely out of the Hudson past Manhattan (Ralston & Geyer, 2019). However, the overall trend toward lesser salt intrusion length changes and recovery time for higher streamflows suggests this is an endmember where there are lesser impacts on salinity, and therefore we did not run simulations for longer durations than the pre-existing 10-day Irene simulation of Orton et al. (2012). As noted in Chen et al. (2020), trapped river water rises high inside the harbor (Figure 5, red line), which would prevent longer-duration closures in compound floods, but here we simply demonstrate the resulting effects of 3-day and 5-day closures for the sake of symmetric comparison to Low- and Mean-Streamflow scenarios.

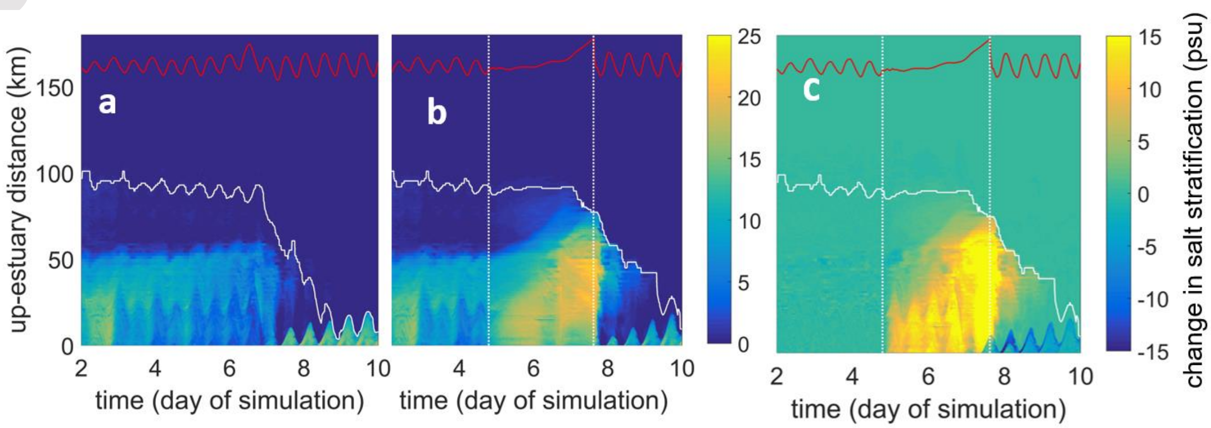

Figure 5. Hurricane Irene Open-Barrier scenario (panel a) and single (annual) 3-day Gate-Closure scenario (panel b) Spatio-temporal stratification plots. These show modeled salinity stratification ($\Delta S = S_{bottom} - S_{surface}$) along the thalweg (color shading), the length of the salt intrusion (white line), and water level at the Battery (red line) with an arbitrary scale. (panel c) The color shading represents the corresponding changes in salinity stratification (Gate-Closure scenario minus Open-Barrier scenario). The vertical dashed lines show the time of gate closure or reopening.

3.3 Stratification, intrusion and recovery time analyses

Gate closures eliminate the tidal mixing process, enabling significant increases in estuary stratification and salt intrusion length. In this section, we evaluate the salinity impacts from single gate closure scenarios and the recovery time after gate reopening, focusing on the Low- and Mean- Streamflow scenarios. The resulting salinity and stratification extremes are also compared to the historical variations arising only from natural forces.

The estuary spatial-average salinity stratification (Figure 6) shows a significant but temporary increase after gate closure. A 3-day (or longer) gate closure can cause comparable or even larger changes of the salinity stratification than its variation between the perigean spring tide (simulation day 119) and apogean neap tide (day 126).

After the gates reopen, the vertical mixing is rapidly restored, though the stratification decreases more slowly than it increased during closure. The excess spatial-average stratification behind the barrier domain caused by gate closure disappears within days, though the excess stratification near the head of the salt intrusion takes longer to disappear. The excess stratification disappears along the salt wedge from the seaward end to the river upstream (shown in the bottom two panels in Figure 4).

After the rapid mixing out of excess stratification, much of the estuary has a lower stratification than that of the Control simulation (Figure 6 and the dark blue shading in the bottom two panels e,f in Figure 4). These negative anomalies in stratification will last until the recovery of the estuary length because during this time the tidal mixing is recovered but its salt intrusion length is still longer than that of the Control. A longer salt intrusion length and resulting weaker along-estuary salinity (and density) gradient results in a weaker baroclinic force. Given the same barotropic forcing as control, a weaker baroclinic force results in reduced subtidal stratification generation below that of the Control (Geyer & MacCready, 2014). As the salt intrusion length decreases, the estuary salinity stratification gradually asymptotes back to the Control.

During recovery from gate closure, the simulation results suggest that the salt wedge can get cut off (e.g., Panel 3 in Figure 3). The Tappan Zee and Haverstraw regions of the estuary (25-40 km) can have saline, stratified water, and an area off Manhattan centered near George Washington Bridge (GWB) can be much more well-mixed and have lower salinity water. This could arise due to stronger tidal currents and associated mixing in the narrower areas from 10-20 km, compared to weaker currents in the wider areas from 25-40 km. The vertical mixing from 10-20 km could also be caused by convergence and particularly strong tidal currents around a constriction at GWB (e.g., Chant & Wilson, 1997).

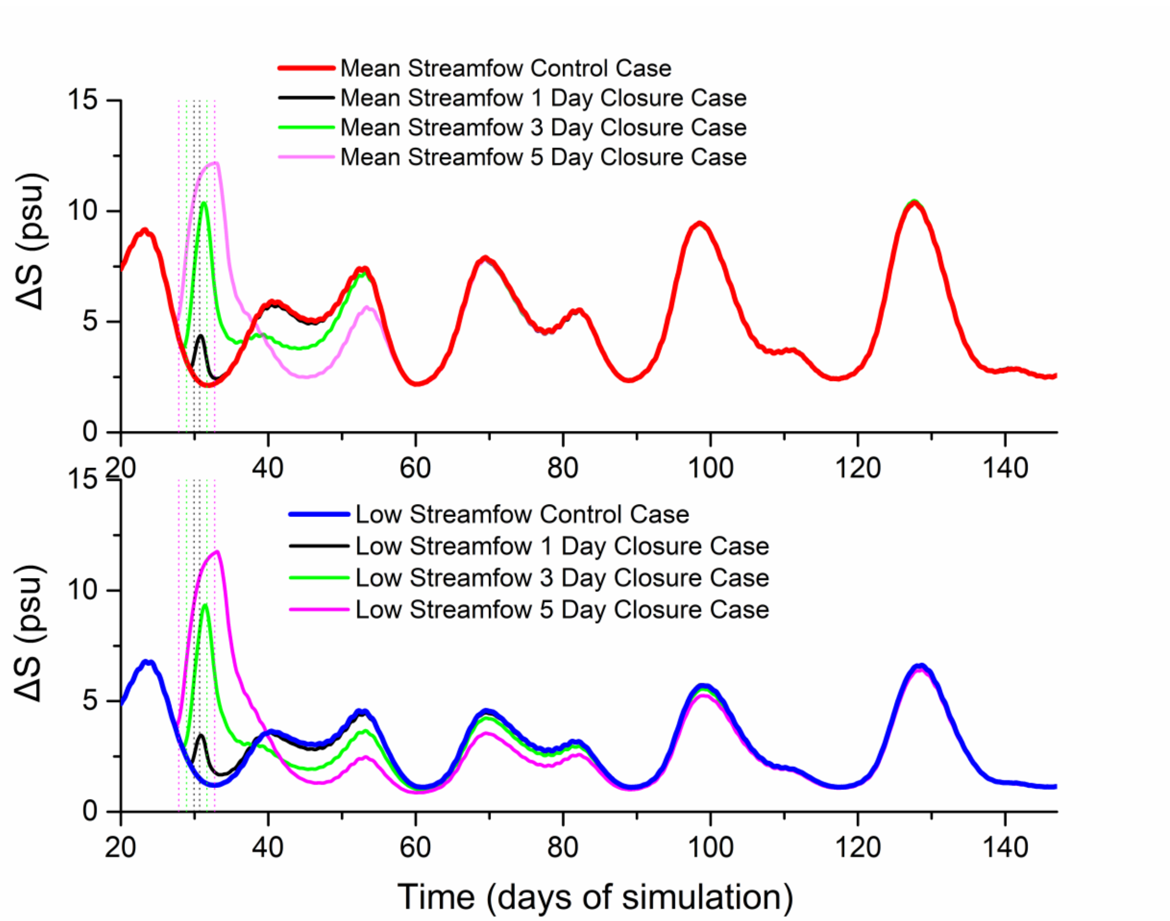

Figure 6. Modeled sub-tidal spatial-average estuary salinity stratification under Mean-Streamflow (top) and Low-Streamflow (bottom). Gate closure times are approximately day 29.9, 28.9, 27.9 and gate reopening times are approximately day 30.7, 31.7, 32.7, for 1, 3, and 5 day "Gate-Closure" scenarios, respectively. The vertical dashed lines show the time of gate closure or reopening.

Figure 7 shows the temporal variation of sub-tidal salt intrusion length along the thalweg. When the barrier gates are closed, it eliminates tidal mixing in the estuary and the salt front location will move rapidly upriver, driven by the baroclinic force. A long duration gate closure (3-day or longer) will cause a significant increase in salt intrusion length which is similar to the annual maximum intrusion induced by an apogean neap tide. However, a short-duration gate closure (e.g., 1 day) only causes a sub-tidal salt intrusion increment of less than 10 km (Figure 7).

The salt intrusion can go further northward to Poughkeepsie and potentially affect its water supply (as described in Section 3.2.1) in the scenarios with 5-day closure under Mean-Streamflow and 3- or 5-day closure under Low-Streamflow (Figure 7). Moreover, the maximum salt intrusion is a few kilometers longer than the sub-tidal salt intrusion length shown, due to the semidiurnal tidal variations of about 5-10 km.

The salt intrusion advance speed during closure under Low-Streamflow is slightly higher than that for Mean-Streamflow, which causes it to have a longer salt intrusion increment (the immediate increase due to closure). More importantly, under low streamflow conditions, there is a combined effect of the salt intrusion from both gate closure and the dry conditions, which could cause salt intrusion extremes for the estuary. Figure 7 shows the maximum sub-tidal salt intrusion length can almost reach 158 km away from the Battery (around the Tivoli Bay wetland reserve site) with a 5-day closure under Low-Streamflow conditions. A gradual salt intrusion increase continues to occur throughout the simulation, driven by a progression toward an apogean neap tide and the extended period of constant low discharge. However, this has a negligible effect on the recovery time evaluations where we evaluate the difference from a control simulation and an experiment.

Recovery of the salt intrusion to normal after gate re-opening is slow under low streamflow, significantly slower than under Mean-Streamflow. The monthly closure simulation results for Low-Streamflow conditions (e.g., Figure S2-o or S2-p) show that repetitive high-frequency closures would enable the salt intrusion length to consecutively increase (relative to control) because there is insufficient time for recovery.

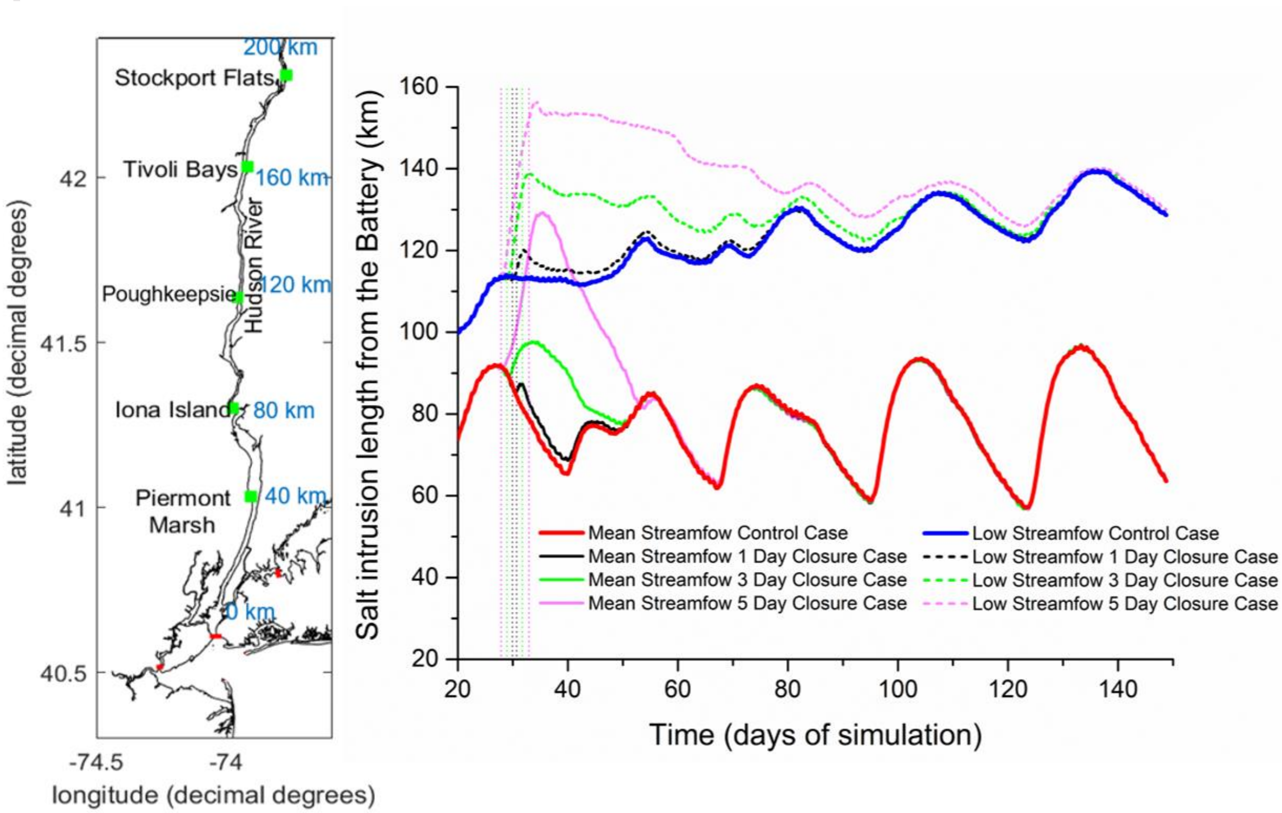

Figure 7. Modeled sub-tidal salt intrusion length under various scenarios (right). The salt intrusion length is defined as the distance of the 1-psu thalweg bottom salinity from the Battery, with distances shown in blue on the Hudson River estuary map (left). The vertical dashed lines show the time of gate closure or reopening.

Figure 8 compares the salt stratification conditions caused by the gate closures to the range of stratification variation from 1979-2013 based on a well-validated hindcast simulation (Georgas, Yin, et al., 2016). This gives a clear picture of how extremes of stratification and saltwater intrusion caused by gate closures along the estuary compare to historic maximum variations under natural forcings (e.g., tide, streamflow). The salt stratification along the upper estuary can be greater than its 35-year maximum values from effects of a single 5-day closure under Mean-Streamflow or single 3- or 5-day closure under Low-Streamflow scenarios. The salinity regime also exceeds its 35-year maximum for these cases. Moreover, these closures all occur during spring tide in the simulations, when the estuary has relatively low stratification. Gate closures at other phases of the spring-neap cycle can cause stronger stratification and longer salt intrusion conditions along the estuary, as demonstrated in SM section (Text S2.2). After a 1-day gate closure, the estuary does not become strongly stratified. Only upstream areas within 30 km from the Battery have the salt stratification above 10 psu (Figure 8), which is lower than its stratification during the neap tide. While 1-day gate closures can cause abrupt physical changes, the effects on salt intrusion and stratification are not extreme (Figure 6-7).

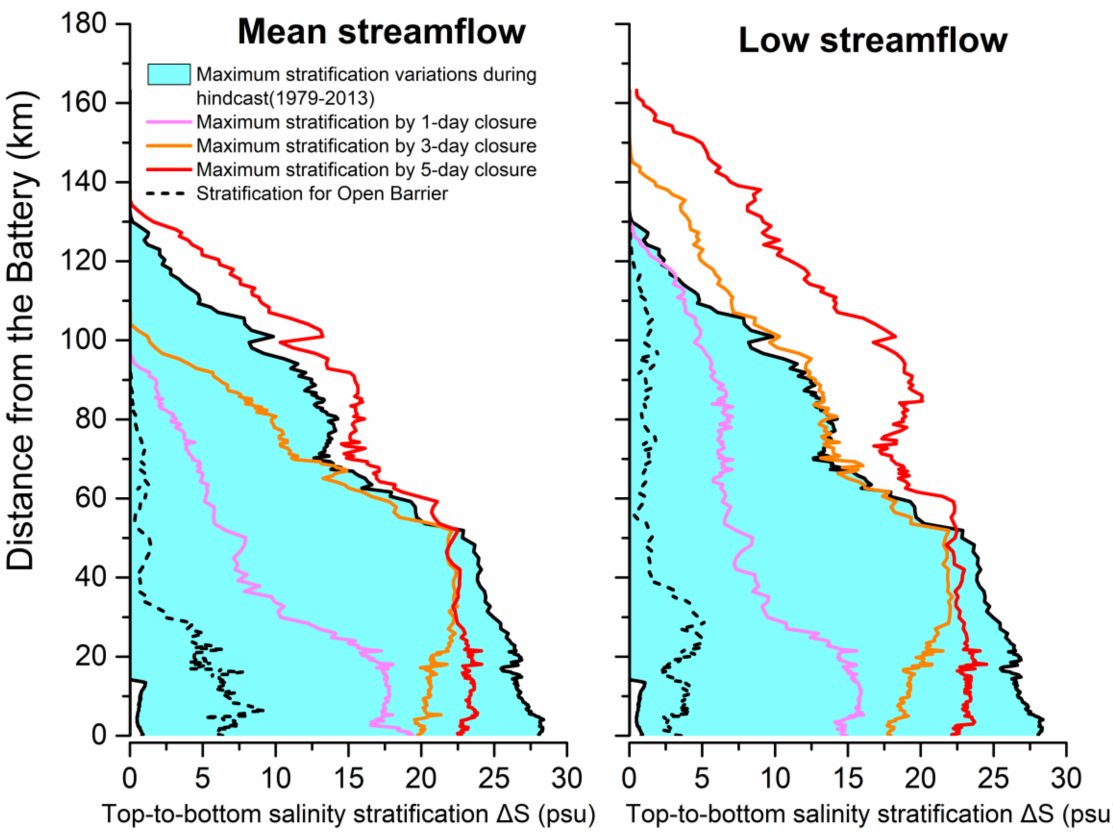

Figure 8. Modeled salinity stratification along the Hudson River thalweg under Mean-Streamflow (left) and Low- Streamflow (right). Color shading in blue is the maximum stratification variations over a 35-year hindcast. The red, orange and pink color lines are the maximum stratification from single (annual) Gate-Closure simulation. While not shown, the maximum salt intrusion length of 127 km is approximately 3 km below (seaward of) the tip of

the blue shading (ΔS~0). The salt stratification for each open-barrier control scenario (dashed lines) at the time of the peak is shown (3-day closure peak) for comparison.

The increment of the estuary salt stratification from gate closure increases asymptotically with closure duration and it is not sensitive to streamflow (Figure 9). After 3-day closure, certain locations along the Hudson (20-60 km) can increase to an extreme stratification condition above 20 psu. The asymptotic behavior arises because a longer gate closure duration cannot make these areas much more stratified, given that 25 psu is the maximum salinity in the estuary and no saltwater is being added to the system during closure. The salt intrusion increment is sensitive to the streamflow. Gate closures that occur under low streamflow will cause a longer increment than under mean streamflow (Figure 9). The increment is almost linearly proportional to the closure duration under low streamflow.

The salt intrusion recovery time is highly sensitive to the streamflow (Figure 9), as the speed for the salt front to move seaward is quite different with various streamflow conditions shown in Figure 7. Low streamflow can significantly extend the salt intrusion recovery time. The excess salt stratification will recover within days after gate closure, which is significantly faster than the salt intrusion length. The excess salt stratification recovery time is not sensitive to the gate closure duration and streamflow condition.

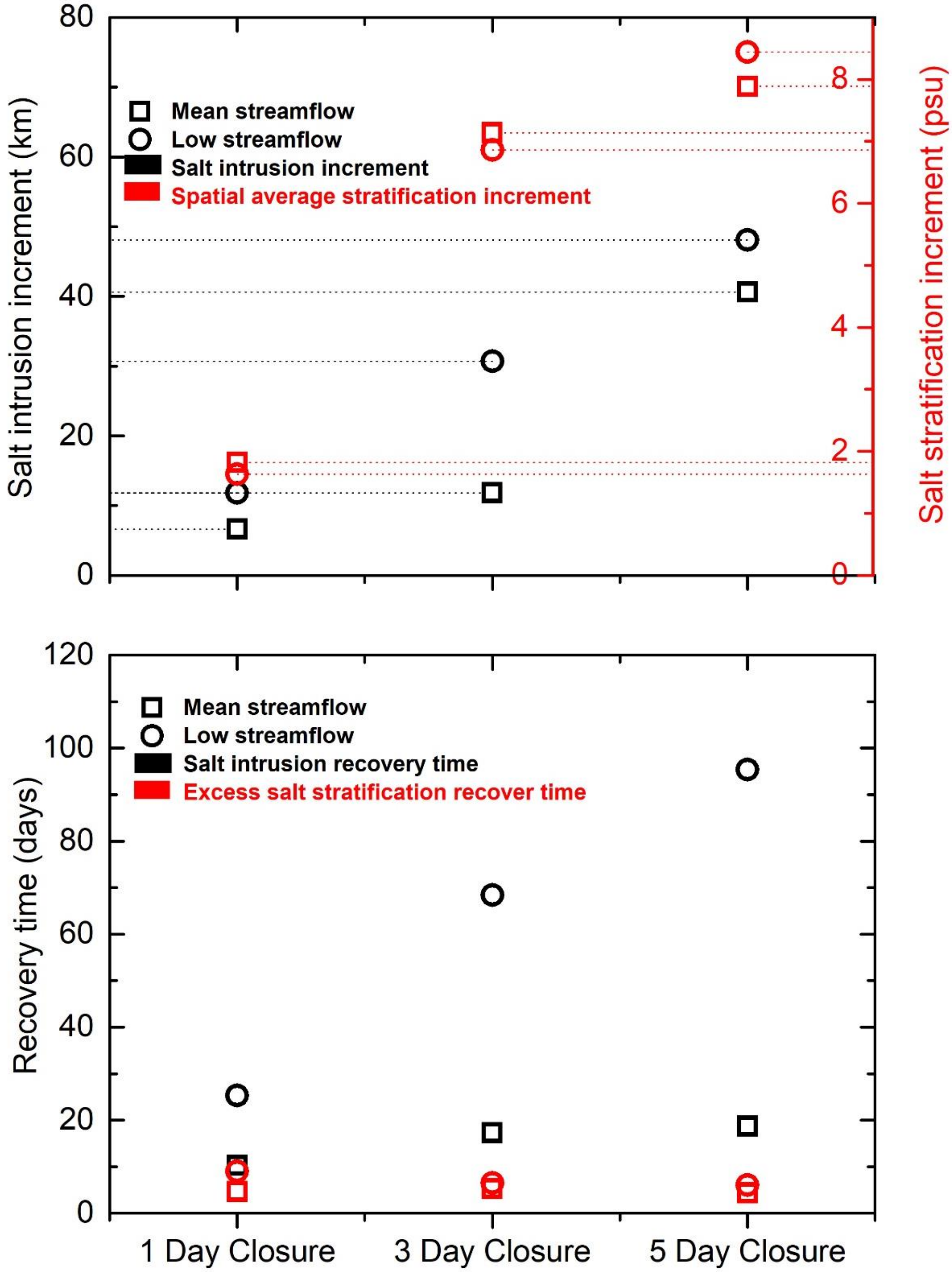

Figure 9. Modeled salt intrusion or stratification increment (top) and their recovery times (bottom) versus gate closure durations under Mean- or Low-Streamflow. The legends show the meaning of the different shapes and colors.

4 Discussion

Our results for the Hudson River estuary show that short-duration surge barrier closures and closures under mean or higher streamflow would have a limited impact on saltwater intrusion and stratification and a short recovery time well below one month. However, longer gate closure durations (3 days or longer) could temporarily increase the salt intrusion and stratification beyond the maxima in a 34-year hindcast (modeled with streamflow, tide, meteorology inputs). Also, results show that monthly closures in dry periods could lead to durable changes to estuary physical conditions, since one month is not sufficient time for recovery.

The salinity, salt intrusion length and stratification are critical physical parameters associated with the estuarine environment, as well as up-estuary wetland habitat and freshwater resources. Increases in stratification can reduce the vertical mixing, then weaken the water exchange, which will affect the water quality by increasing residence time and potentially increasing the tendency toward eutrophication, hypoxia (Paerl et al., 1998) and harmful algal blooms (Cousins et al., 2010). For a tidal river estuary such as the Hudson, the extended salt intrusion can threaten the freshwater supply at upstream locations (Hoagland et al., 2020), and increases in salinity can threaten freshwater marshes and other vegetation (de Leeuw et al., 1994).

In the context of the USACE HAT study and barrier systems being studied that would affect the Hudson, smaller Auxiliary Flow gates (46 m wide) could be temporarily opened during low tides during a long-duration flood event (B. Wisemiller, USACE, pers. comm., 2021). This would allow elevated water levels from river streamflows to escape and could feasibly enable some tidally driven mixing within the estuary. However, if the much wider Navigational Gates were not also opened, the influence of this pulsing on tidal propagation and mixing in the estuary is likely small given that currents are flowing strongly outward at low tide. Moreover, tide propagation into the estuary is very limited when only a small gated flow area of the barrier is opened (Orton & Ralston, 2018). It is not clear how this could change the gate closure effects and recovery, and an extremely high-resolution modeling study would be needed to simulate these auxiliary flow gates and assess these specific management considerations.

Salinity recovery time in all our simulations is less than 100 days, which indicates that annual or less frequent closures would allow for recovery between closures. The management plan initially presented for the HAT Study would involve surge barrier closures for 2-year return period events or worse (USACE, 2019, p69). This would be a rational management plan for the surge barrier system, with respect to recoverability of salinity conditions. Other recent surge barrier studies have similarly recommended infrequent closures and management planning so that SLR doesn’t raise the closure frequency (e.g., USACE, 2020b, 2021a).

However, a new HAT Study report includes no limits on closure frequency, leaving it open to further study (USACE, 2022, p220). If the gate is closed more frequently in response to SLR, as was demonstrated as a possible future scenario by Chen et al. (2020), monthly gate closures with low streamflow will be problematic because the system needs more time to recover. For example, with 0.6 m SLR, the gate closure frequency at the Hudson would increase from 0.15 times per year to 3 times per year. This would increase the likelihood of higher frequency closures (e.g., monthly) and potential associated estuary aggregate impacts with consecutive salt intrusion increasingly moving up the estuary (e.g., Figure S2-o or S2-p).

Our results are focused on modeling of one estuary and are based on several simplifying assumptions to demonstrate the primary factors, processes and effects of surge barrier closures. We focus on a long river-estuary, yet other types of estuaries can have different salinity dynamics, as discussed below in Section 4.3. We use simplified constant Mean- and Low Streamflow condition scenarios, whereas streamflow can vary in response to rain events and snowmelt. We assume that the water depth is not changing and ignore the large uncertainties of future SLR, geomorphic response, and dredging for shipping. We show in Supplementary Text S2.1 how increased water depths can have similar effects to surge barriers and these results are discussed below in Section 4.1 in the context of historical changes to the Hudson. We neglect wind effects in the modeling, but we demonstrate that this is a secondary factor in a narrow estuary like the Hudson (Text S2.4). Complexities of diffusion in the salt intrusion modeling during gate closure are addressed through the sensitivity to the horizontal Prandtl number (Text S2.3). Also, some modeling studies (e.g., Kärnä et al., 2015) have struggled to accurately produce sharp salinity fronts in highly energetic estuaries due to numerical diffusion, and others have shown how grid resolution can affect results (e.g., Ralston et al., 2017). The problem of numerical diffusion could affect the results, but this is somewhat mitigated by the use of a structured grid model like sECOM (e.g., Ralston et al., 2017). Moreover, in our study there are low water speeds during barrier closures and relatively small salinity gradients around the salt front. As a result, we expect numerical diffusion to have a limited effect on our results. Nevertheless, numerical diffusion and resolution sensitivity studies would be useful in future research.

Below in Section 4.1, we contextualize the surge barrier effects relative to future SLR, climate change and historical dredging effects. In Section 4.2 we further discuss how the surge barrier closure effects compare to normal estuary variations and SLR. In Section 4.3, we consider the general applicability of the gate closure assessment approach taken here for other constructed or proposed estuary surge barriers, and in Section 4.4, we synthesize our results with the estuary dynamics literature to outline the critical factors governing recovery time from gate closure.

4.1 Combined effects from sea-level rise, dredging and climate change

Increasingly extreme salt intrusion effects may appear from the surge barrier protection coupled with future SLR and dredging. First, SLR (or dredging) could increase the water depth and increase the salt intrusion of an estuary. The salt intrusion effects of gate closure also are amplified by SLR or dredging (Text S2.1). Moreover, SLR could cause there to be more frequent gate closures which may not allow enough time for estuary conditions to recover, as noted above (Chen et al., 2020). These cumulative effects could raise the frequency and intensity of salt intrusion changes for an estuary, which will increase the risk of affecting the upstream freshwater resources.

The effect of SLR on estuary depths depends on whether increasing sedimentation raises the bed level (e.g., Nichols, 1989), so areas with lower sediment delivery (e.g., New York Harbor; Rodenburg & Ralston, 2017) are more likely to have water depth increases than areas replete with sediment (e.g., the Hudson; Ralston et al., 2013). Predicting the future sedimentary response of estuaries to SLR is a challenging problem for models (e.g., Baar et al., 2019). Furthermore, depths are also often increased by dredging of major estuaries for shipping. For example, the channel deepening on the Hudson River in the past 150 years increased the estuary salinity intrusion by about 30% and increased the stratification by 5% to 30% depending on streamflow (Ralston & Geyer, 2019).

Climate change can also affect the salt intrusion by altering future precipitation and the seasonal hydrograph. Climate change has somewhat complex and competing effects on future streamflow, causing both drying of the land due to increasing evaporation and intensified rainfall due to increased atmospheric moisture. Globally, temperatures will become warmer which will increase the drying of the land due to evaporation. Enhanced drought conditions may worsen surge barrier effects due to lower streamflows and slower recovery times. However, the extreme events could have increased rainfall, particularly for the Northeastern US (Horton et al., 2014), which could result in increased storm-driven and mean streamflows. It is challenging to predict the streamflow variations in the future. Overall, an important additional area of future research is that of the combination of climate change, human interference and surge barrier effects on estuaries.

4.2 Context of surge barrier effects relative to normal estuary variations

The Hudson River estuary salt intrusion and stratification are typically controlled by tidal amplitude and streamflow (Orton & Visbeck, 2009; Ralston et al., 2008). For example, observation shows that the spring-neap tide modulation can cause about 30 km salinity intrusion length variation (Ralston et al., 2008) and a ~15 psu mid-estuary salinity stratification variation (Orton & Visbeck, 2009) for the Hudson River under a relatively stable moderate streamflow condition. Streamflow variation can also strongly affect the salt intrusion length, as the salt intrusion can be as short as 40 km from the Battery after an extreme spring freshet (Geyer et al., 2001) and reach about 120 km after a severe summer drought (Bowen & Geyer, 2003).

The surge barrier system can bring similar magnitude perturbations to estuary conditions when there are gate closures (Figure 9), but these occur more rapidly (Figure 4). Also, this anthropogenic disturbance can work together with other natural forces and create more extreme salinity spatial distributions than normally occur in an estuary (Figure 8).

4.3 Research framework (or metrics) recommendations for other estuary barrier evaluations

In this research, we developed a computational modeling approach and set of metrics to assess the potential physical estuary effects of storm surge barriers. Our analysis in this paper is based on one widely-studied estuary, but similar research could be performed on a wide range of estuary types. Our assessment approach focused on year-round open barrier effects, modeling effects of barrier closures, assessing saltwater intrusion and stratification recovery times, and comparing the changes to data on past historical variations.

Considering the broader range of estuary types characterized by Geyer and MacCready (2014) with a freshwater Froude Number and Mixing Number parameter space, the Hudson has a varying character from strongly stratified salt-wedge to partially-mixed estuary. In this regard, our range of conditions represents a wide range of river-estuaries, but neglects relatively well-mixed and only periodically stratified systems (e.g., San Francisco Bay, Tamar River, Willapa Bay) and the bay-type and lagoonal estuary systems (e.g., Barnegat Bay, Narragansett Bay). Our study captures the range of freshwater Froude numbers modestly well but does not span a wide range of mixing numbers.

Estuaries with high populations vulnerable to storm surge flooding are both likely locations for surge barrier construction and for pollution. The temporary and potential chronic changes identified in this study, increased stratification and salt intrusion, can also reflect increases in residence times that can worsen problems with hypoxia and pollution (e.g., Wurtsbaugh et al., 2019). Thus, water (and nutrient and pollutant) residence times and potentially biogeochemical modeling should be used to evaluate surge barrier effects in such systems (e.g., Marsooli et al., 2018) to better understand these broader possible effects on the estuary environment and ecosystems.

4.4 Controlling factors for estuary recovery time after closure

The response of stratification and salt intrusion to variations in river flow and tidal mixing has been explored by many past studies (e.g., Kranenburg, 1986; MacCready & Geyer, 2010). The length of the salt intrusion and the mean outflow velocity (due to streamflow) are the main driving mechanisms that control the “estuary adjustment timescale” to a new equilibrium (MacCready, 2007). With surge barrier closures, we are interested in the timescale to recover back to a prior equilibrium after an abrupt perturbation (gate closure), but there is some similarity to the estuary adjustment timescale and its dynamics, as shown by our results and discussed below.

The closure duration is a primary factor influencing recovery time as it defines the magnitude of the initial perturbation to the estuary conditions. The dense salty water on the bottom layer will keep move upriver until the gate is reopened and the estuary tidal mixing restarts. Both long duration flood events and multiple flood events in tandem could cause long gate closure duration.

Our results indicate that streamflow is an important factor governing recovery time, similar to the estuary adjustment timescale. During high river discharge like Irene (Section 3.3), there is no salt intrusion increase. The salt intrusion length recovers much faster with Mean-Streamflow than with Low-Streamflow. However, the rate of streamflow varies lot during a storm surge flooding event or a tidal flooding event. So, the gate closure’s impact and its recovery time will vary with different flood events depending on the streamflow conditions.

SLR can also affect the recovery time in an indirect way because it could cause more closures due to tidal flooding that often occurs under low streamflow, non-storm conditions. It is not uncommon for there to be 2-4 month periods with streamflows similar to our Low-Streamflow scenario in summertime (Green Island Station 01358000; USGS, 2021). The most extreme long-duration example was a drought period in 1995 when streamflow was below our “dry” value of 150 m^3/s for about 5 months with a mean of only 111 m^3/s. Normally, there is a low probability to have repeated storm surge events with low streamflow conditions. However, if barrier closure is managed by a constant water level threshold, instead of a constant return period, a growing number of spring tide flood events will trigger the gate closure without storms (Chen et al., 2020), which have a high probability to occur during periods of low streamflow.

Estuary length is another factor that affects the adjustment timescale, and due to the dynamical similarity of recovery from barrier closures, likely also the estuary recovery time. Estuaries with a longer estuary length (e.g., MacCready, 2007) or with a temporarily longer length (e.g., Lerczak et al., 2009) could slow its estuary response time to estuary physical changes. For example, SLR (Tabak et al., 2016), channel dredging (Ralston & Geyer, 2019) or construction of fixed surge barrier infrastructure (Orton & Ralston, 2018) can all extend the mean salt intrusion length of the Hudson Estuary, which will increase the recovery time from gate closure effects as well. Given the large range in estuary lengths with consideration of surge barrier construction (e.g., Boston Harbor estuary with a shorter estuary length and Chesapeake Bay estuary with longer estuary length; Du et al., 2017; Kirshen et al., 2020), the estuary recovery timescale from gate closure will likely also depend on their estuary length.

5 Conclusions

In this study, we analyze the estuary effects of storm surge barriers, in particular gate closures, on estuarine salt intrusion and stratification which have not been studied in the past academic research. We develop a transferable framework to investigate the barriers closure effects on estuary conditions considering control factors including closure frequency, duration and streamflow conditions. Our research focuses on a narrow partially mixed estuary where wind effects are secondary, and it would be worthwhile to perform similar research on other types of estuaries with proposed surge barriers (e.g., lagoonal estuaries or wide estuaries). Our approach here is to use simplified forcing scenarios, but future work could also apply full, variable forcing with multi-year simulations.

The results for the Hudson River estuary indicate that an episodic gate closure event could cause significantly larger but more temporary physical changes compared with the open barrier effects. Gate closure causes rapid increases in stratification and salt intrusion length with the latter increment proportional to the closure duration. So, a short-duration closure has limited estuary impact. However, for 3-day duration closures, the estuary length experiencing unusually high stratification values (over 20 psu) rises to equal the maximum length during 1979-2013 (52 km). For low or mean river discharge, 3 days closures can also lead to a 14-30 km excursion of the salt intrusion up the estuary (an 18-40% increase). This can lead to conditions of salt intrusion and stratification beyond their maxima over the past several decades, especially during a low streamflow condition. If the surge barrier closures are not managed to avoid these extreme conditions, they could threaten upstream municipal water supplies, and they could also affect the estuary environment beyond these physical variables (e.g., estuary hypoxia, sediment trapping, floodplain vegetation).

Increases in stratification are rapidly mixed out within days after gates reopen, and negative anomalies in stratification last for a longer period. However, recovery time of salt intrusion to normal is strongly dependent on streamflow, with the longest recovery times of well over one month (but far less than one year) under low flow conditions. Monthly closures in dry periods could lead to durable changes to estuary physical conditions. A biannual average gate closure frequency, as initially proposed for the prospective surge barrier alternatives in the HAT Study, would allow for physical recovery for the Hudson River estuary.

More broadly, we summarize the controls on gate closure recovery time that may have implications on the consideration of surge barriers for flood risk reduction in other estuaries. Long-duration closures lead to extended recovery times, as a longer closure duration creates a larger initial perturbation to the estuary. A longer estuary length results from a long-duration closure, then also slows the recovery time due to weakened longitudinal salinity gradient. The river discharge is also a primary controlling factor in limiting the duration of any extension of the salt intrusion. Gate closures during low streamflow situations need significantly longer recovery time.

The physical influences of open storm surge barriers and more acute changes when they are closed could lead to long-term changes to estuaries and their habitats. Our results show similar effects as those arising from SLR, climate warming and dredging in estuaries (e.g., Najjar et al., 2010; Ralston & Geyer, 2019; Rice et al., 2012). Therefore, an important continued area of research is on the combination of climate change and surge barrier effects on the physical and ecological conditions of estuaries.

Acknowledgments

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Open Research

The model inputs, bathymetric data and selected model results are available at (Chen, Z. & Orton, P. 2022）.

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