Assessing the Effects of Storm Surge Barriers on the Hudson River Estuary
Candidate Near-Term Research Topics

The purpose of this document is to lay out a list of potential near-term physical oceanographic or flood hazard-related research topics and tasks relating to environmental effects of storm surge barriers on the Hudson River Estuary.

Possible Research Topics and Tasks within this Project

Research on physical influences of gated surge barriers on the Hudson and potentially also other parts of the New York/New Jersey Harbor estuary system will be performed at Stevens Institute of Technology under this study. The time available this spring/summer for this research is 3 months for a doctoral student and about 0.5 to 1.0 months for PI Orton. Work will need to be completed by November 2019 at the latest because this is a one-year project.

Present research capabilities include:

- Modeling of estuary circulation, residence time, and water level under a very wide range of forcing conditions (e.g. storms, droughts, freshets, sea level rise)
- Analysis of changing historical physical conditions in model (1979-2019) or observational data
- Statistical /frequency analysis of hazards resulting from high streamflows, tides, storm surge and waves

Widely-used, well-validated coastal ocean/estuary models are available at Stevens that resolve the area's waterways (e.g. NYHOPS; http://stevens.edu/maritimeforecast). However, these do not have specially-designed high-resolution gridding around barriers and their gates, and without further model development these may give biased estimates of barrier effects (Orton & Ralston, 2018). A sample model grid from a surge barrier experiment is included in the Technical Appendix.

Below is a list of candidate topics for research. A plan will be finalized based on feedback from the Scoping Session, the survey, and in subsequent discussion with the PAC. The Technical Appendix gives additional details and references regarding methods. Some of these topics may be covered in the coming year in the HAT Study, but we presently have incomplete knowledge of the study's plans. The list does take into consideration the prior HAT Study analyses summarized in the Interim Report and Engineering Analyses Appendix (USACE, 2019). Of all the topics, only #11 would require new models to be created that resolve surge barrier gates.

Possible Research Topics

1. Study gate closure frequency and its future evolution (10% effort[1])

Rationale – the gate closure frequency strongly influences the effect of a surge barrier system on the enclosed estuaries. The HAT Study alternatives with cross-harbor surge barriers (Alt 2 and 3a) also include shorefront residual risk reduction features, so that the gates will not need to be closed during frequent low flood events (e.g. weak nor'easters). However, sea level rise will cause the number of floods per year to increase, leading to a requirement for either more frequent closures or additional risk reduction measures (e.g. retreat, construction of higher shorefront barriers).

Approach – given an input of a threshold water level for neighborhood flooding, one can compute the number of expected events requiring closure per year for the present and also how this number changes with future sea level rise. The threshold that triggers gate closure may be defined by several factors, including the resulting flooding caused inside the estuary, costs of lost port commerce, and environmental concerns. The Corps will also be studying gate closure frequency, and we will collaborate to ensure our approaches are compatible or complementary. This task only requires analysis of observational data, with no new modeling.

2. Study duration of storm tides and gate closures (60% effort)

Rationale – the gate closure duration strongly influences the effect on the estuary during storms. Storm frequency (or return period) and peak water levels have been studied extensively for this region, but duration has not and for that reason is poorly understood. Our region's more common storms are extratropical cyclones, which often have a multi-day duration spanning several high tides. Multiple-day closures could present a challenging problem for balancing flood mitigation and water quality, or for river water backup behind the barrier.

Approach – historical tide gauge data can be analyzed to create datasets of both peak water level and surge duration. These data can be used for a purely empirical/historical analysis. Also, a more comprehensive analysis can be performed by adding synthetic storm event data (standard practice for coastal flood risk assessment; FEMA, 2014b; Orton et al., 2016), and performing joint extreme value probability analysis of the relationship between high water levels and their duration. This approach would enable the analysis to include unusual events that are not reflected in our limited historical record. This task only requires analysis of observational data, with no new modeling; possible study topics of closure impacts on estuary conditions (e.g. salinity, stratification, circulation, residence time or pathogens) are presented in separate topic areas below.

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[1] Approximate percent effort is given, as compared with 100% effort total available during the project (based on the total time budgeted for research in the project). The final set of research topics will total roughly 100% effort.

3. Intercomparisons of existing model results (20% effort)
Rationale – stakeholders were interested in seeing a closer examination of existing modeling results to study and seek to better understand the models and their differences. Models may have differences in estuary stratification, or in the turbulent mixing or tide dissipation caused by surge barrier gates, even when resolved with high resolution.

Approach – seek to match up periods with similar forcing for the existing models and model runs (Stevens NYHOPS and the Corps AdH) as well as possible, so their results can be compared and differences can be studied. The Corps modeling was for 1995, and it would be a large effort to simulate weather and tidal forcing conditions for the same year. Existing tide modeling results could be used to study salinity, stratification and salt intrusion including the regions near the barriers and regions up the entire length of the estuary. This would likely require finding Corps model results and requesting data/graphics for a period with similar (mean) streamflows and weak meteorological forcing (e.g. August/September).

4. Assist the HAT Study (10% effort)
Help improve the science in the HAT Study by advising the Corps and its consultants with model development, risk assessment, dataset sharing, qualitative exploratory physical analyses, etc. – this is already occurring simply through our interactions, presentations and discussions.

5. Assist the HAT Study with discovery-mode modeling (50% effort)
Rationale – our relatively comprehensive system knowledge can be used to explore and reveal important influences that may be overlooked in the complex NY/NJ Harbor estuary system, which includes dozens of sub-estuaries.

Approach – help the Corps and its consultants by performing exploratory physical modeling and analyses in spring 2019. A more comprehensive "discovery" mode could be used, wherein we use our existing models or deeper analyses of past simulations to identify possible additional Corps' analyses – e.g. we could do a full preliminary examination of spatial variability in effects including the Hudson's sub-estuaries (e.g. the Hackensack or Long Island Sound), or probe additional variables or processes that might also be quantified by the HAT Study models.

6. Study the potential for trapped water river flooding (50% effort)
Rationale – intense rain and storm surge often occur simultaneously in coastal storms, and a recent study by the lead-PI quantified this joint hazard for the Hudson (Orton et al., 2018). The risk of river flooding behind a closed surge barrier is likely low because surge and river streamflows are typically offset in time (Orton et al., 2012). However, this topic – not yet studied comprehensively – can be better understood using our data.

Approach – the NYHOPS estuary-ocean model is unique in level of detail, including more than 100 freshwater sources in the Hudson-Raritan Estuarine system. The pre-existing historical and synthetic storm data and probabilistic analysis datasets of river and coastal flooding for the Hudson-Raritan (Orton et al., 2018) can be analyzed to better understand this potential problem. This research may also consider the potential for climate change to cause more intense storm-driven precipitation and streamflows in the future, perhaps as a sensitivity analysis with possible high-end streamflow increases (e.g. 20%).

7. Quantify effects of changes to tides and waves on marshes (50% effort)
Rationale – water level fluctuations during storms and waves strongly influence sedimentation and edge erosion (e.g., Hu et al., 2018) and should be quantified. Closing surge barrier gates during storms will lead to lower peak water levels at many locations, yet local wind waves will still exist, and the resulting combination will have different effects on marshes.

Approach – the changes to tides and waves can be quantified with the NYHOPS model (e.g., Orton et al., 2019), which includes both water elevation and wind wave height and period. We can compute various measures of wave forces on marshes such as “wave attack” (e.g., Tonelli et al., 2010). We can also include effects of sea level rise and river streamflow on tides along the Hudson (Orton et al., 2018). However, we do not have a sediment transport or erosion model.

8. Study how barrier gate closures influence estuary physical changes (80% effort)
Rationale – Most analysis so far has focused on the influence of surge barrier infrastructure on estuary physical conditions when gates are open, during normal conditions (Orton & Ralston, 2018; USACE, 2019). However, periodic gate closure can also have an aggregate impact on estuary conditions, and this impact will increase if the frequency of closure increases with sea level rise.

Approach – Simulate conditions causing a range of gate closure frequencies and durations (e.g. back-to-back nor’easters), then evaluate the influence on estuary conditions. Evaluate the changes to mean and extreme conditions of the estuary, in terms of salinity, temperature, stratification and salt intrusion. A better understanding of the relationship between estuary changes and closure frequency could help the Corps work backward to an appropriate maximum frequency for gate closures, which would also help determine the required elevation (and cost) of on-shore residual risk/high frequency measures.

9. Model surge barrier influences on pathogens (80% effort)
Rationale – a concern about surge barriers is the impact on Combined Sewer Overflow pathogen concentrations during storm conditions with closed barriers. A lack of estuary exchange with the open ocean could lead to rising pathogen concentrations.

Approach – We have experience with modeling pathogens in the harbor region (Wen et al., 2017). Depending on what analyses the HAT Study will undertake this year, we could do some additional modeling with our existing NYHOPS model that is complementary.

<u>10. Model surge barrier influences on residence time</u> (80% effort)
Rationale – a concern about surge barriers is the impact on estuary residence time during normal open gate conditions. A longer residence time can lead to reduced oxygen levels and higher pollutant or pathogen concentrations.

Approach – We have experience with modeling residence time in the harbor region (e.g., Marsooli et al., 2018). Depending on what analyses the HAT Study will undertake this year, we could do some additional modeling with our existing NYHOPS model that is complementary. However, if simulation with higher-resolution models were desired to capture open gate areas, this topic would require additional funding for model development and validation.

<u>11. Multi-model uncertainty/ensemble analysis</u> (>= 100% effort)
Rationale – a weakness of estuarine hydrodynamic models is their ability to accurately model stratification (e.g., Warner et al., 2005), and stratification is a critical factor for some of the more important effects of surge barriers (e.g. residence time). Recent studies of water quality for Chesapeake Bay have utilized an ensemble of different models to quantify uncertainty and biases (Irby et al., 2016), and we could follow this approach here.

Approach – repeat HAT Study or Orton and Ralston (2018) model simulations and analyses as a method of quantifying modeling uncertainties, which could be seen as a use of "complimentary models." Other institutions such as Stony Brook, University of Florida, Woods Hole and University of Connecticut may have (or be developing) models that could be added to the ensemble. However, this would require additional funding for model development and validation, and it may not be possible to complete this analysis before this project ends.

Technical Appendix

Modeling methods

Computational modeling of storm tides, overland flooding and waves can be performed using both the three-dimensional Stevens Estuarine and Coastal Ocean Model (e.g., Blumberg et al., 1999; Georgas & Blumberg, 2009) or the widely-used two-dimensional coupled modeling system ADCIRC (ADvanced CIRCulation model) /SWAN (Simulating Waves Nearshore) (Booij et al., 1996; Luettich et al., 1992). SECOM can be used on the NYHOPS model domain (e.g., Orton et al., 2016) as is done operationally (Georgas et al., 2016a; Georgas & Blumberg, 2009) or on higher-resolution grids such as for Hoboken at resolutions as high as 3m (e.g., Blumberg et al., 2015). ADCIRC may be run on the FEMA Region II unstructured numerical grid covering the Northwestern part of the Atlantic with resolution of up to 70 m in the NYC region (Brandon et al., 2016; FEMA, 2014a; Orton et al., 2015), or a modified version of the same grid that was developed with higher resolution of about 40m in the NYC region for the SIRR study (City of New York, 2013). A modified NYHOPS grid, with a case of a 62% Gated Flow Area, is shown in **Figure 1**. This is similar to the 55-60% GFA of barrier concepts in the HAT Study, and can be adjusted to provide a better GFA match or to study other surge barrier sites.

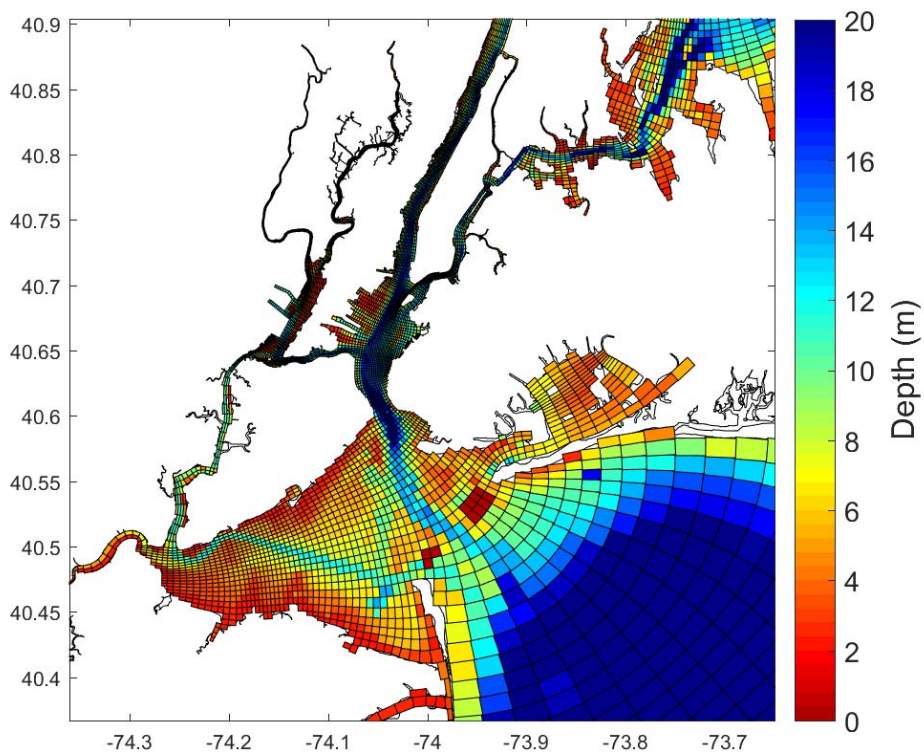

Figure 1: Adapted NYHOPS grid showing a hypothetical case of partial blockage (dark red cells) due to surge barrier infrastructure with a 62% Gated Flow Area (percentage of cross-sectional area openness to flow) between Sandy Hook and Rockaway Peninsula (Orton & Ralston, 2018).

Analysis of model-based historical "reanalysis" data

A unique advantage of the NYHOPS model is its accuracy and historical record for capturing (generally forecasting) stratification and the location of the salt front along the Hudson. The location of the salt front was forecast accurately with an r^2 of 0.83 in a recent two-year period. In a 1979-2013 reanalysis simulation, average indices of agreement were 0.99 for water temperature (1.1C RMSE, 99% of errors less than 3C), and 0.86 for salinity (1.8 psu RMSE, 96% of errors less than 3.5 psu) (Georgas et al., 2016b). Analyses of the influences of surge barrier plans on stratification and on salt intrusion can easily be performed under a wide range of conditions, tapping the existing simulation archive from 1979-2013 (Georgas et al., 2016b) and for the aforementioned storm surge and rainfall flood assessments.

Rain/Surge probabilistic data analysis

One risk with closing surge barrier gates during a storm is that rainfall runoff is trapped and could cause flooding. This risk is likely low because storm surge and runoff are typically offset in time (Orton et al. 2012), but has not yet been quantified and can be using our data. The NYHOPS model is unique in capturing over 500 freshwater and heat sources to its domain, with over 150 in the Hudson-Raritan Estuarine system. The streamflow reaching the ocean during Hurricane Irene was over three times higher (13500 m^3/s) than the streamflow gauged at Troy, New York (4700 m^3/s), demonstrating that during some coastal storms most of the streamflow enters the system from estuarine tributaries (Orton et al., 2012). Preliminary modeling shows that after a storm like Hurricane Irene passes, the water behind the barrier would rise at 3 meters per day, rapidly causing flooding if the barrier was held closed for more than one day.

The Project PI has created probabilistic flood hazard assessments to quantify annual probabilities of coastal flooding (storm surge plus tide) and flooding from rainfall, tides, storm surge and sea level rise (Orton et al., 2015; Orton et al., 2018; Orton et al., 2016). Data from these pre-existing studies can be used here to quantify flood probabilities, surge barrier induced reductions in flooding, and flood area for specific return periods. It can also be used to study the potential problem of trapped river water flooding behind closed barriers.

Joint probabilistic analysis of hazards

The relationship between storm tide maxima, surge duration, and possibly also river flood timing can be studied using statistical models. Extreme value distributions can be fitted for marginal distributions for each variable (Orton et al., 2018; Orton et al., 2016), and copulas can be used to form a multivariate probabilistic model that addresses correlation and timing between rain and river water level (e.g., Lian et al., 2013; Wahl et al., 2015). Copulas and distributions can be fitted using maximum likelihood approach, and a set of different but widely-used extreme value distributions and copula types will be evaluated for best-agreement using a least-squares criterion (e.g., Lian et al., 2013).

The resulting copula models can be utilized to create time series (e.g., Wahl et al., 2016) for stremflow and storm surge (plus time-varying tide) for synthetic storm sets that are associated with a range of return periods. These can help more comprehensively test out and plan for barrier gate closure management.

Other assessment capabilities

Other analyses are possible and available depending on End User and scientific needs. Barrier influences from changes to tide range and wave impacts on marshes can be quantified with the model using measures of "wave attack" on marshes along the Hudson (e.g., Tonelli et al., 2010). Recent work using NYHOPS included tide simulations to determine tidal range changes and possible resonance or flood reflection throughout the estuarine system in response to sea level rise or flood mitigation (e.g., Fischbach et al., 2018; Kemp et al., 2017) and residence time simulations to study impacts of grey and green flood mitigation measures on water quality (Fischbach et al., 2018; Marsooli et al., 2018).

Stevens ECOM has previously been used for residence time simulations (e.g., Marsooli et al., 2018), and these could be performed with coarsely-resolved gate areas (e.g., Orton & Ralston, 2018). We do not presently have a model that resolves surge barrier gate openings at high resolution, so if simulation with higher-resolution models were desired, this topic would require additional funding for model development and validation. The model and NYHOPS grid have also been used for pathogen transport simulations in collaboration with NYC's Department of Environmental Protection and could be repeated with opening and closing gates (Wen et al., 2017).

PI Orton is a member of the NY Panel on Climate Change, serving on the expert teams for sea level rise and coastal flooding. NPCC projections (Gornitz et al., 2019; Orton et al., 2019) can directly be tapped to study the frequency of barrier closures for various flood prevention goals over the long-term, the influence of climate change on this frequency, and effects of such closures on the estuarine system.

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