Preliminary Evaluation of the Physical Influences of Storm Surge Barriers on the Hudson River Estuary

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1.0 Introduction

Storm surge barriers are being evaluated by the Corps of Engineers as an option for flood risk reduction for the New York City metropolitan area under the *New York/New Jersey Harbor & Tributaries Focus Area Feasibility Study*[1]. The decision of whether or not to build surge barriers to protect one of our nation's main commercial hubs and ports, crossing one of our most iconic estuaries, is a major decision worthy of thorough analysis of potential impacts. The Corps is evaluating multiple flood mitigation alternatives near the mouth of the Hudson River estuary, including "Alternative 2", which has surge barriers between Sandy Hook and Rockaway Peninsula (the "Gateway" barrier) and at Throgg's Neck in East River, "Alternative 3A" which has barriers at Verrazano Narrows, Arthur Kill and Throgg's Neck, and "Alternative 3B" which has barriers at Arthur Kill and Kill van Kull to protect only New Jersey harbor areas.

Storm surge barriers have the potential to cause large-scale changes to the Hudson River estuary ecosystem. Gates in the barriers are left open under normal conditions to allow exchange of water due to the tides and smaller storm surge events, but can be closed when extreme storm surges are expected. However, even when the surge gates are open, fixed infrastructure remains in place and partially blocks the waterway. The effects of the fixed infrastructure of barriers during non-storm conditions on the circulation, physical conditions, and ecosystem of the estuary should be carefully assessed for a full range of possible impacts. To avoid unintended negative consequences for the estuary, a rigorous scientific evaluation of potential physical, chemical and biological effects is needed in parallel with the assessment of other factors such as flood risk reduction and costs for the barrier configuration alternatives.

This report, commissioned by the New York - New Jersey Harbor & Estuary Program and the Hudson River Foundation, presents a first look at the possible direct influences of hypothetical surge barriers on physical conditions in the Hudson River estuary. Prior barrier systems have typically been placed in well mixed estuaries that are relatively shallow and have large tides, or on freshwater tidal rivers, so effects of barriers on partially mixed estuaries like the Hudson have received little rigorous evaluation. We first review the existing scientific literature on effects of barriers on estuarine conditions, identifying potential circulation, salinity, stratification, and general hydrodynamics[2] changes associated with barriers. We then adapt existing hydrodynamic models of the Hudson to qualitatively evaluate potential changes by inserting various barrier configurations into the model grids. In doing so, we preliminarily evaluate the utility of existing models, identify model issues, data gaps, and near-term research needs. The Foundation convened a webinar on July 19 where invited experts on storm surge barriers, hydrodynamic modeling, and estuarine physics contributed to a discussion of the topics. Also invited were representatives of the Corps of Engineers and the other sponsors of the Harbor and Tributaries Focus Area Feasibility Study (HATS) study: New York State Department of Environmental Conservation, New Jersey Department of Environmental Protection, and New York City.

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[1] http://www.nan.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/11241/Article/644997/fact-sheet-new-yorknew-jersey-harbor-tributaries-focus-area-feasibility-study.aspx

[2] The branch of physics pertaining to forces acting on and within water, and resulting water flows

The goal of this report is to preliminarily identify and evaluate possible hydrodynamic changes resulting from a large barrier at the entrance to the Harbor, as well as to evaluate the utility of existing models, data gaps, and research needs. The report does not evaluate any specific proposed barrier designs, nor does it characterize in detail potential impacts that may depend on barrier configuration or implementation. Representative barriers at the mouth of the Harbor with varying degrees of closure were examined to characterize a range of potential impacts. Results of this preliminary research are intended to inform discussion and future work on how potential hydrodynamics changes associated with barriers would affect water quality, fish migration, larval recruitment, contaminant transport, and other topics of interest in the Hudson. The preliminary results may also help inform the Corps' HATS study, the HATS study's partners, the Hudson River Foundation's 2019 Call for Proposals for scientific research, and Harbor & Estuary Program (HEP) partners, including the HEP Policy Committee.

2.0 Literature Review: Surge Barrier Physical Influences on Partially-Mixed Estuaries

The Hudson River is a partially-mixed estuary, where salinity stratification and the distance that salty ocean water moves landward both vary with spring-neap changes in tidal mixing [*Orton and Visbeck*, 2009; *Ralston et al.*, 2008]. During neap tides, mixing decreases, stratification increases, and the salinity intrusion moves farther up the river due to stronger estuarine circulation[3]. During spring tides mixing increases, so stratification and the estuarine circulation decrease and the salt is pushed back toward the mouth. The salinity intrusion and stratification in the Hudson also vary seasonally with river discharge: higher flows push the salt seaward and increase stratification, while during summer low discharge conditions the salt moves landward and stratification decreases.

In contrast to the stratified Hudson, many of the estuaries where surge barriers have been built are more well-mixed. Barriers have been built on broad, shallow deltas (Netherlands Delta Works, New Orleans), on freshwater tidal rivers (Thames, Ems, Eider), and estuaries with minimal freshwater input (Oosterscheldt, New Bedford, Providence, Stamford) [*Kirshen et al.*, 2018]. A barrier with physical scales similar to the Hudson was constructed for St. Petersburg, but the tides in the Baltic are negligible, and no large-scale studies have been done on its effects. Impacts of the barrier for the relatively well-mixed Oosterscheldt in the Netherlands have been studied extensively and provide some guidance. Flow restriction by the barrier reduced the tidal amplitude in the eastern part of the estuary, resulting in greater stratification, less sediment in suspension, increased water clarity, and major changes in the phytoplankton community [*Bakker et al.*, 1990] and salt marsh vegetation [*De Jong et al.*, 1994]. A modeling study of potential impacts of storm surge barriers for Boston Harbor found that the effect on the tidal amplitude was small, but that circulation patterns were drastically altered and increased tidal velocities in the vicinity of barrier openings could be hazardous to navigation [*Kirshen et al.*, 2018].

A modeling study of potential effects of storm surge barriers on Chesapeake Bay addresses partially mixed conditions that are more similar to those found in the Hudson [*Du et al.*, 2017].

[3] "Estuarine circulation" refers to the typical two-layer flow pattern in an estuary, where average bottom flow is directed upriver and average surface flow seaward, driven by the density (salinity) gradient between ocean and river water [Geyer and MacCready, 2014].

Depending on barrier configuration, tidal amplitude decreased by 13-20%, with greater impacts during spring tides, and both stratification and the length of the salinity intrusion increased. The decrease in vertical mixing due to weaker tides and stronger stratification resulted in longer residence times, with potentially increased extent of hypoxia. An observational study on the *removal* of a barrier in the Sheepscot River Estuary (Maine) is consistent with these physical responses [*McAlice and Jaeger*, 1983]. After removal of a causeway, the tidal amplitude increased by about 50%, and both the stratification and estuarine circulation were reduced.

Partially mixed estuaries are distinctive from well-mixed systems in that the estuarine circulation is the dominant mechanism of exchange with the coastal ocean, and variations in tidal amplitude, natural or anthropogenic, substantially affect this estuarine exchange. The limited literature on the effects of surge barriers on estuarine conditions indicate that reductions in tidal amplitude associated with barriers can increase the estuarine circulation, stratification, and the length of the salinity intrusion. These physical alterations can affect habitat through changes in residence time, dissolved oxygen exchange, water clarity, salinity regime, and tidal inundation.

3.0 Preliminary Modeling

This study focuses on assessing potential effects of flow obstruction by barriers across the estuary-ocean entrance (the Sandy Hook-Rockaway cross-section) on physical conditions in the Hudson estuary, in particular examining changes in tidal range, stratification and salt intrusion with various barrier configurations. As an initial step, we adapt existing models of the Hudson that have previously been calibrated to represent the current condition without barriers, and then add barriers to the model grids. Models are run in "control" simulations using the regular model grids and bathymetric configuration, and run using the same boundary forcing but with different grid configurations adapted to incorporate dry grid cells that represent a surge barrier blocking flow. The East River is left open in all simulations to focus on potential effects of barriers across the much larger opening across the lower harbor.

To compare the different barrier configuration cases, we quantify the relative *openness to flow* based on the reduction in cross-sectional area (CSA) across the inlet due to the barrier, or the CSA with the barrier (assuming open gates) divided by the total CSA of the inlet. We refer to this metric as the "gated flow area"[4], represented as a percentage of the flow area in the case without barriers. The models were run with experimental surge barrier grids having gated flow areas ranging from 10-80%, in addition to control simulations (100%). Example grids with gated flow areas of 44% from two of the models used in this study are shown in **Figure 1**. Note that the models do not simulate actual gates, but instead focus on the non-storm conditions when gates would be open and flow can pass through the openings.

The challenges of modeling effects of surge barriers in estuaries include:

- A three-dimensional (3D) model is needed to quantify many important effects – e.g. stratification, flushing, salt intrusion

[4] In the webinar slides (**Appendix A**) the term "porosity" is used instead, but here we use "gated flow area" to avoid confusion with other meanings of porosity.

- The model should incorporate a broad range of physical forcing factors that affect the system (e.g. salinity, storms, tides, freshwater inputs)
- Resolving flow in the vicinity of the gates requires high resolution grids, increasingly so for smaller openings. If the main navigation gate is O(500 m) wide, O(50 m) grid resolution is needed, while flow gates of O(50 m) correspond with O(5 m) grid resolution. Both high spatial resolution and the 3D configuration greatly increase the computational costs.

The preliminary model results presented here include 3D simulations at moderate resolution under a limited set of forcing conditions. Addressing these modeling challenges more completely would require more extensive, comprehensive studies.

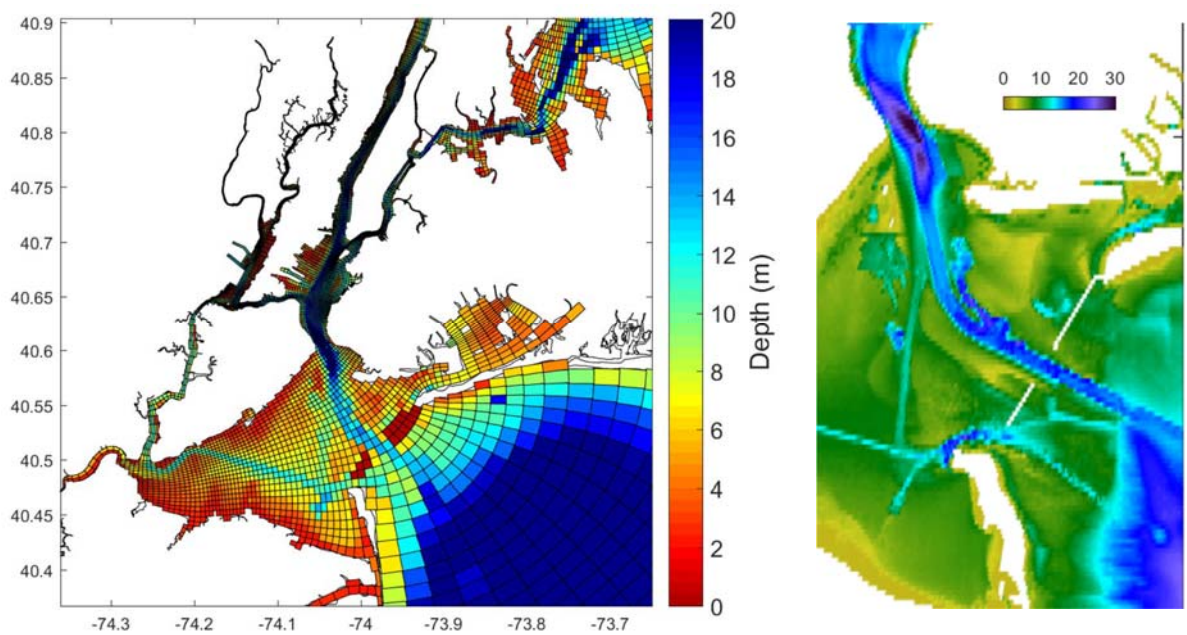

Figure 1: Two example grids with surge barriers with a gated flow area of 44% from (left) NYHOPS and (right) the ROMS grid. Color shading in both cases represents model bathymetry. On the NYHOPS grid, dark red grid cells in the estuary-ocean entrance represent areas blocked at all times by a surge barrier, whereas in the ROMS grid these are colored white.

3.1 Modeling methods

Three different models were run using grids adapted from existing configurations, with the goals of (a) evaluating potential influences of surge barriers on physical conditions, and (b) evaluating the models and their differences, and thus gaining perspective on their possible accuracy or biases. The study included two three-dimensional (3D) models as well as a two-dimensional (2D) model for comparison. The models tested used sECOM (3D) [*Georgas and Blumberg*, 2010; *Marsooli et al.*, 2017] on the NYHOPS grid [*Georgas and Blumberg*, 2010], ROMS (3D) [*Haidvogel et al.*, 2008] on a Hudson and New York Harbor grid [*Ralston et al.*, 2013], and ADCIRC (2D) [*Bunya et al.*, 2010; *Luettich et al.*, 1992] on the FEMA Region 3 grid [*FEMA*, 2014a]. The 3D models were forced with tides, no wind, and freshwater flow from the Hudson of 550 m^3/s, which is similar to

the annual average discharge. ADCIRC-2D had no river input. Brief summaries of each model and grid are given below, with further details in the webinar slides (**Appendix A**).

The Stevens Institute of Technology's version of the Estuarine and Coastal Ocean Model (ECOM) is called sECOM, and has been used by Stevens researchers for a wide range of 3D coastal and estuarine applications [*Georgas et al.*, 2016; *Georgas and Blumberg*, 2010; *Orton et al.*, 2012; *Orton et al.*, 2018; *Orton et al.*, 2016; *Wen et al.*, 2017]. The most widely used application of the model is forecasting on the New York Harbor Observing and Predictions System domain, which has a horizontal resolution of up to 100 m in New York Harbor and vertically has 10 evenly distributed terrain-following layers [*Georgas and Blumberg*, 2010]. The sECOM-3D model was used on the NYHOPS grid, and a shortcoming is that resolution in the estuary-ocean entrance region is poor, at 500-1200 m (e.g. **Figure 1**). This is a very coarse resolution relative to possible surge barrier gates, only enabling the model grid to be used to study gate openings of a very large size. Therefore, the model/grid likely has errors simulating tidal currents through poorly resolved gates, a topic further discussed in **Section 3.3**.

The 3D Regional Ocean Modeling System (ROMS) model of the Hudson has been evaluated extensively against observed water level, salinity, stratification, and velocity [*Ralston and Geyer*, 2017; *Ralston et al.*, 2012; *Ralston et al.*, 2013; *Warner et al.*, 2005]. The domain extends from New York Bight and Eastern Long Island Sound to the tidal limit of the Hudson and includes all of New York Harbor. Horizontal grid resolution is 100 to 300 m in the Harbor, with higher resolution in the lower Hudson (50-100 m). Vertically, the grid has 16 evenly distributed sigma layers. Storm surge barriers were represented by masking out cells across the mouth, which blocks flow across those cells. The grid does not resolve well the details of flow near the barrier openings, particularly for cases where the openings are small. The structured grid also makes it difficult to resolve natural or constructed bathymetric complexity, and tidal flows or bathymetric features that are not aligned with the grid orientation are represented less well.

The third model used was the vertically-integrated, 2D, ADCIRC (ADvanced CIRCulation model) [e.g., *Bunya et al.*, 2010; *Luettich et al.*, 1992]. The model is run on the FEMA Region II unstructured numerical grid with resolution as fine as 70 meters. The model and grid have been validated in prior studies, including a comprehensive model validation for tides and a set of historical storms [*FEMA*, 2014b]. The resolution around the estuary-ocean entrance is higher than the other two models' grids, typically about 70-150 m, enabling better resolution of barrier gate openings. However, unlike the other two model/domains, this 2D model does not include river inflow or capture vertical stratification.

3.2 Modeling results

The three models all predict time and space-dependent tidal water level and velocity fields, and these results can be compared. The tide range conveyance captures how tide range changes for a variety of gated flow area values across the three models (**Figure 2**). Changes in the tide at a location in the Hudson River off upper Manhattan is shown, but similar decreases in tidal amplitude occur throughout the Harbor and estuary landward of the barriers.

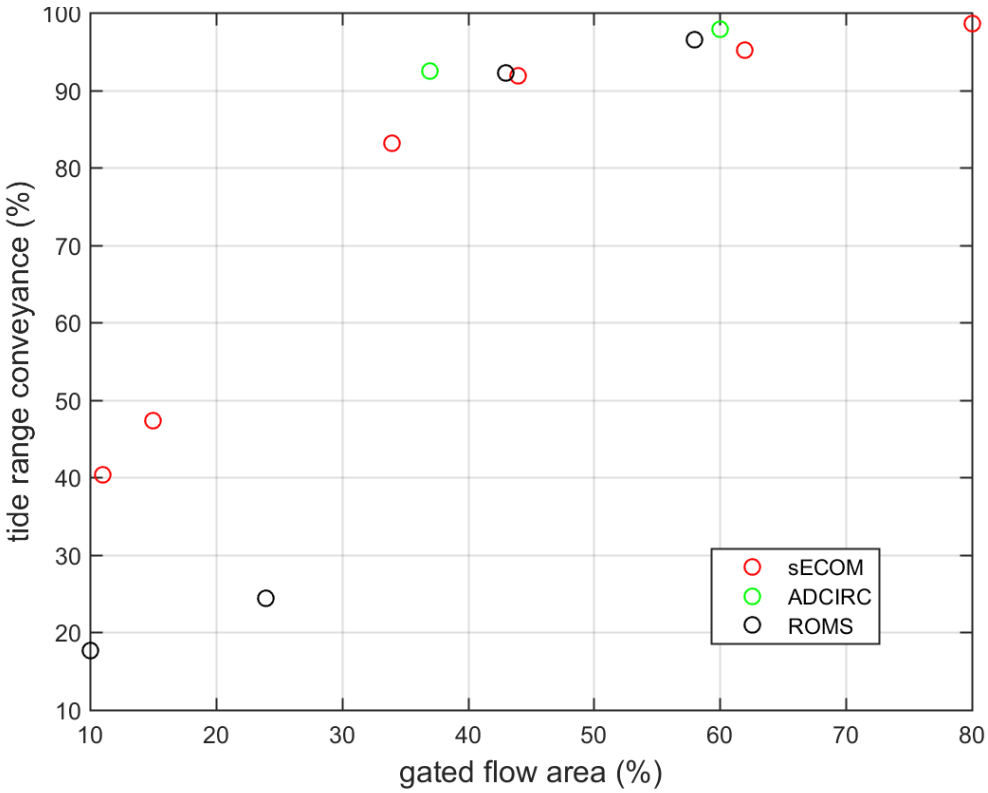

Figure 2: Modeled conveyance of tide range into the estuary as a function of gated flow area. Tide range conveyance is calculated as the percentage tide range in experiment relative to the control simulation. The site for the computation is in the Hudson River estuary off upper Manhattan.

The models indicate that tide range would decrease by 2-10% (or a tidal range conveyance of 90-98%) for gated flow area greater than about 40%, while for lower gated flow areas the tidal range conveyance into the estuary drops off sharply. The reduction in tidal range is greater during spring tides than during neap tides (**Appendix A**). The reduction in tidal amplitude for relatively open barrier configurations (gated flow area > 40%) is modest compared to the more restrictive barrier cases, but the associated reduction in tidal mixing could still significantly alter the salinity dynamics and lead to changes to the stratification and length of the salinity intrusion. The general trend of decreasing tidal range for decreasing gated flow area is consistent across the models, but inter-model differences make it clear that these results should be viewed as preliminary and in need of additional analysis to resolve discrepancies, as is discussed in **Section 3.3**.

Maximum tidal velocities in the vicinity of the barrier openings were over 3 m/s for some of the cases, which is consistent with intensified currents found for other surge barrier openings [e.g., *Kirshen et al.*, 2018; *Mooyaart and Jonkman*, 2017]. Strong velocities near the barrier openings increase frictional energy loss and likely explain the reductions in tidal amplitude in the estuary. Moreover, the non-linear dependence of frictional effects on velocity would explain the result that tide reductions are more pronounced due to the stronger velocities of spring tides or cases with a small gated flow area. Tidal reflection by the barriers may also contribute to the reductions in tidal range inside the estuary.

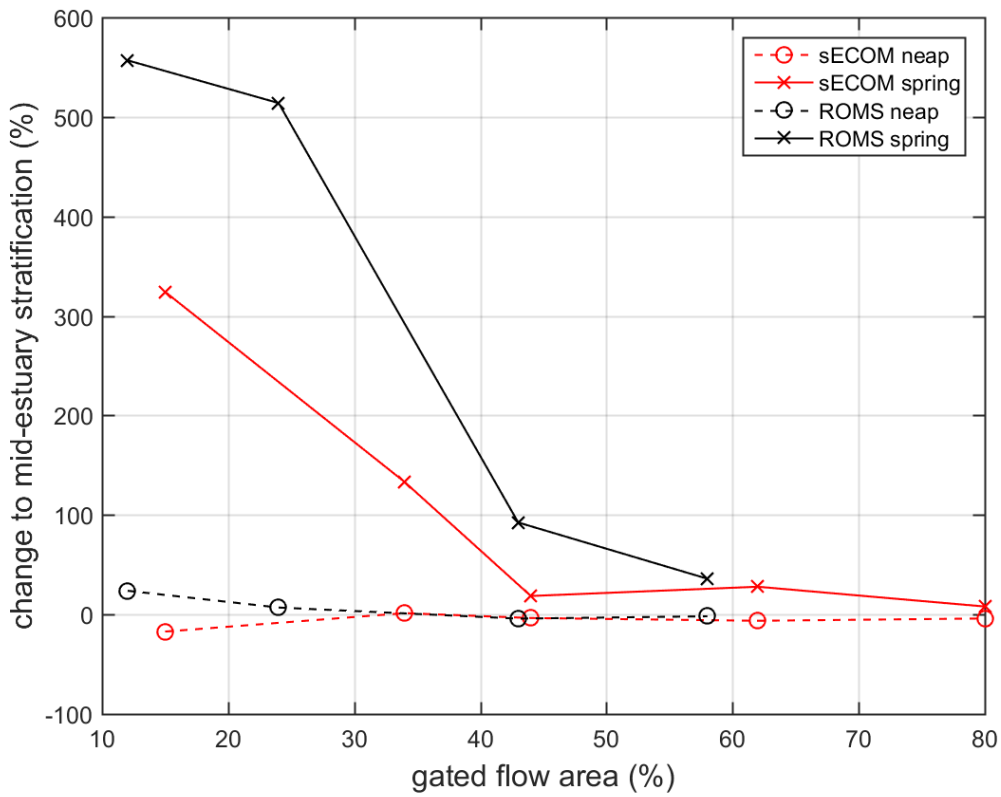

Figure 3: Modeled change in mid-estuary stratification as a function of gated flow area, relative to control. Mid-estuary stratification is computed as the near-bed minus surface salinity near the middle of the salinity distribution, or where the vertically averaged salinity is 15 psu.

In addition to water level and velocity, the 3D models produce a detailed picture of the circulation and stratification in the estuary, and how they may be modified by barriers. The modeled change in stratification for experimental runs versus control conveys how stratification may change for a variety of gate flow area values (**Figure 3**). The general pattern, as found in prior studies (**Section 2**), is that decreasing gated flow area leads to increasing stratification. Specifically, the models suggest that stratification during spring tides may be very sensitive to flow obstruction by barriers, with an increase of 50-100% for gated flow area from 40-70%, and much larger increases for lower gated flow areas. Modeled stratification during neap tide is relatively insensitive to changing gated flow area. During neap tides, mixing is relatively weak and stratification strong in the estuary without barriers, so the reduction in tidal amplitude due to barriers has less of an effect than during spring tides. Additional details on the along- and across-channel distributions of salinity and stratification during neap and spring tide conditions are presented in **Appendix A**.

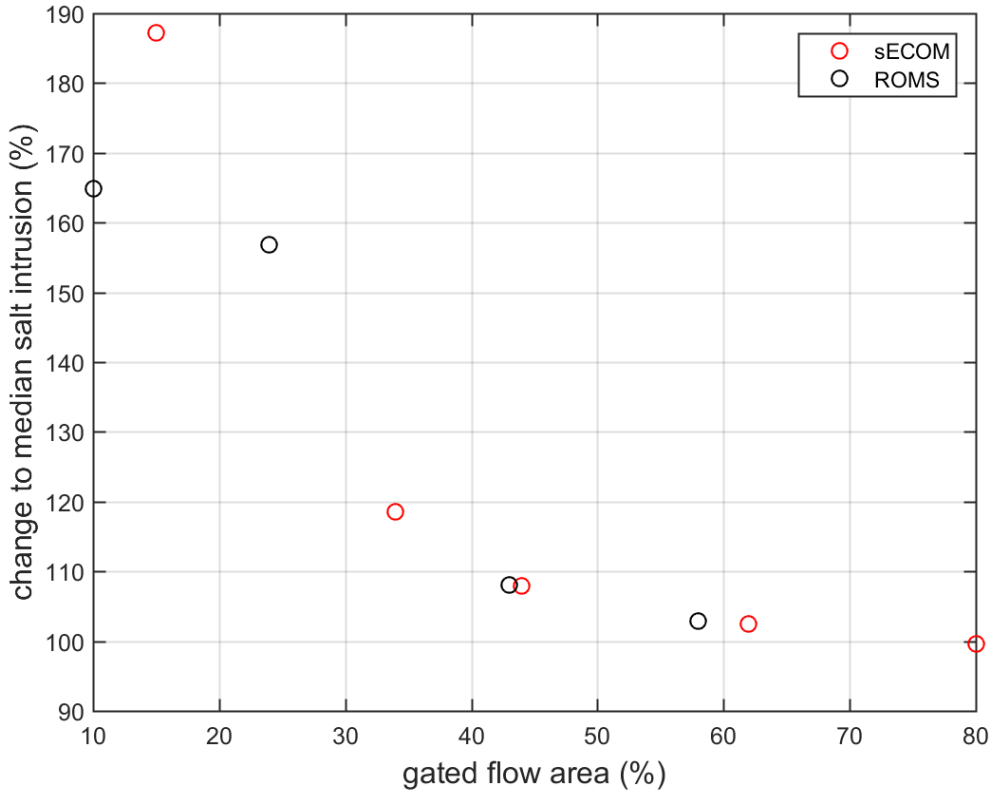

Figure 4: Modeled change in median salt intrusion length as a function of gated flow area, relative to control. Salinity intrusion length is computed from the model results as the distance from Battery to the location with a salinity below 0.1 ppt.

Model results also show an increased length of the salinity intrusion with more restrictive barrier configurations (**Figure 4**). The reduction in tidal amplitude due to the barriers leads to a reduction in tidal mixing, an increase in estuarine circulation, increased landward salt transport, and therefore a longer salinity intrusion for a given discharge. This is analogous to the response of the estuary to the decrease in tidal amplitude from spring to neap tides, when the salinity intrusion also moves farther landward. Modeled increases in the median salt intrusion length are smaller for the barrier configurations that block less than half the cross-sectional area (<10%), but increase substantially for more restricted openings, as with the tidal conveyance and stratification results. Locally the impacts on habitat for even small increases in the salinity intrusion may be significant, particularly in regions near the transition to freshwater. Despite many differences in model formulations and grid configurations, the two models evaluated here give strikingly similar results for the change in the salinity intrusion changes over most of the barrier configurations tested.

3.3 Discussion and webmeeting inputs

The two 3D models were not originally developed to address the questions posed in this study, and yet the model results on the effects of barriers on physical conditions are largely consistent with each other and with our understanding of the dominant physical processes in the Hudson. For barrier configurations where more than about half of the cross-sectional area at the mouth

was blocked, the models showed significant decreases in tidal conveyance, increases in stratification, and increases in the salinity intrusion. The model results did have clear differences between them, particularly for the more restrictive barrier cases, which reflect the increasing importance of grid resolution in the vicinity of the barrier openings and that these models were not designed specifically for that task. Barrier openings for some of the cases were only 1-2 cells in width, when at least 6 or more cells across is typically more appropriate to resolve the flow structure and reduce errors. However, the model grids presented here did typically have resolution greater than the preliminary analysis (a "screening-level") approach with a coarse grid (e.g. one grid cell per opening) recently used in a USACE study [*NYC-DEP*, 2016; *USACE*, 2016] or in some of the barrier configurations from a study of Chesapeake Bay (openings with one cell width) [*Du et al.*, 2017]. While the ADCIRC-2D model had the highest resolution and is better able to resolve flow near the barrier openings, it too would benefit from a grid configuration that is optimized to represent specific barrier configurations. More importantly, the 2D formulation is unable to represent the fundamentally 3d processes that are of interest in the estuary.

Gated flow area is a relatively straightforward metric to compare effects among different barrier configurations, but the change in flow cross-section is not the only relevant factor. For example, the effect of many smaller gated openings on the tidal conveyance and estuarine dynamics is likely different than for a single, larger opening with the same total cross-sectional area. Estuarine circulation and stratification are extremely sensitive to water depth, so a broad, shallow gated area is likely to have different effects than a narrow, deep opening. The effects of the configuration of gated openings and appropriate metrics for comparison merit additional investigation in more comprehensives studies.

One interesting result was the sharp contrast in stratification response to decreasing gated flow area during neap versus spring tides (**Figure 3**). Stratification during spring tides increased for even minor decreases in gated flow area, while conditions during neap tides were less sensitive to barrier configuration. This difference could occur because frictional losses near barrier openings depend non-linearly on tidal velocity, so losses in tidal energy are much greater during spring tides due to the stronger tidal velocities. This is most readily seen in model results for tide range, which show greater reductions in tidal amplitude for spring tides (**Appendix A)**. A result of smaller tide ranges and weaker tide currents is less vertical mixing and stronger stratification. During neap tides, the tide-induced mixing is already low, so a reduction of tidal energy in the system has little additional effect on the stratification.

Several topics were left unstudied here, but could be considered in future work. Differing magnitudes of river streamflow may influence the results, and simulations could cover dry and wet seasons in addition to the mean streamflow conditions presented here. The construction of the bottom of the passage within the gates may affect turbulent mixing or velocities around the gates. The influences of specific, realistic designs of surge barriers and gates will need to be studied as part of any comprehensive analysis. Similarly, the optimization of surge barrier designs with engineers and scientists could be helpful for evaluating feasibility in terms of a balance of impacts, costs, benefits and navigability.

4.0 Conclusions

Both the modeling and literature provide consistent qualitative conclusions on the physical effects of surge barriers on the Hudson River estuary. More restrictive barriers lead to:

- Stronger tidal currents and mixing near the barrier gate openings
- Widespread reductions in tidal range, currents and mixing through the rest of the estuary
- Increased stratification in the estuary due to the reduction in tidally-driven mixing
- Greater salinity intrusion due to the stronger stratification and estuarine circulation
- More pronounced changes during spring tides than neap tides

These results are consistent with other studies of effects of barriers on estuaries and are consistent with basic processes in estuarine physics. These preliminary results provide a baseline for more in-depth studies of physical processes and for interdisciplinary studies of related effects. Discrepancies between model results reflect a need for additional model development to create tools specifically designed to address these issues.

5.0 Recommendations

Based on the above considerations and conclusions, we recommend the following next steps relating to physical estuary changes induced by surge barriers:

- Continue with 3D estuary modeling of estuary conditions and surge barrier-induced changes
- Conduct sensitivity studies to determine the grid resolution or a model nesting approach that is required to appropriately characterize flows through barrier gates
- Create new regional model grids specifically designed to address storm surge barriers and flow through their gates
- Continue to develop a more detailed set of parameters describing influences of barriers on physical conditions in estuaries
- Find/fund studies of barriers that have actually been built on partially-mixed estuaries (or estuaries that periodically meet that definition) – what do models predict and what actually happened?

In addition to the physical impacts, prospective or planned surge barriers should also be carefully assessed for a broader range of possible side effects impacting estuarine conditions and habitats. Modeling or other analyses should be performed on topics such as dissolved oxygen, residence time, sediment transport and trapping, contaminant transport, and habitat changes.

Multiple opportunities exist to address these recommendations, including modeling under the Corps' HATS study, as well as research funded under the Hudson River Foundation's 2019 Call for Proposals. A one-year study funded by NOAA (Orton, PI) will have multiple workshops and enable more physical modeling and analyses, as well as interdisciplinary interactions. Addressing these modeling challenges more completely for the Hudson and for the broader topic of surge barriers across any estuary motivates seeking additional resources from beyond this short list.

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References

Bakker, C., P. Herman, and M. Vink (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.

Bunya, S., J. C. Dietrich, J. J. Westerink, B. A. Ebersole, J. M. Smith, J. H. Atkinson, R. Jensen, D. T. Resio, R. A. Luettich, C. Dawson, V. J. Cardone, A. T. Cox, M. D. Powell, H. J. Westerink, and H. J. Roberts (2010), A high-resolution coupled riverine flow, tide, wind, wind wave, and storm surge model for Southern Louisiana and Mississippi. Part I: Model development and validation, *Mon. Weather. Rev.*, *138*(2), 345.

De Jong, D., Z. De Jong, and J. Mulder (1994), Changes in area, geomorphology and sediment nature of salt marshes in the Oosterschelde estuary (SW Netherlands) due to tidal changes, *Hydrobiologia*, *282*(1), 303-316.

Du, J., J. Shen, D. M. Bilkovic, C. H. Hershner, and M. Sisson (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, *Estuar. Coasts*, *40*(2), 387-403.

FEMA (2014a), Region II Coastal Storm Surge Study: Overview*Rep.*, 15 pp, Federal Emergency Management Agency, Washington, DC.

FEMA (2014b), Region II Storm Surge Project -- Model Calibration and Validation*Rep.*, Prepared by Risk Assessment, Mapping, and Planning Partners (RAMPP), Washington, DC.

Georgas, N., A. Blumberg, T. Herrington, T. Wakeman, F. Saleh, D. Runnels, A. Jordi, K. Ying, L. Yin, and V. Ramaswamy (2016), The Stevens Flood Advisory System: Operational H3e Flood Forecasts For The Greater New York/New Jersey Metropolitan Region, *International Journal of Safety and Security Engineering*, *6*(3), 648-662.

Georgas, N., and A. F. Blumberg (2010), Establishing Confidence in Marine Forecast Systems: The Design and Skill Assessment of the New York Harbor Observation and Prediction System, Version 3 (NYHOPS v3), paper presented at Eleventh International Conference in Estuarine and Coastal Modeling (ECM11), ASCE, Seattle, Washington, USA, 4-6 November.

Geyer, W. R., and P. MacCready (2014), The estuarine circulation, *Annual Review of Fluid Mechanics*, *46*.

Haidvogel, D. B., H. Arango, W. P. Budgell, B. D. Cornuelle, E. Curchitser, E. Di Lorenzo, K. Fennel, W. R. Geyer, A. J. Hermann, L. Lanerolle, J. Levin, J. C. McWilliams, A. J. Miller, A. M. Moore, T. M. Powell, A. F. Shchepetkin, C. R. Sherwood, R. P. Signell, J. C. Warner, and J. Wilkin (2008), Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System, *Journal of Computational Physics*, *227*(7), 3595-3624.

Kirshen, P., K. Thurson, B. McMann, C. Foster, H. Sprague, H. Roberts, M. Borrelli, J. Byrnes, R. Chen, L. Lockwood, C. Watson, K. Starbuck, J. Wiggin, A. Novelly, K. Uiterwyk, K. Bosma, E. Holmes, Z. Stromer, J. Famely, A. Shaw, B. Hoffnagle, and D. Jin (2018), Feasibility of Harbor-wide Barrier Systems: Preliminary Analysis for Boston Harbor*Rep.*, 250 pp, Sustainable Solutions Lab, University of Massachusetts Boston.

Luettich, R., J. Westerink, and N. W. Scheffner (1992), ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries. Report 1. Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL, Vicksburg, MS.

Marsooli, R., P. M. Orton, G. Mellor, N. Georgas, and A. F. Blumberg (2017), A Coupled Circulation-Wave Model for Numerical Simulation of Storm Tides and Waves, *J. Atmos. Oceanic Technol.*(2017), doi:http://dx.doi.org/10.1175/JTECH-D-17-0005.1.

McAlice, B. J., and G. B. Jaeger (1983), Circulation changes in the Sheepscot River Estuary, Maine, following removal of a causeway, *Estuaries*, *6*(3), 190-199.

Mooyaart, L., and S. N. Jonkman (2017), Overview and Design Considerations of Storm Surge Barriers, *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *143*(4), 06017001.

NYC-DEP (2016), Jamaica Bay Tidal Barrier Water Quality Modeling Analysis, New York City Department of Environmental Protection, prepared by HDR, Inc., p. 44, New York, New York.

Orton, P., N. Georgas, A. Blumberg, and J. Pullen (2012), Detailed modeling of recent severe storm tides in estuaries of the New York City region, *J. Geophys. Res.*, *117*, C09030, doi:10.1029/2012JC008220.

Orton, P. M., F. R. Conticello, F. Cioffi, T. M. Hall, N. Georgas, U. Lall, A. F. Blumberg, and K. MacManus (2018), Flood hazard assessment from storm tides, rain and sea level rise for a tidal river estuary, *Natural Hazards*, 1-29, doi:10.1007/s11069-018-3251-x.

Orton, P. M., T. M. Hall, S. Talke, A. F. Blumberg, N. Georgas, and S. Vinogradov (2016), A Validated Tropical-Extratropical Flood Hazard Assessment for New York Harbor, *J. Geophys. Res.*, *121*, doi:10.1002/ 2016JC011679.

Orton, P. M., and M. Visbeck (2009), Variability of internally generated turbulence in an estuary, from 100 days of continuous observations, *Cont. Shelf Res.*, *29*(1), 61-77.

Ralston, D. K., and W. R. Geyer (2017), Sediment transport time scales and trapping efficiency in a tidal river, *Journal of Geophysical Research: Earth Surface*, *122*(11), 2042-2063.

Ralston, D. K., W. R. Geyer, and J. A. Lerczak (2008), Subtidal Salinity and Velocity in the Hudson River Estuary: Observations and Modeling, *J. Phys. Oceanogr.*, *38*(4), 753-770.

Ralston, D. K., W. R. Geyer, and J. C. Warner (2012), Bathymetric controls on sediment transport in the Hudson River estuary: Lateral asymmetry and frontal trapping, *J. Geophys. Res.*, *117*(C10).

Ralston, D. K., J. C. Warner, W. R. Geyer, and G. R. Wall (2013), Sediment transport due to extreme events: The Hudson River estuary after tropical storms Irene and Lee, *Geophys. Res. Lett.*, *40*(20), 5451-5455.

USACE (2016), Atlantic Coast of New York, East Rockaway Inlet to Rockaway Inlet and Jamaica Bay: Draft Integrated Hurricane Sandy General Reevaluation Report And Environmental Impact Statement, US Army Corps of Engineers New York District, New York, New York.

Warner, J. C., W. R. Geyer, and J. A. Lerczak (2005), Numerical modeling of an estuary: A comprehensive skill assessment, *J. Geophys. Res.*, *110*, doi:10.1029/2004jc002691.

Wen, B., N. Georgas, C. Dujardins, A. Kumaraswamy, and A. Cohn (2017), Modeling pathogens for oceanic contact recreation advisories in the New York City area using total event simulations, *Ecological Modelling*, *365*, 93-105.

Appendix A – Webmeeting Slides:
Physical Influences of Storm Surge Barriers on the Hudson River Estuary

Physical Influences of Storm Surge Barriers on the Hudson River Estuary

A MEETING SPONSORED BY THE HUDSON RIVER FOUNDATION AND THE NY/NJ HARBOR & ESTUARY PROGRAM

Background

Why us?

- HRF supports scientific research about the Hudson River Estuary relevant to public policy
- HEP convenes partners around important issues and implements an action develops agenda to protect and conserve estuarine resources

Why this topic?

- Large barriers are being considered to mitigate storm surge damage
- Large barriers have the potential to cause large-scale changes to the ecosystem
- Relevant science will be critical in evaluating potential physical, chemical and biological effects

Today's webinar

What we plan to do

- Preliminarily identify and evaluate possible hydrodynamic and hydrologic changes resulting from a large barrier at the Harbor's entrance
- Preliminarily evaluate the utility of existing models
- Identify model issues, data gaps, research needs, etc.

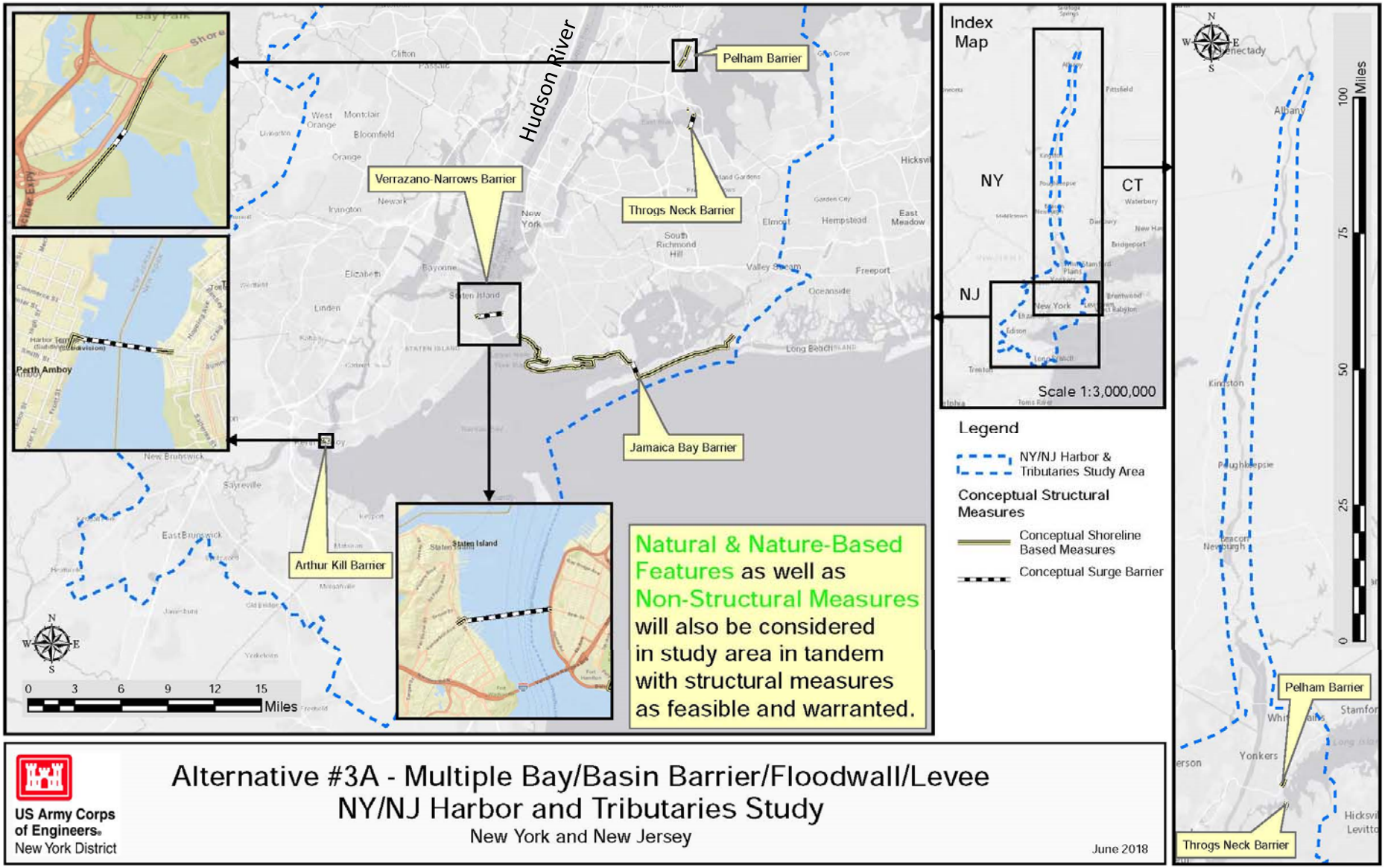
What we don't plan to do

- Discuss the details of the Corps of Engineers HATS study
- Formulate ideas for other coastal storm protection strategies

Work products and next steps

- Supporting Dr. Philip Orton (Stevens Inst. of Tech.)and Dr. David Ralston (WHOI) to present preliminary modeling and background information
- White paper will be produced summarizing today's deliberations
- Results will be available to:
  - Examine how potential hydrodynamics changes could affect water quality, fish migration, larval recruitment, contaminant transport, etc.
  - Inform HRF's 2019 Call for Proposals for scientific research
  - Inform HEP partners, including Policy Committee
  - Inform Corps' HATS Study, including the study's partners (i.e., NYSDEC, NYC, and NJDEP)

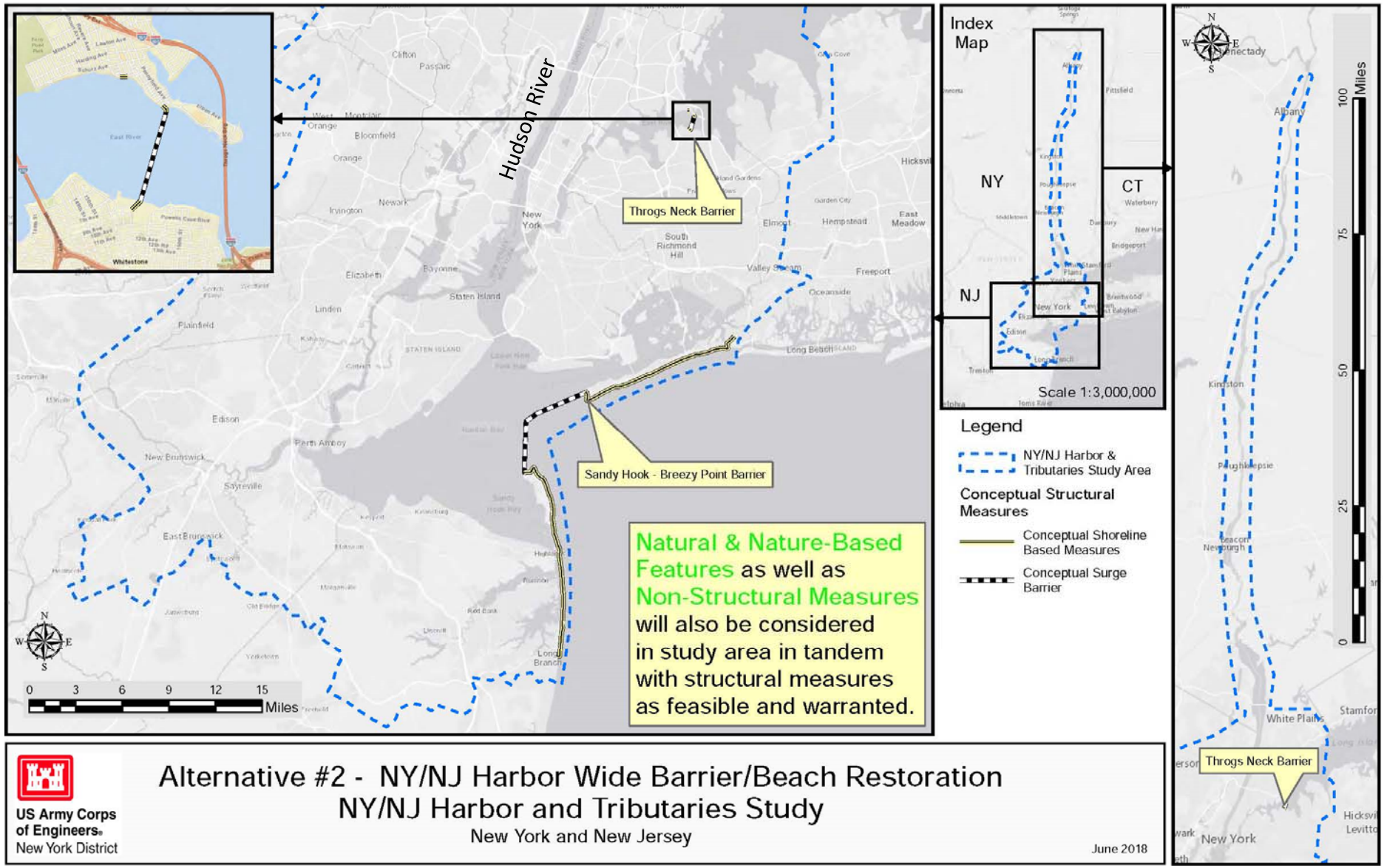
Possible Surge Barrier Locations



US Army Corps of Engineers
New York District

Alternative #3A - Multiple Bay/Basin Barrier/Floodwall/Levee
NY/NJ Harbor and Tributaries Study
New York and New Jersey

June 2018



US Army Corps of Engineers
New York District

Alternative #2 - NY/NJ Harbor Wide Barrier/Beach Restoration
NY/NJ Harbor and Tributaries Study
New York and New Jersey

June 2018

Dave Ralston –
Review of Surge Barrier
Physical Influences on Estuaries

Effects of storm surge barriers on partially mixed estuaries

Not many barriers constructed on partially mixed estuaries →

- Shallow or tidally energetic
- Low river discharge
- Well mixed salinity or tidal fresh

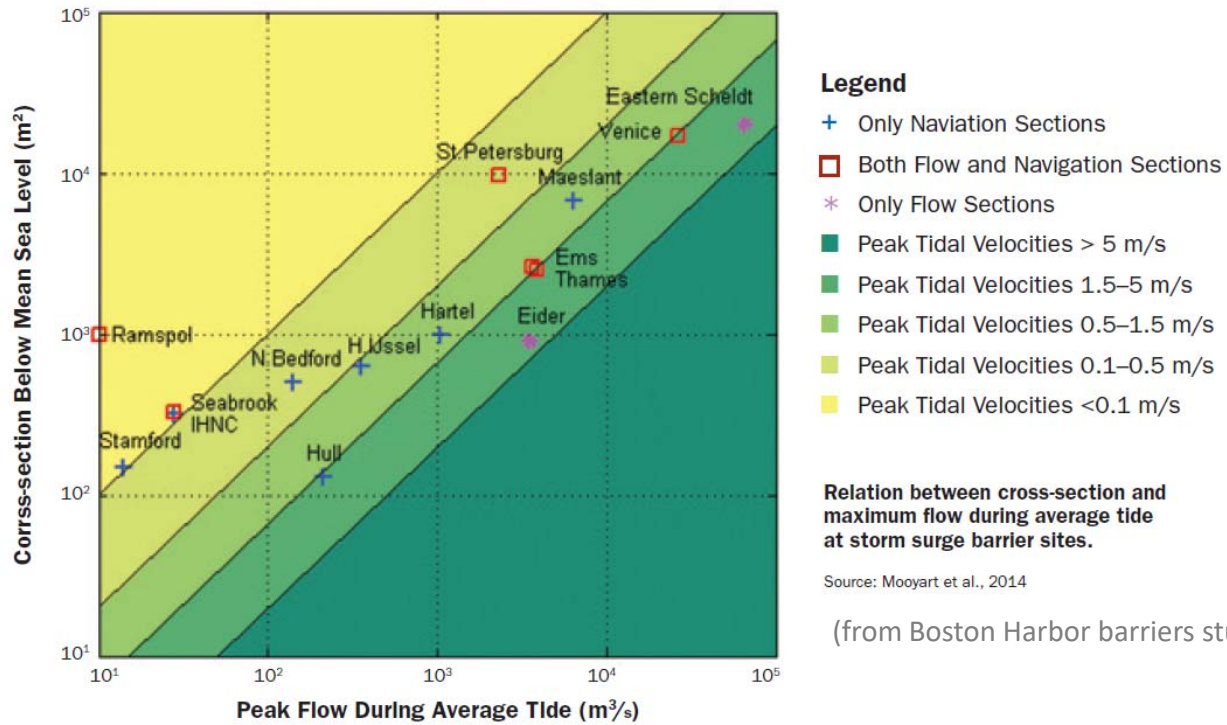
Major barriers:

- Broad, shallow deltas (Netherlands, New Orleans)
- tidal rivers (Thames, Ems, Eider),
- small freshwater input (Eastern Scheldt, New Bedford, Providence, Stamford),
- weak tides (St. Petersburg)

Impact assessments often focus on changes to tidal amplitude and associated effects

FIGURE 2.1

Storm Surge Barrier Velocity Properties



Relation between cross-section and maximum flow during average tide at storm surge barrier sites.

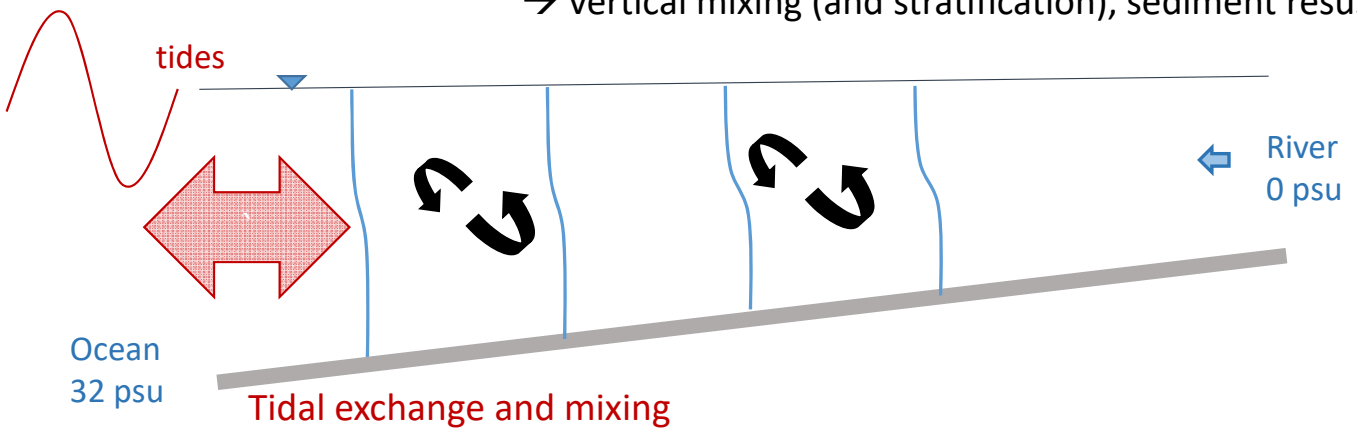
Source: Mooyart et al., 2014

(from Boston Harbor barriers study)

Well mixed estuary

Tidal processes dominate exchange with the coastal ocean

→ length of salinity intrusion, residence time of nutrients, contaminants, organisms, etc.
→ vertical mixing (and stratification), sediment resuspension



Well mixed estuary

Lots of studies on ecological impacts of barriers in Eastern Scheldt, Delta Works in Netherlands

Decrease in tidal amplitude → increased stratification → reduced sediment suspension → increased clarity → change in phytoplankton assemblage

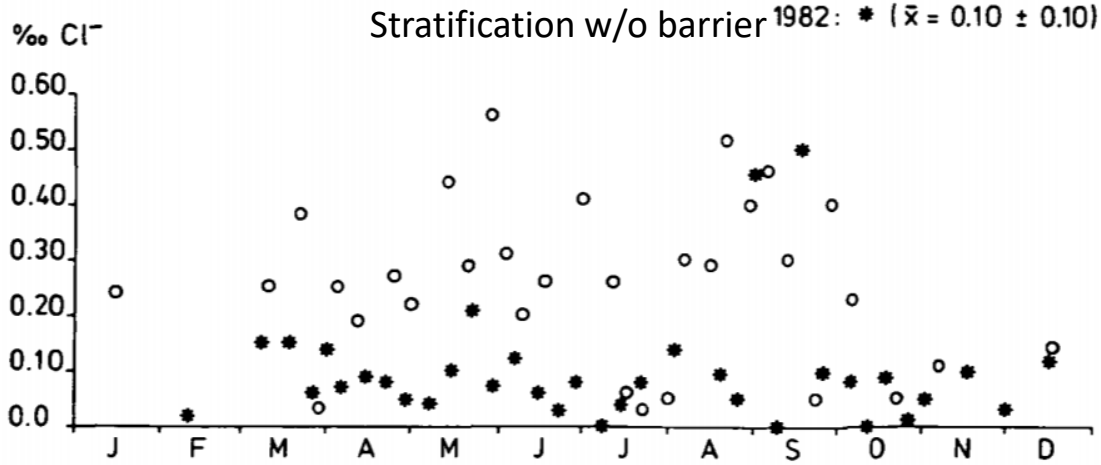


Fig. 2. Vertical differences in chlorinity (%) at station LG–PK (Figure 1) in the eastern compartment of the Oosterschelde. Depths of measurement: 2, 5, 10 and ~20 m. Years 1982 (pre-barrier period) and 1986 (last year of barrier period).

951

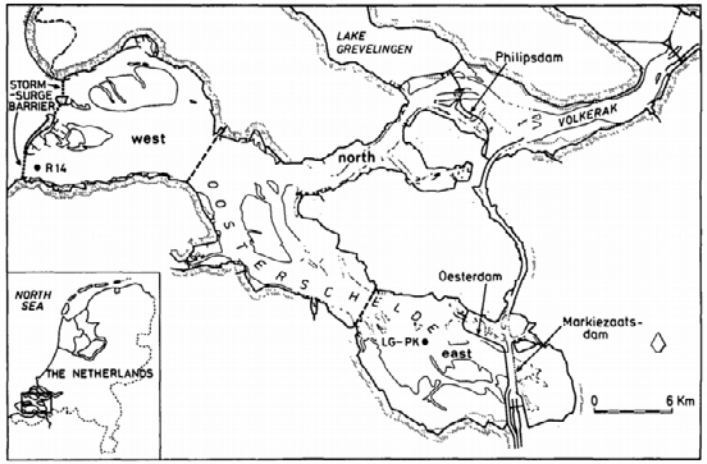


Fig. 1. Map of the Oosterschelde estuary with indication (broken lines) of western and eastern compartments and sampling localities; position of the estuary in The Netherlands (inset).

C.Bakker, P.M.J.Herman and M.Vink

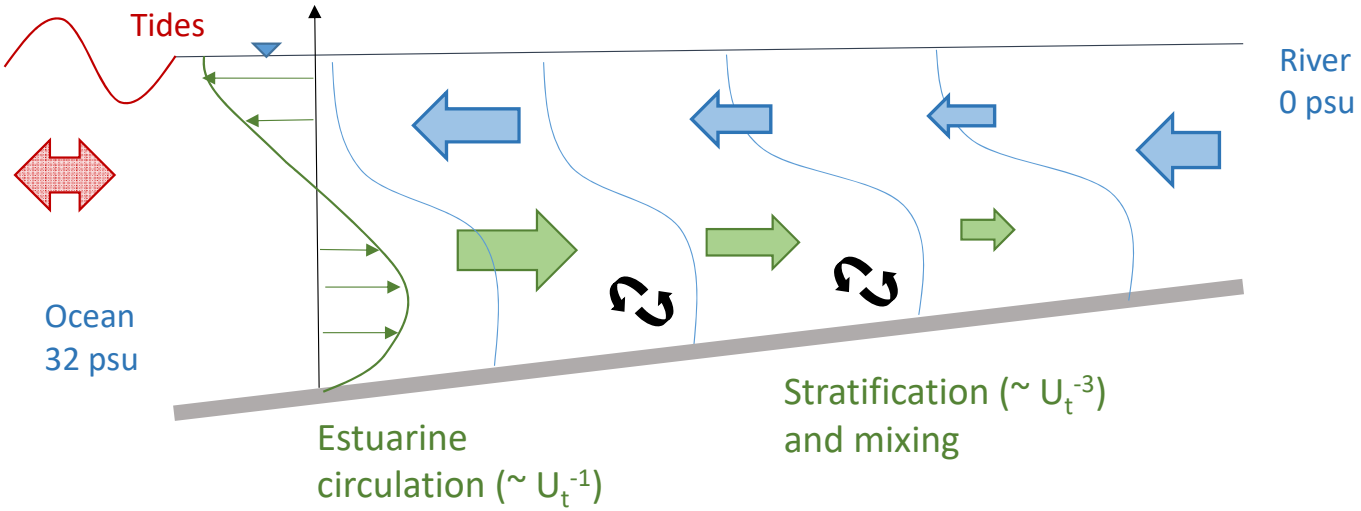
(Bakker et al., JPR, 1990)

Partially-mixed estuary

Estuarine circulation dominates exchange with the coastal ocean

→ length of salinity intrusion, residence time of nutrients, contaminants, etc.

→ tidal amplitude affects estuarine circulation and stratification non-linearly



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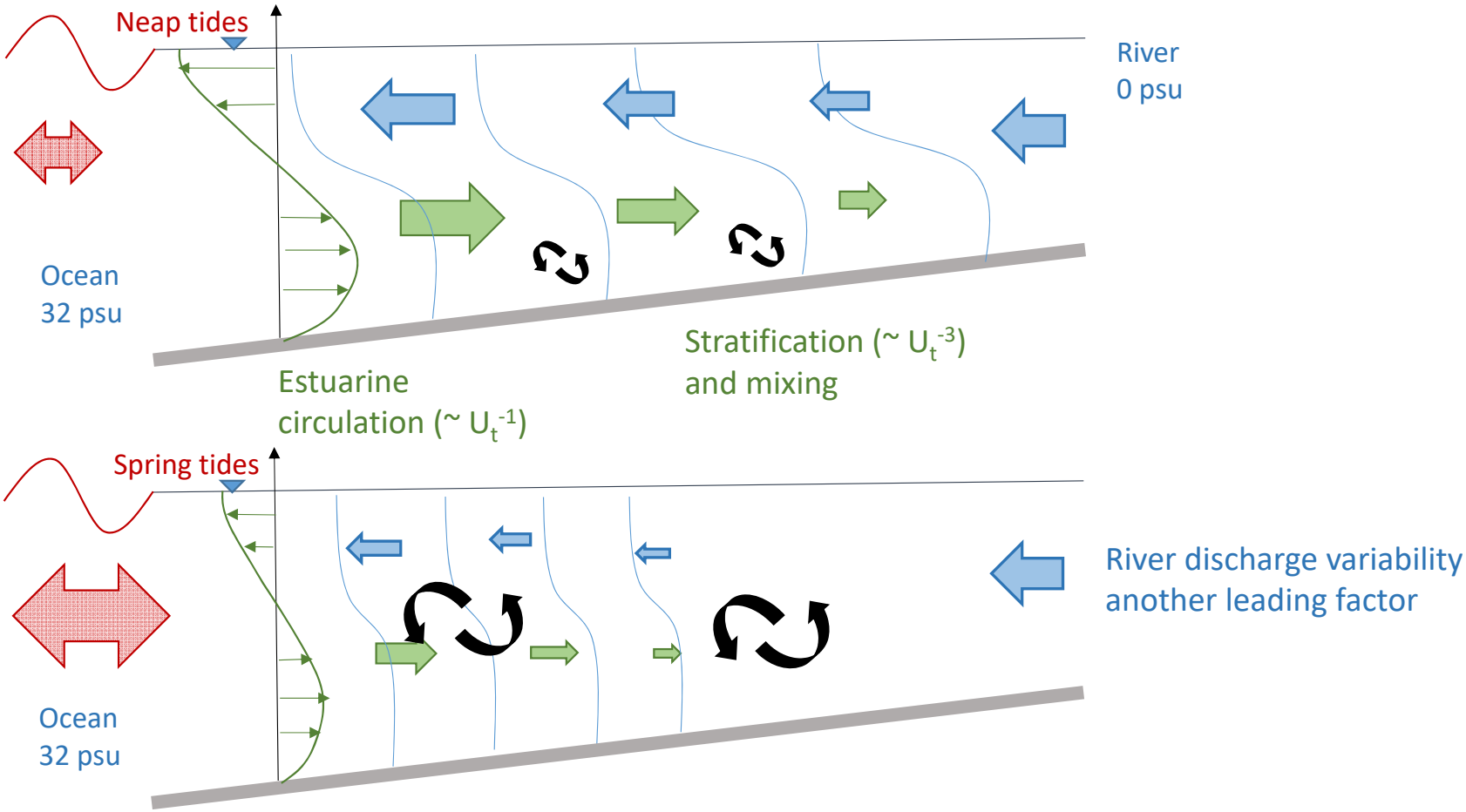
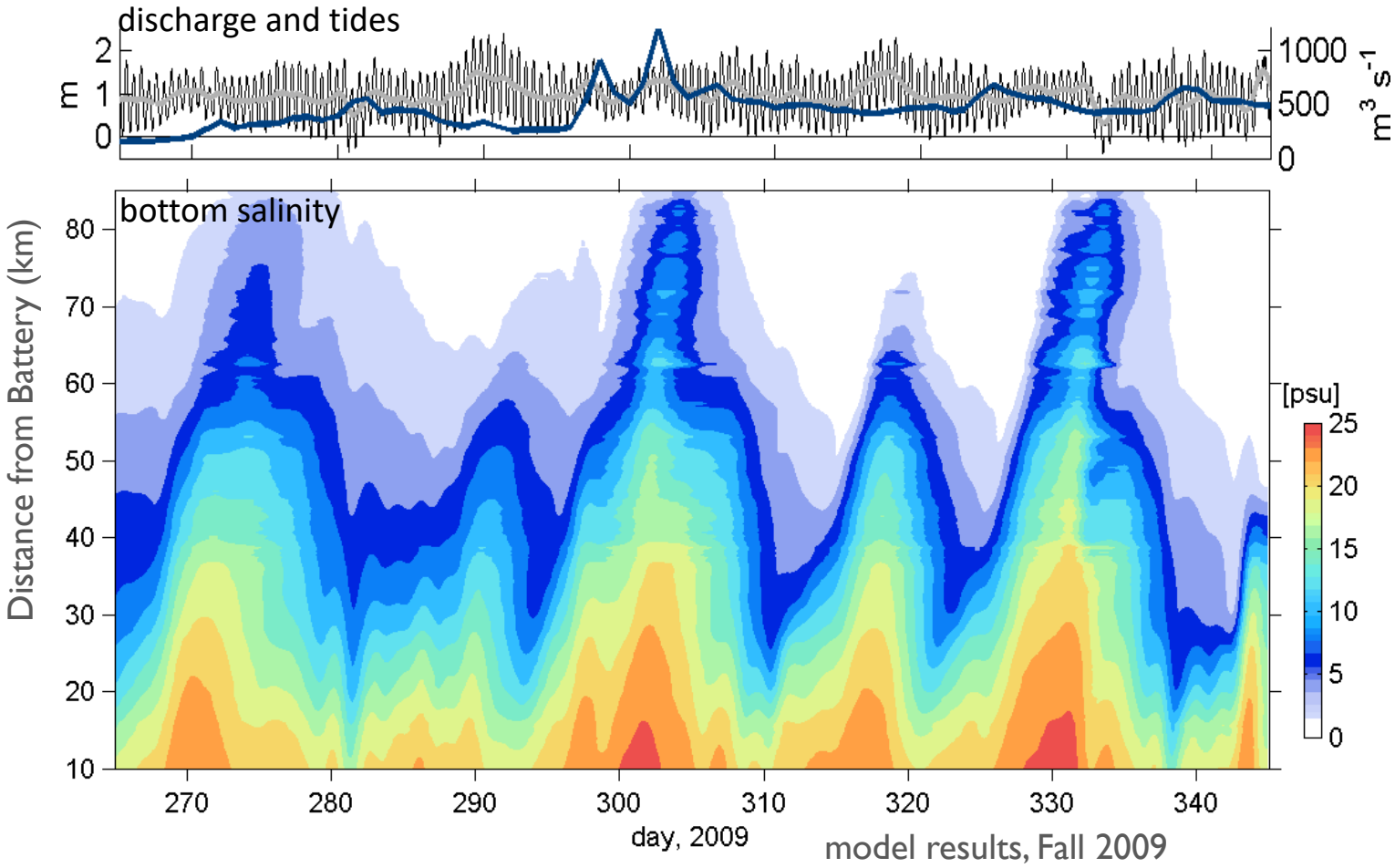
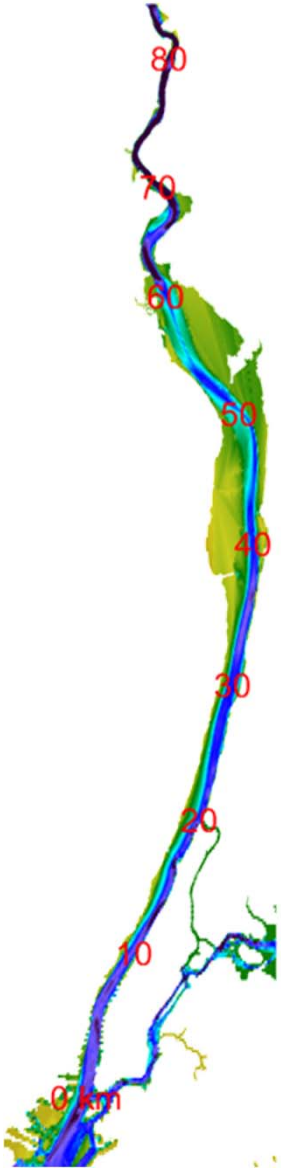


Salinity intrusion in the Hudson

Salinity moves landward during neap tides,
retreats seaward during spring tides
→ During neaps stratification increases, residence times increase



model results, Fall 2009



Studies on effects of storm surge barriers – Boston Harbor

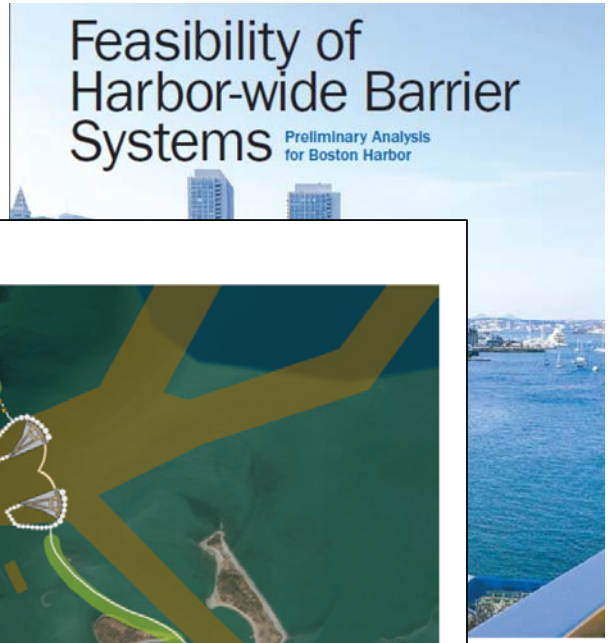


FIGURE 1.1
Recommended Possible Harbor-wide Protection Schemes

Source: Climate Ready Boston, 2016

FIGURE 4.5
Outer Harbor Barrier Configuration

Sources: Arcadis, Esri World Imagery, USACE

Gates
- Vertical Lift Gate
- Floating Sector Gate
- Platform
- Coffer

Walls
- Caisson Wall
- Overland Levee
- Improvement to Existing Sea Wall

Other
- Disposal Islands
- USACE Dredged Areas

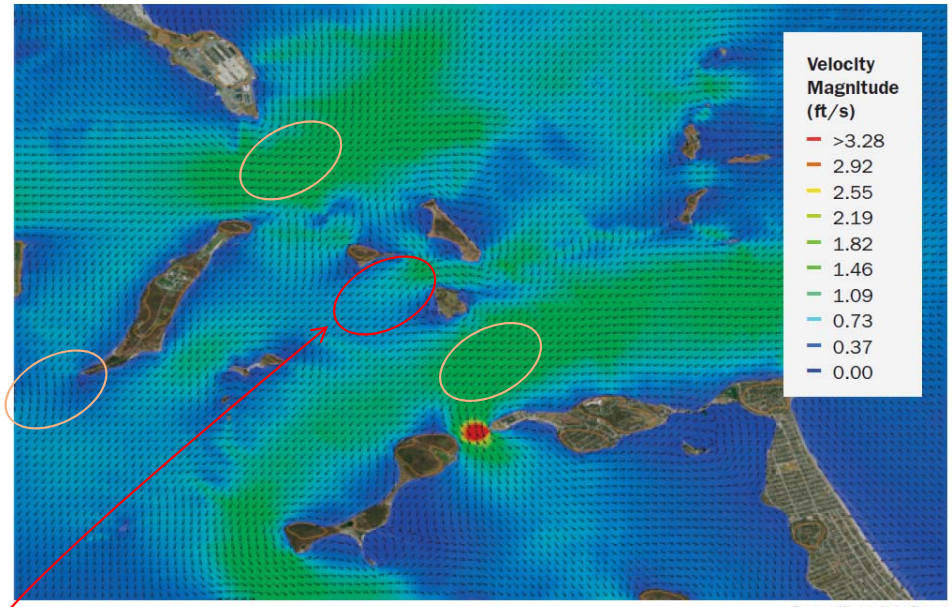
Outer Harbor Barrier, 3.8 miles with 2 gates (1500' wide by 40-50' deep and 650' wide by 30-40' deep) → ~20% porosity?

2dv model → no effect on tidal amplitude in Boston Harbor

Studies on effects of storm surge barriers – Boston Harbor

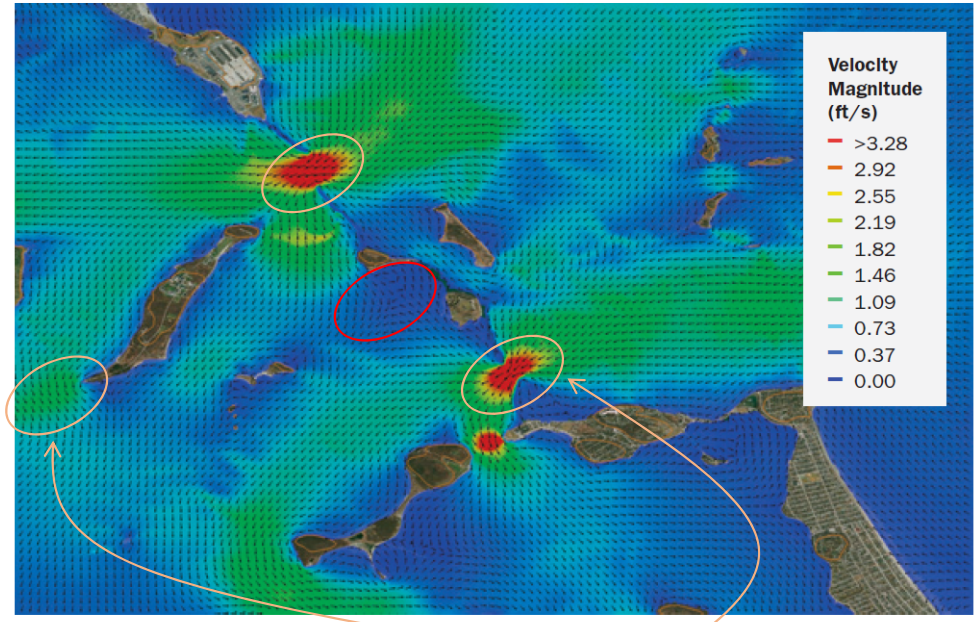
Tidal currents altered, particularly near barriers

FIGURE 5.9
Simulated Existing Tidal Currents in Boston Harbor During Peak Flood Tide (1 ft/sec = 0.6 knots)



Source: Woods Hole Group

FIGURE 5.10
Simulated Tidal Currents in Boston Harbor During Peak Flood Tide with Outer Harbor Barrier (1 ft/sec = 0.6 knots)



Source: Woods Hole Group

Greatly increased tidal velocity at gates (from ~1 to 3.5-5 knots) and within Harbor between gates

Reduced velocity in stagnation zones behind barriers

→ Overall exchange and residence time similar, but large spatial changes in circulation patterns (and potentially hazardous currents)

Study on removal of a barrier – Sheepscot River estuary, Maine (observations)

Causeway with narrow opening (~10% porosity?) removed in 1974 (McAlice and Jaeger, Estuaries, 1983)

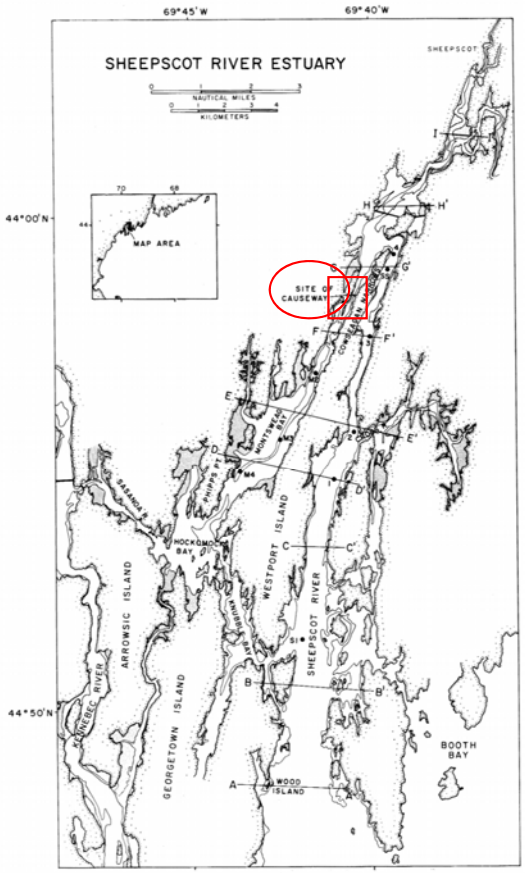
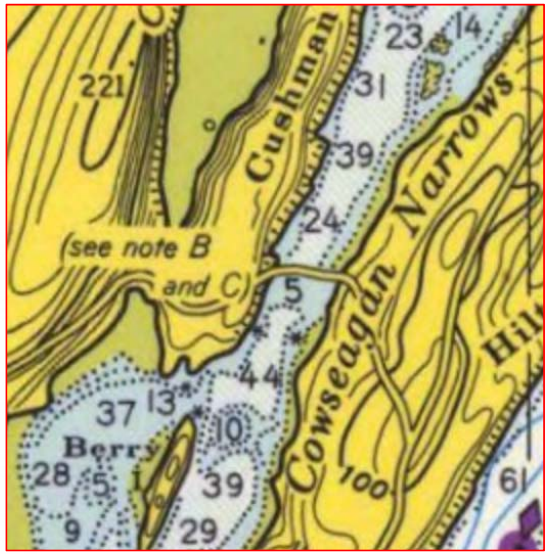
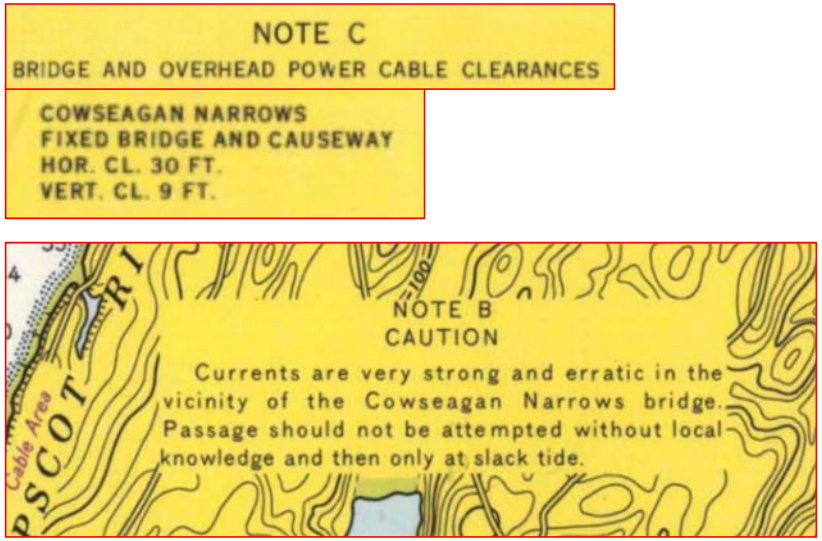


Fig. 1. Sheepscot River estuarine system, showing sampling stations. Intertidal areas are shaded. The 3 m depth contour is shown. Lines A-A', etc., identify the sections shown in Fig. 2. Head Tide is 6 km north of Sheepscot.



NOAA chart (1963)



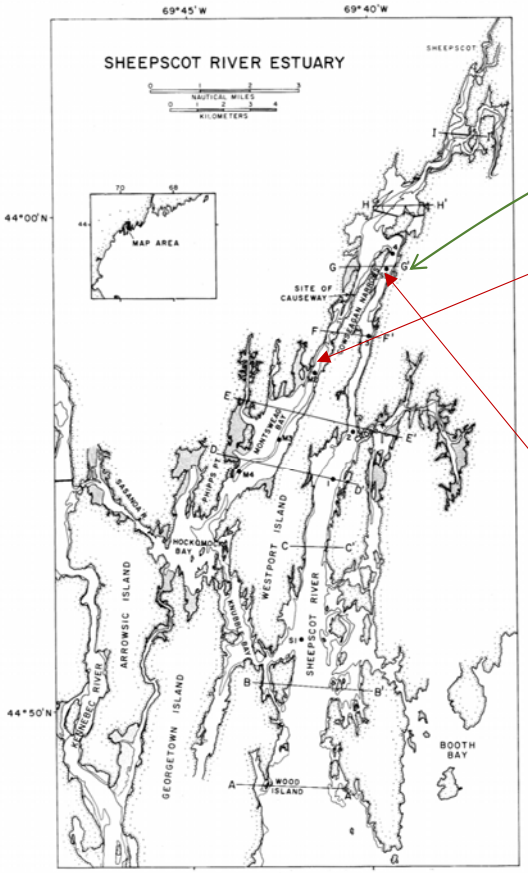
Study on removal of a barrier – Sheepscot River estuary, Maine (observations)

Causeway with narrow opening (10% porosity?) removed in 1974 (McAlice and Jaeger, Estuaries, 1983)

→ Tidal amplitude increased by ~50%

→ Stratification decreased

→ Estuarine circulation reduced, even more so during high discharge



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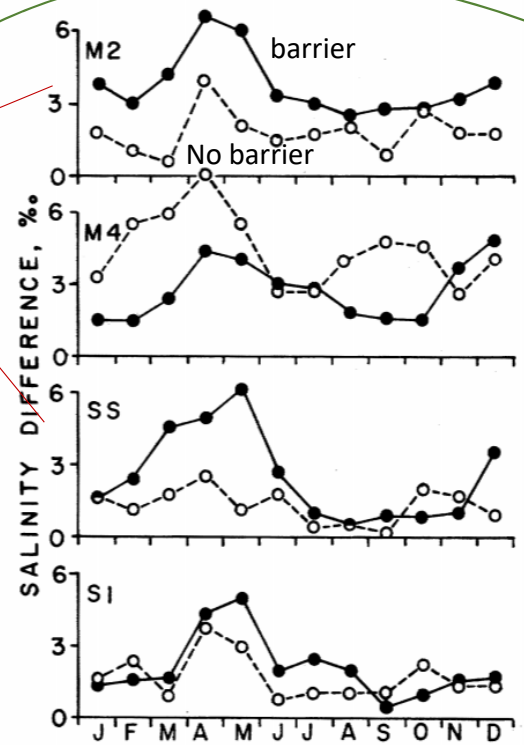
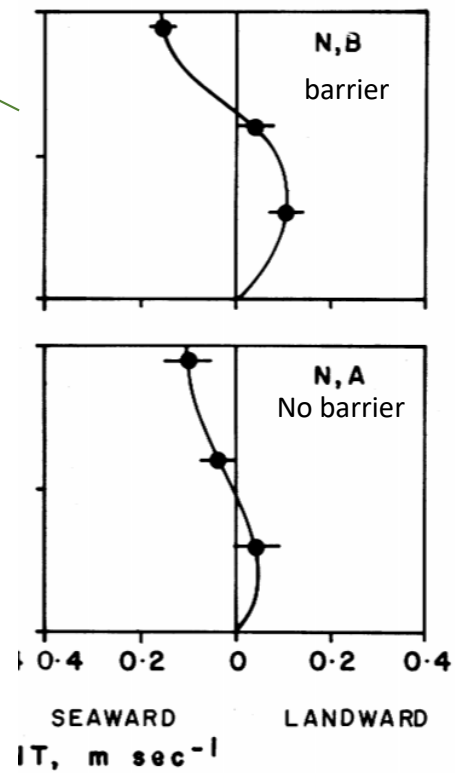
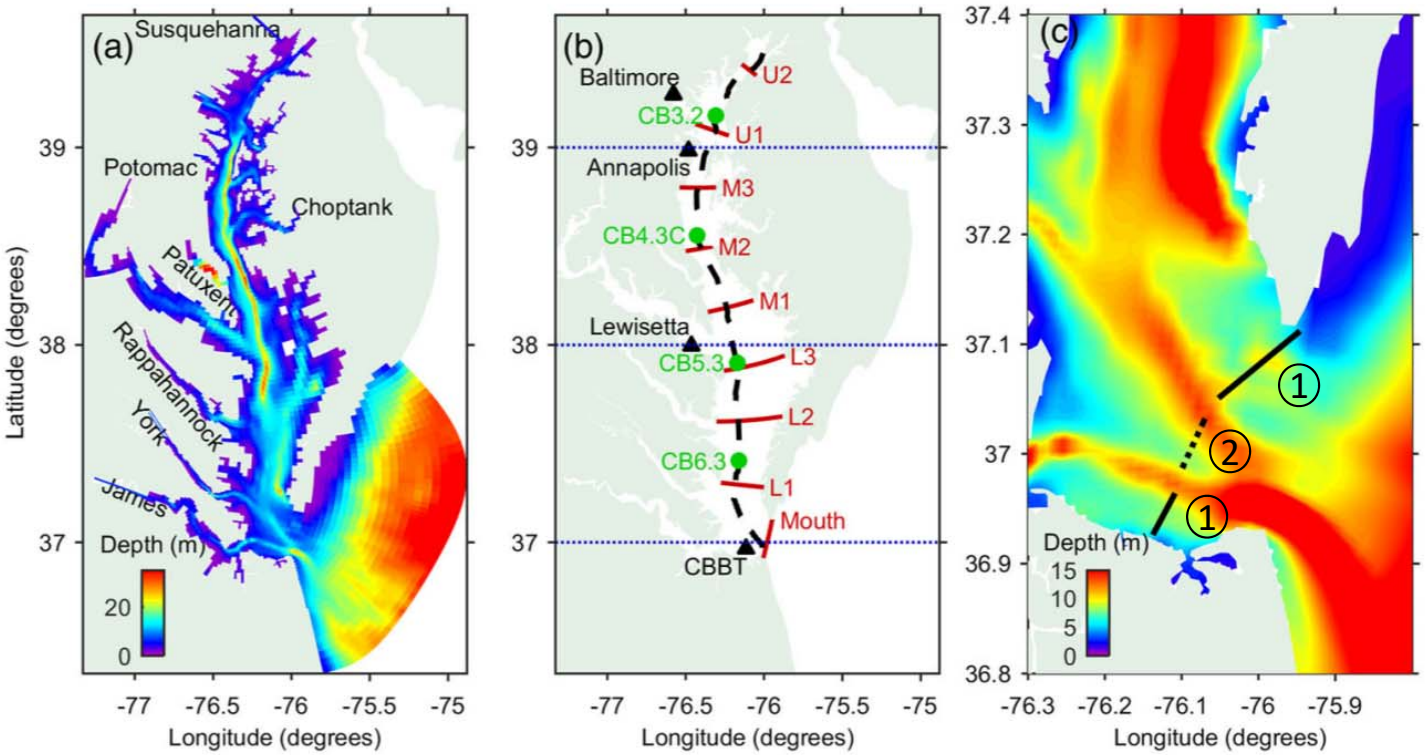




Modeling study on barriers in Chesapeake Bay (Du et al., Estuaries and Coasts, 2017)

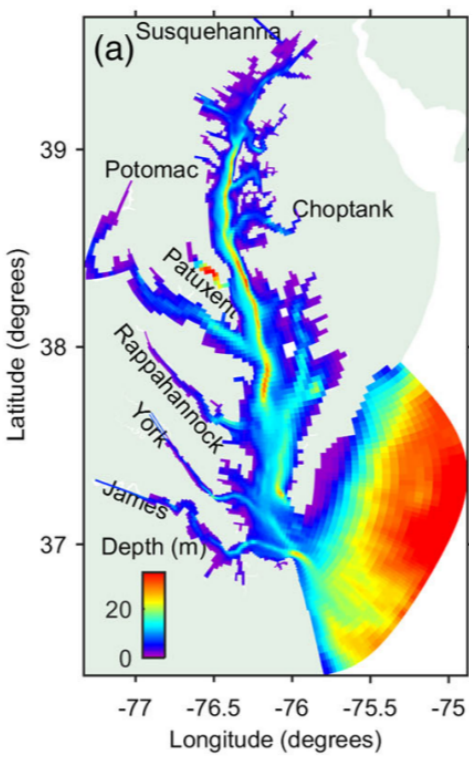
Test effects of two barrier configurations: ①15 km total length, 40% porosity; ②21 km length, 15% porosity

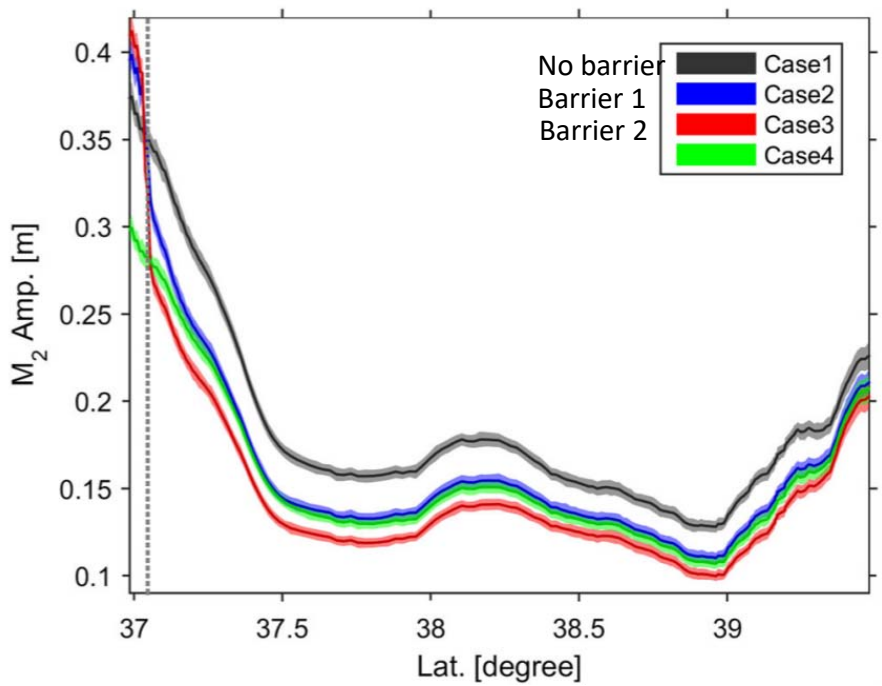


Modeling study on barriers in Chesapeake Bay

(Du et al., Estuaries and Coasts, 2017)

Tidal amplitude decreased 13-20%, more so during spring tides





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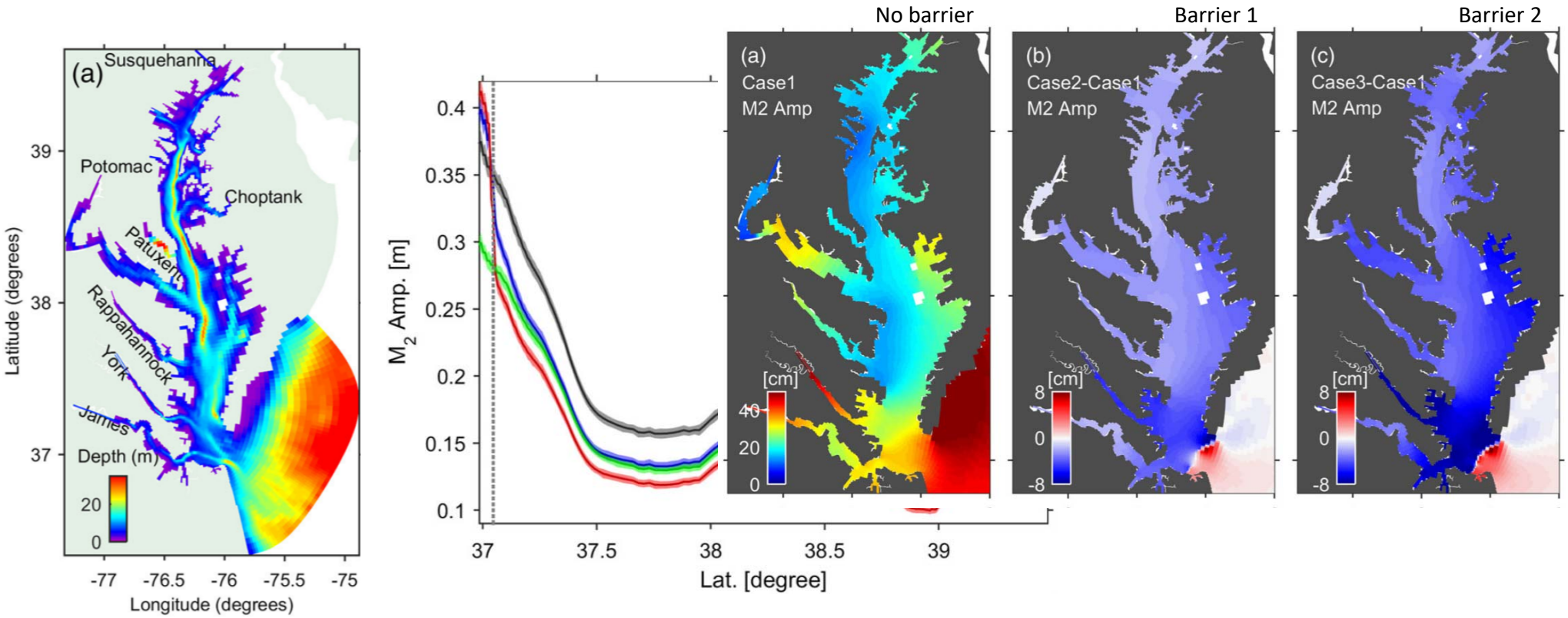
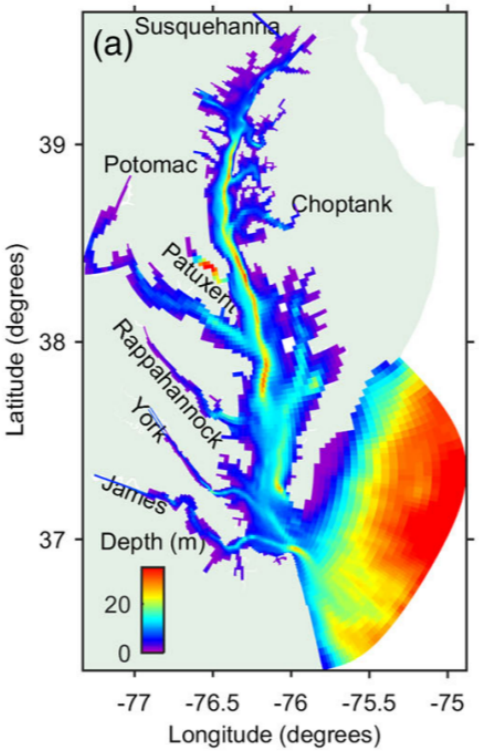
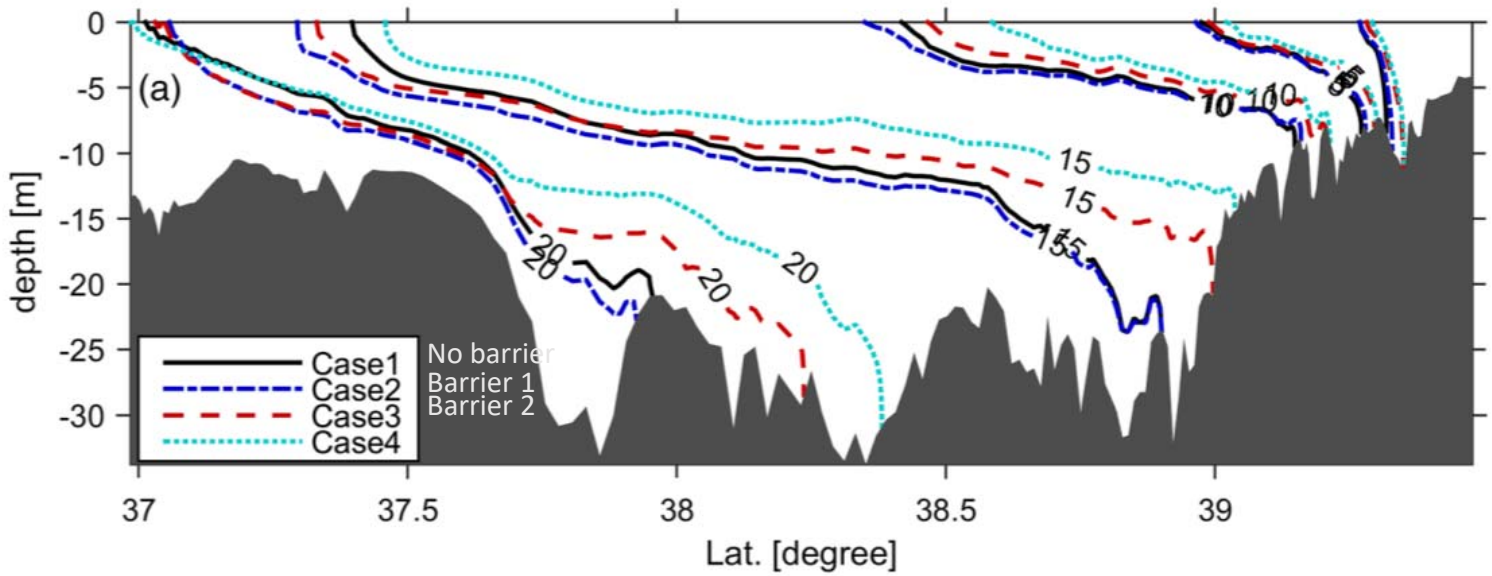


Modeling study on barriers in Chesapeake Bay

(Du et al., Estuaries and Coasts, 2017)

Stratification and salinity intrusion increased, especially for low porosity





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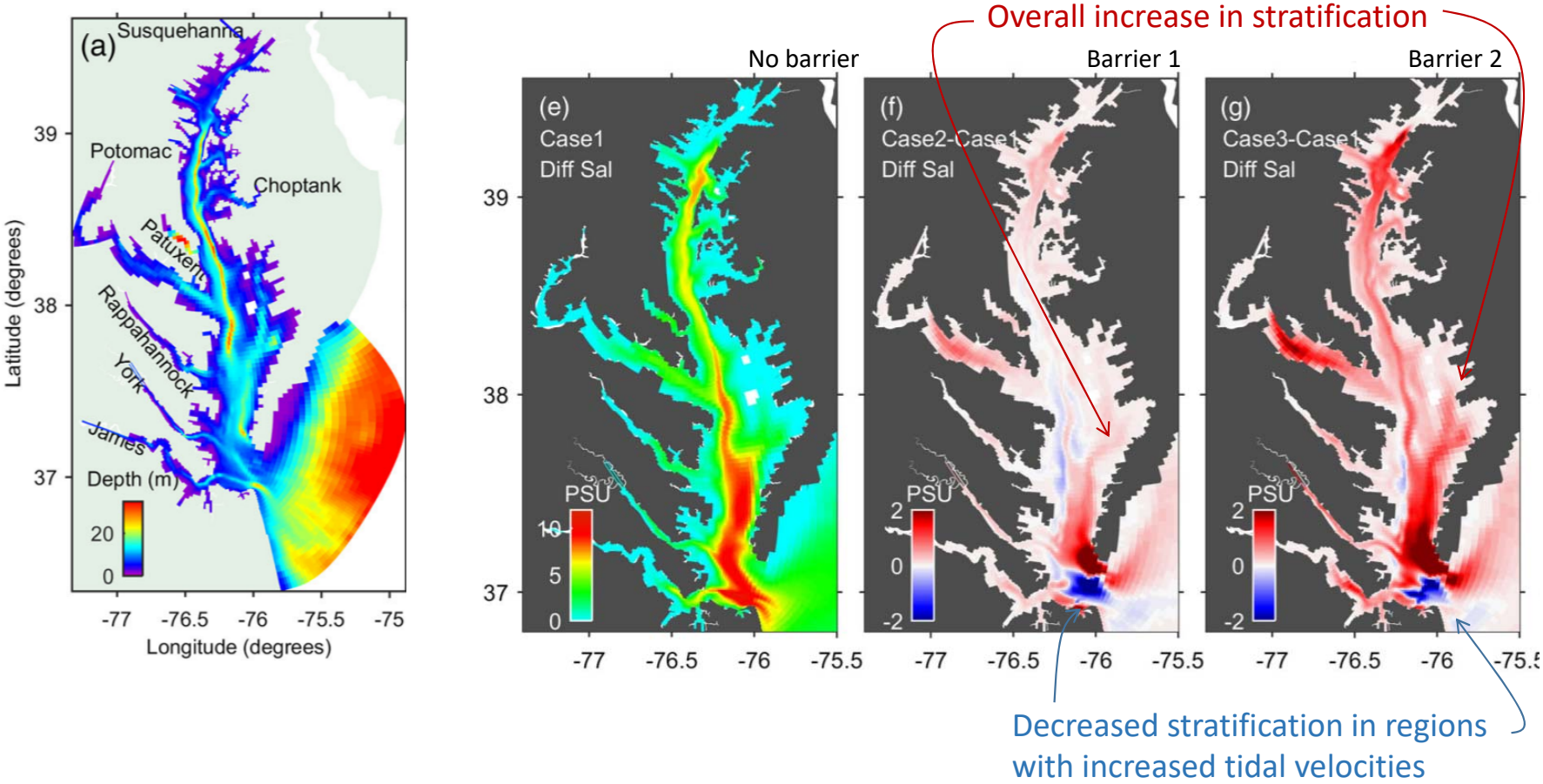
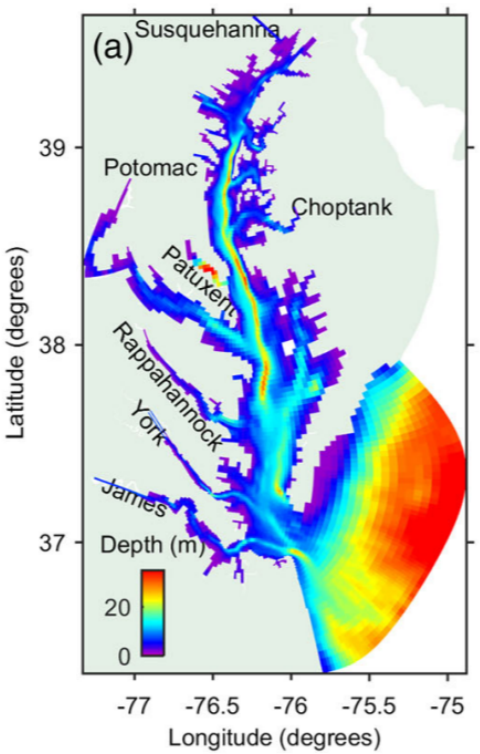
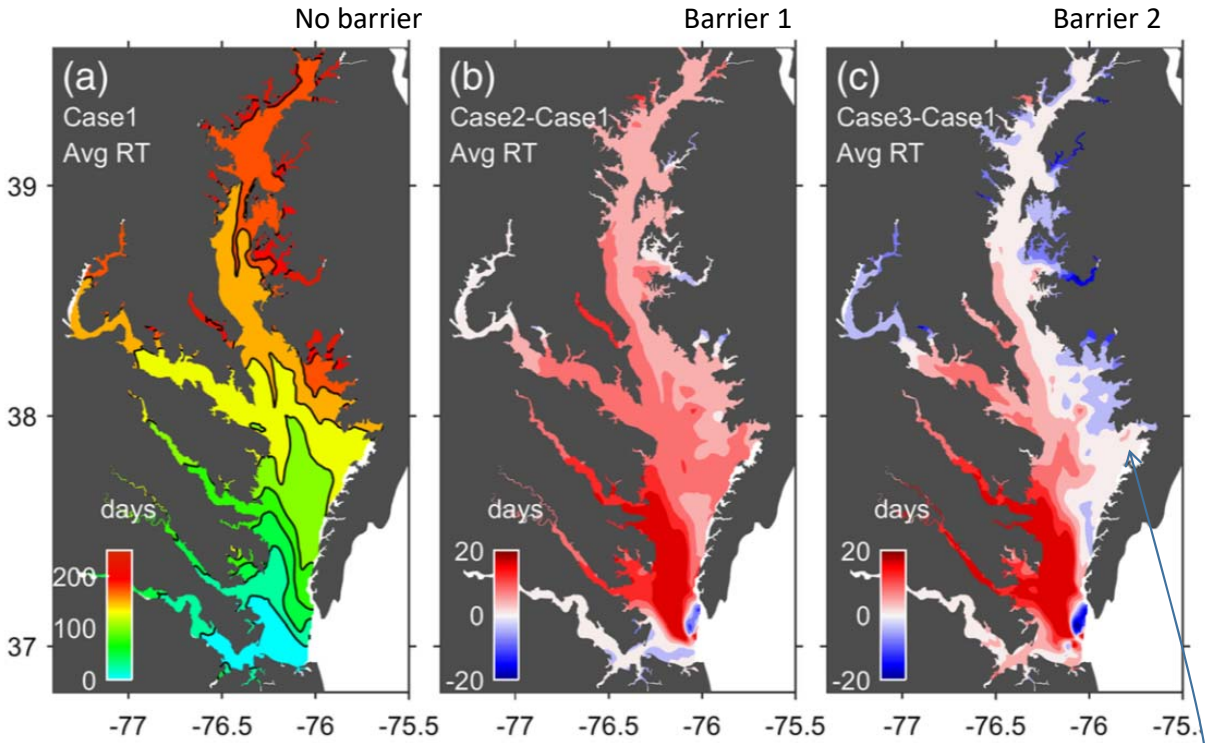


Modeling study on barriers in Chesapeake Bay

(Du et al., Estuaries and Coasts, 2017)

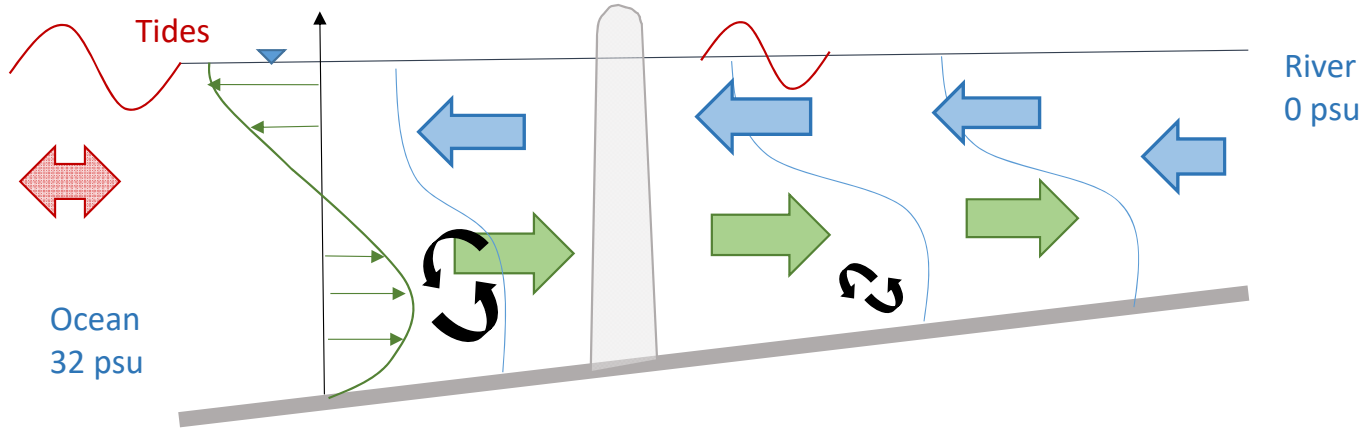
Generally increased residence time and decreased vertical mixing (= more hypoxia) because of stronger stratification





Some reductions in residence time where estuarine exchange dominates

Effects of storm surge barriers on partially mixed estuaries



Few observational or modeling studies on barrier effects in partially mixed estuaries

Non-linear response of estuarine circulation and stratification means small changes in tidal amplitude can cause big changes in the salinity distribution (and associated processes)

Decrease in tidal energy → greater salinity intrusion and stratification, reduced vertical mixing, longer residence time (generally) but spatial variability in U_{tidal} is major factor

Philip Orton – Preliminary Modeling of Surge Barrier Physical Influences on the Hudson River Estuary

Our Challenge: Modeling Effects of Surge Barriers in Estuaries

- Need a 3D model to quantify many important effects – e.g. stratification, flushing, salt intrusion
- Need fundamental characterization of system
  - e.g. storms, tides, streamflows, initial conditions, boundary conditions
- To best capture flows through tide gates will require developing one or more custom grids
  - If the main navigation gate is O(500) meters wide, you need O(50) meter resolution
  - If flow gates are O(50) meters wide, you need O(5) meter resolution
- To accomplish all this in one model would require additional funding or collaboration

Quick Analysis – Existing Available Models/Grids

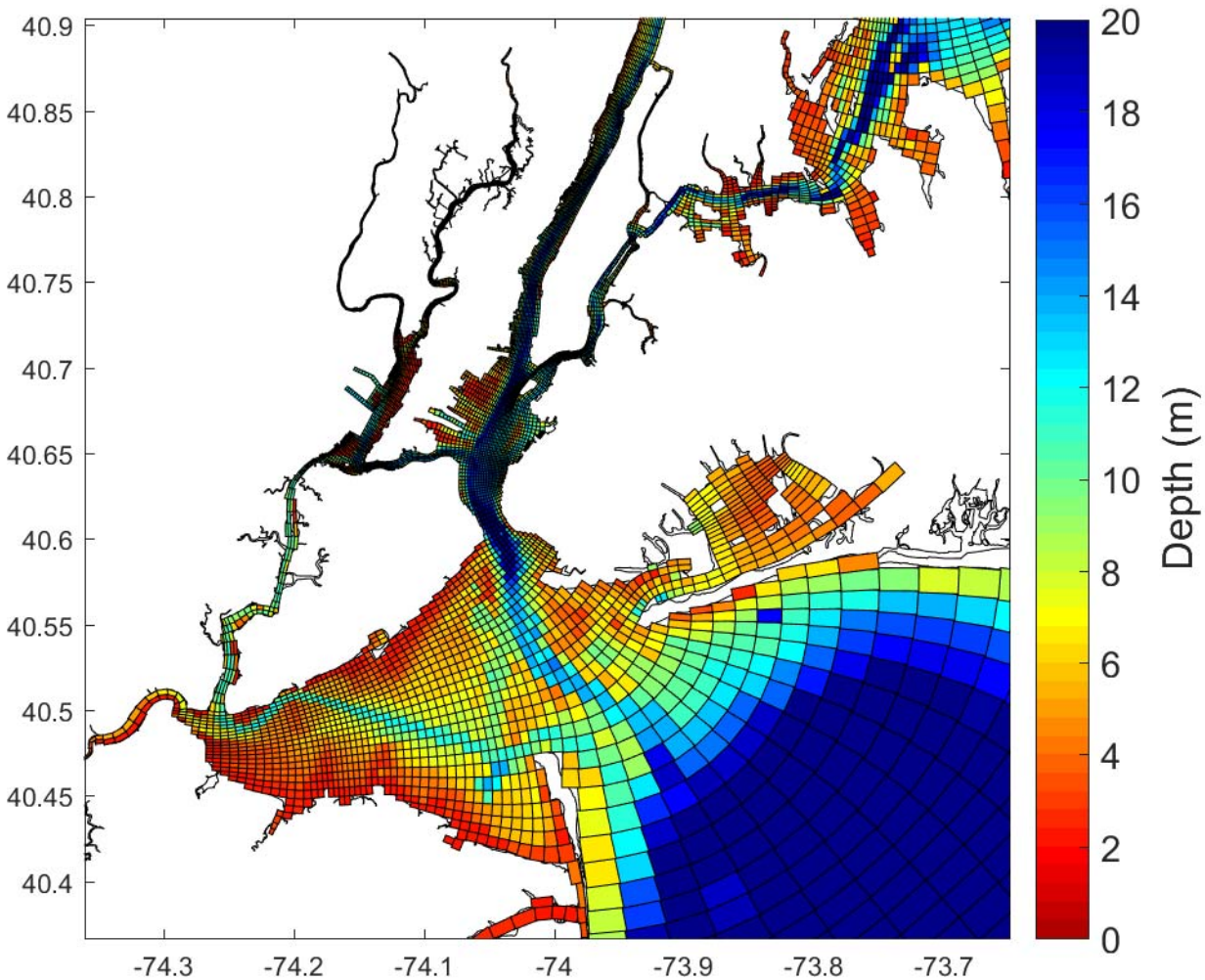
- sECOM-3D, NYHOPS grid (NY Harbor Observing and Prediction System)
  - Rapid, moderate-resolution (up to 100m) curvilinear grid used primarily for ensemble forecasting, assessment
- Regional Ocean Modeling System (ROMS-3D), David Ralston's grid
  - Moderate-resolution (up to 100m) orthogonal grid used for detailed studies of estuary dynamics
- ADCIRC-2D – FEMA-Region2 Grid
  - Moderate-resolution (up to 70m) grid used for flood forecasting and hazard assessment

sECOM-3D Modeling

Stevens ECOM (sECOM) Model Setup: Tide-Only Simulations

- NYHOPS curvilinear grid
- Resolution 100m in harbor, but more like 500-1200m at inlet
- August/Sept 2015, 35-day simulation
- Tide forcing only (9 constituents); no wind
- Streamflows steady at Green Island 400 m^3/s, total of 550 m^3/s past Piermont
- Cold start with modified DEM to create tall flow barriers
- Initial conditions from operational system
- East River is completely open – assumed to have many gates at Throgs Neck for strong flushing

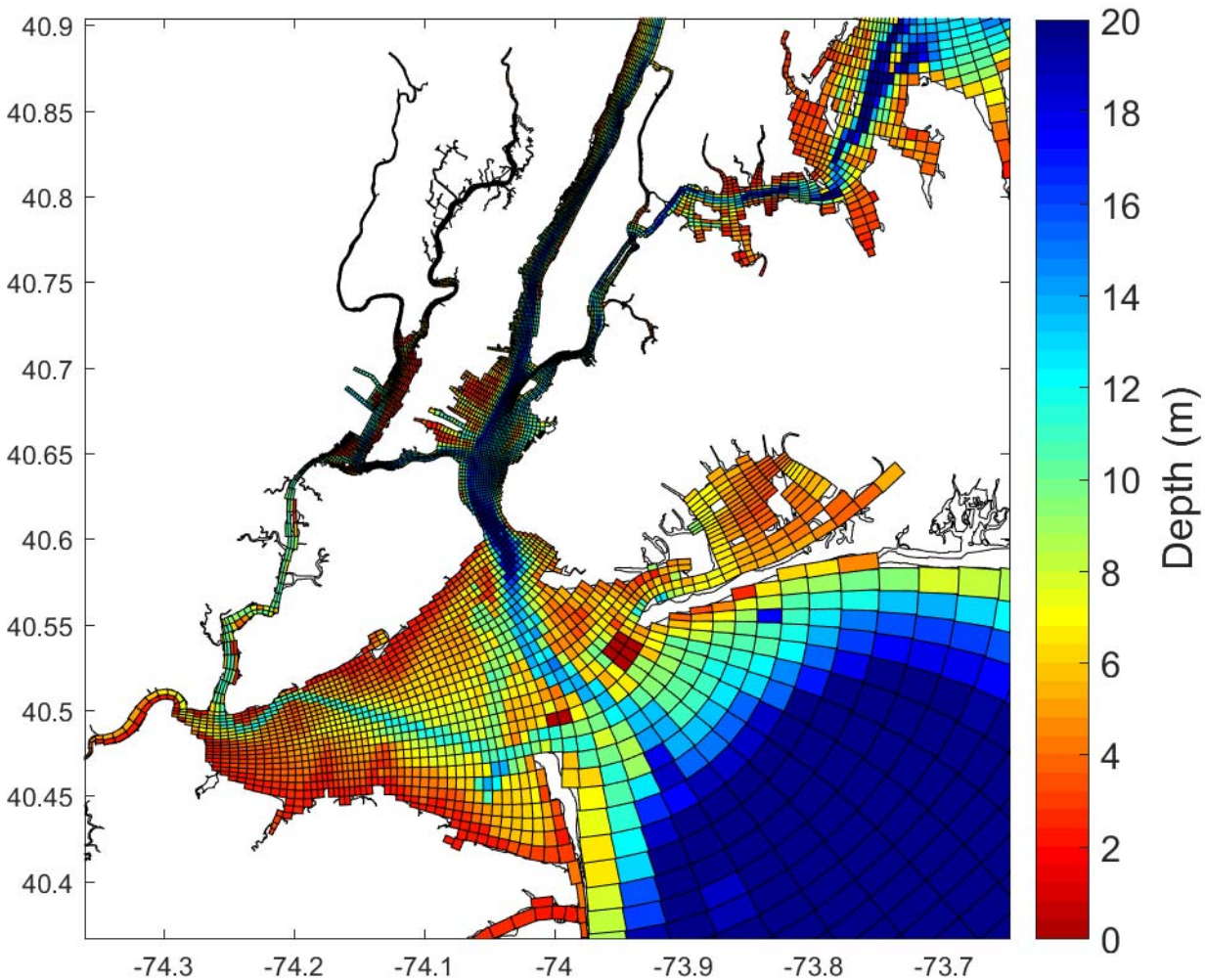
Control Grid



NYHOPS model grid/domain

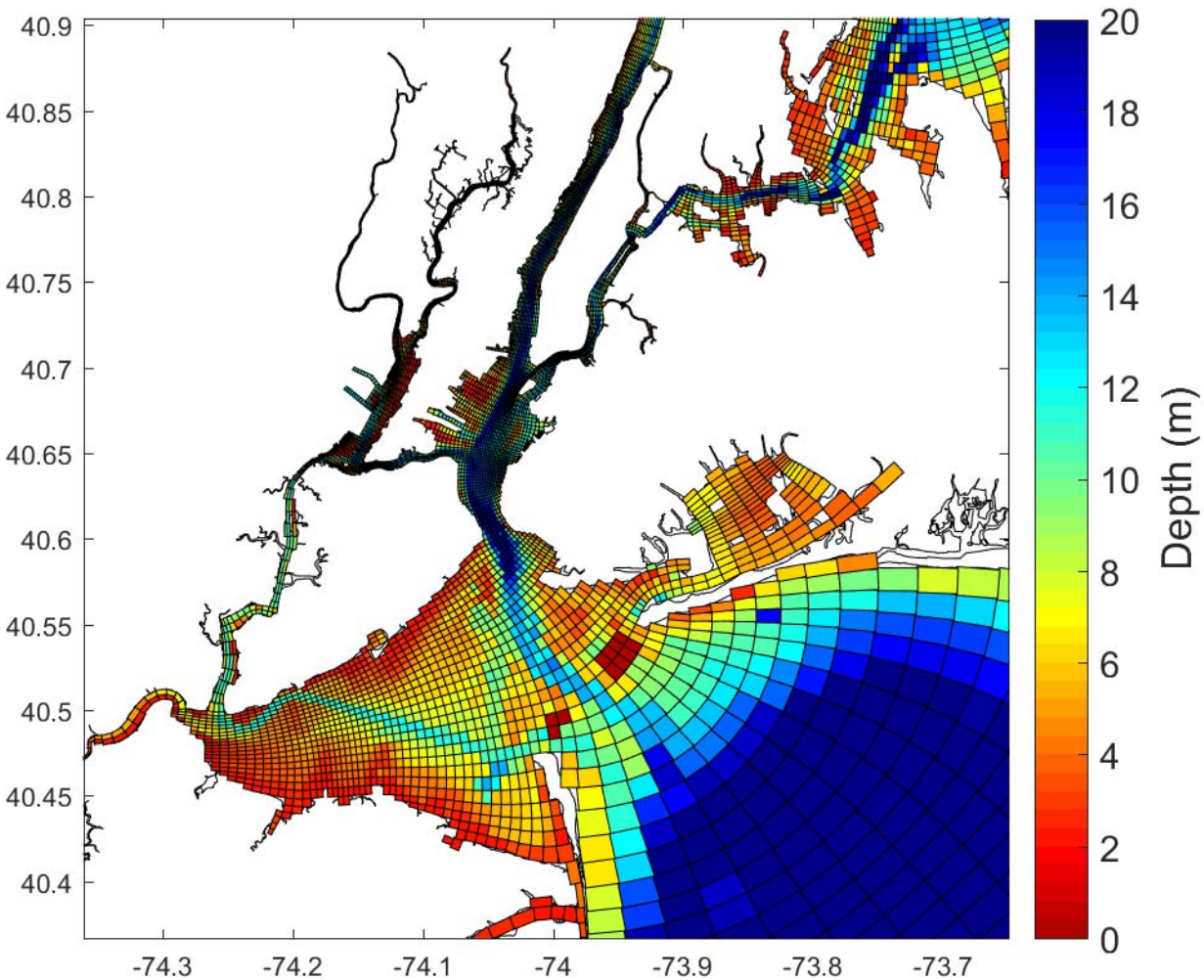
Total cross-sectional area at inlet between Rockaways and Sandy Hook in NYHOPS is 80000 m^2.

sECOM Case A: Porosity 80%

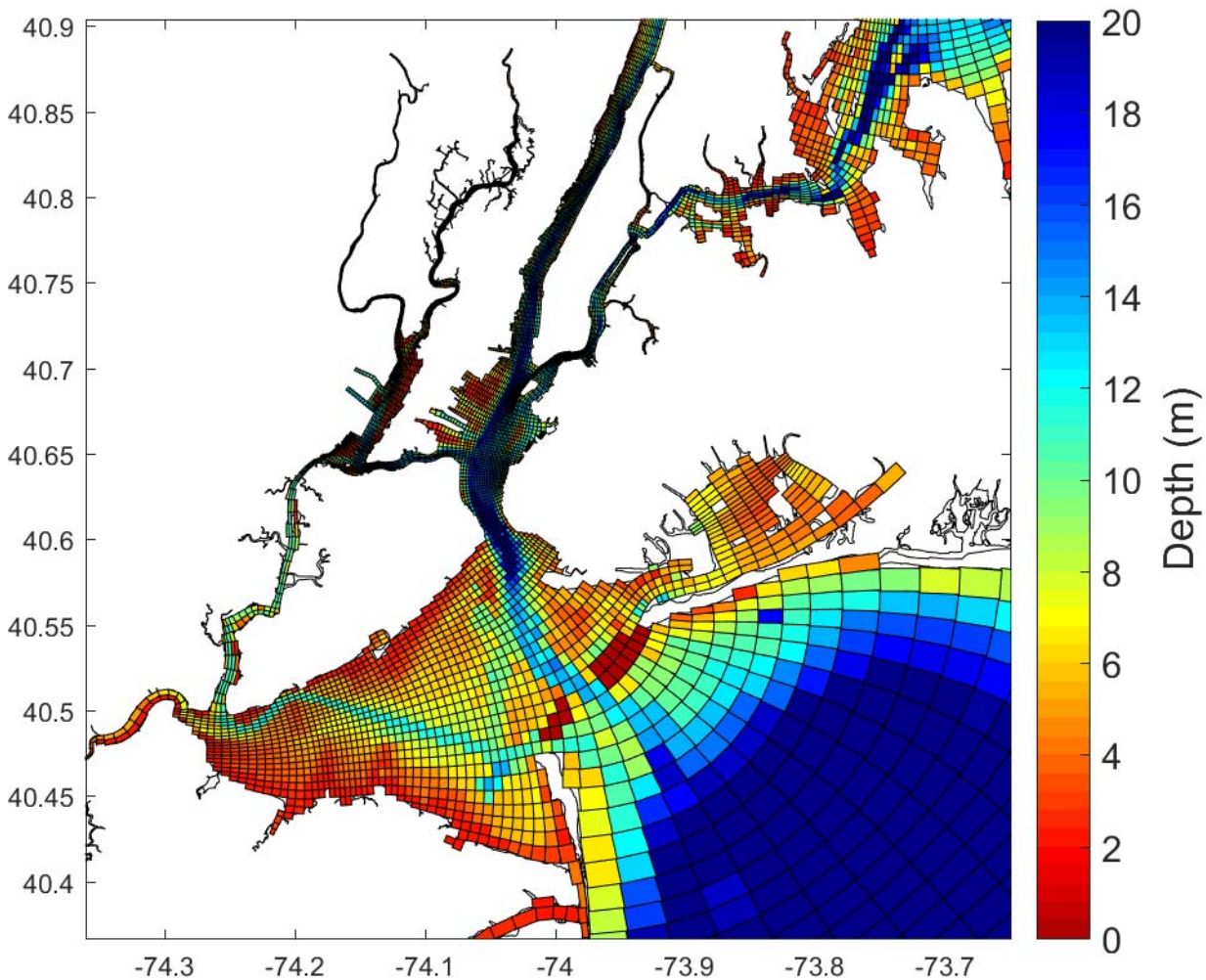


10m high blockages to cells in ungated, closed areas of barrier.

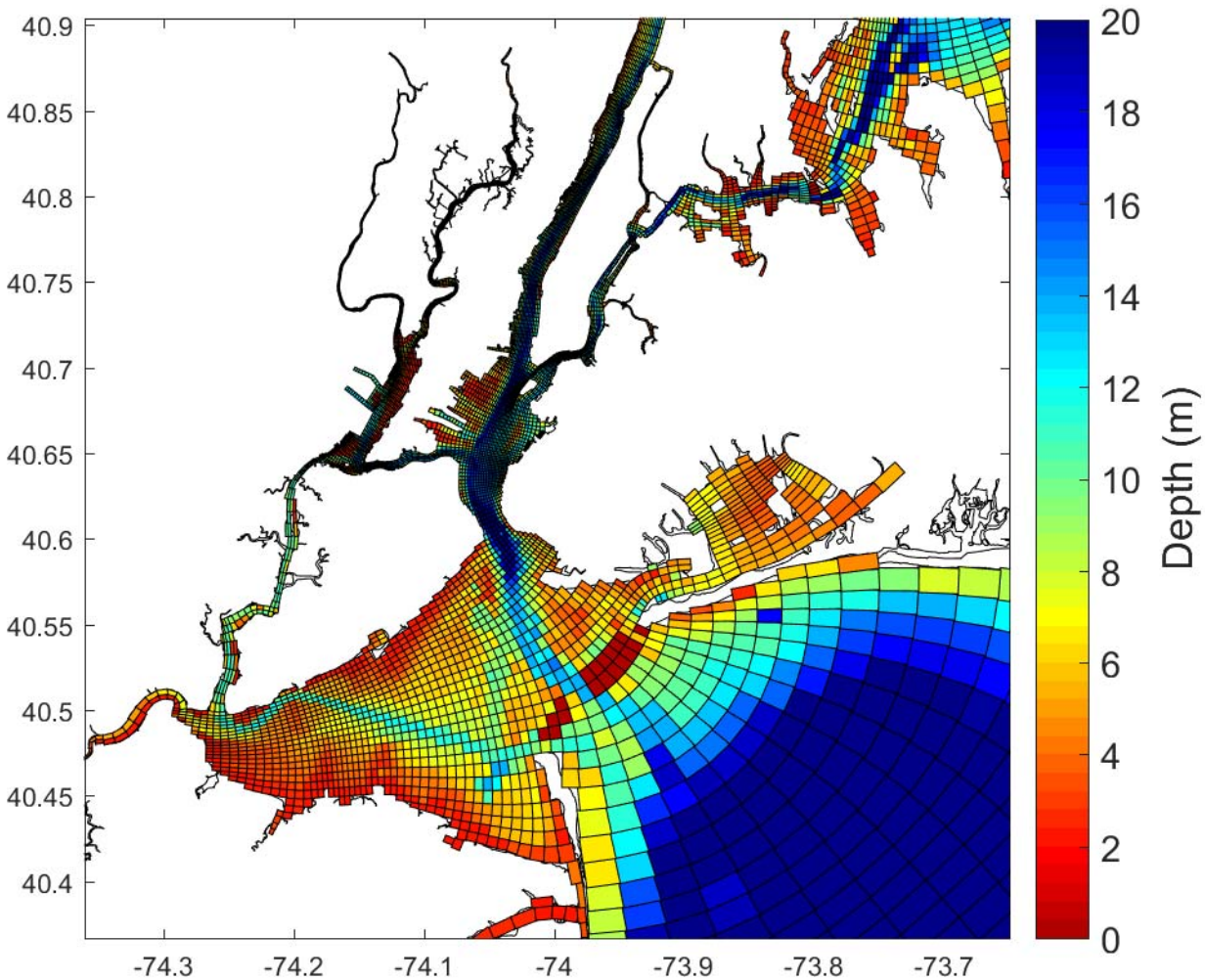
sECOM Case B: Porosity 62%



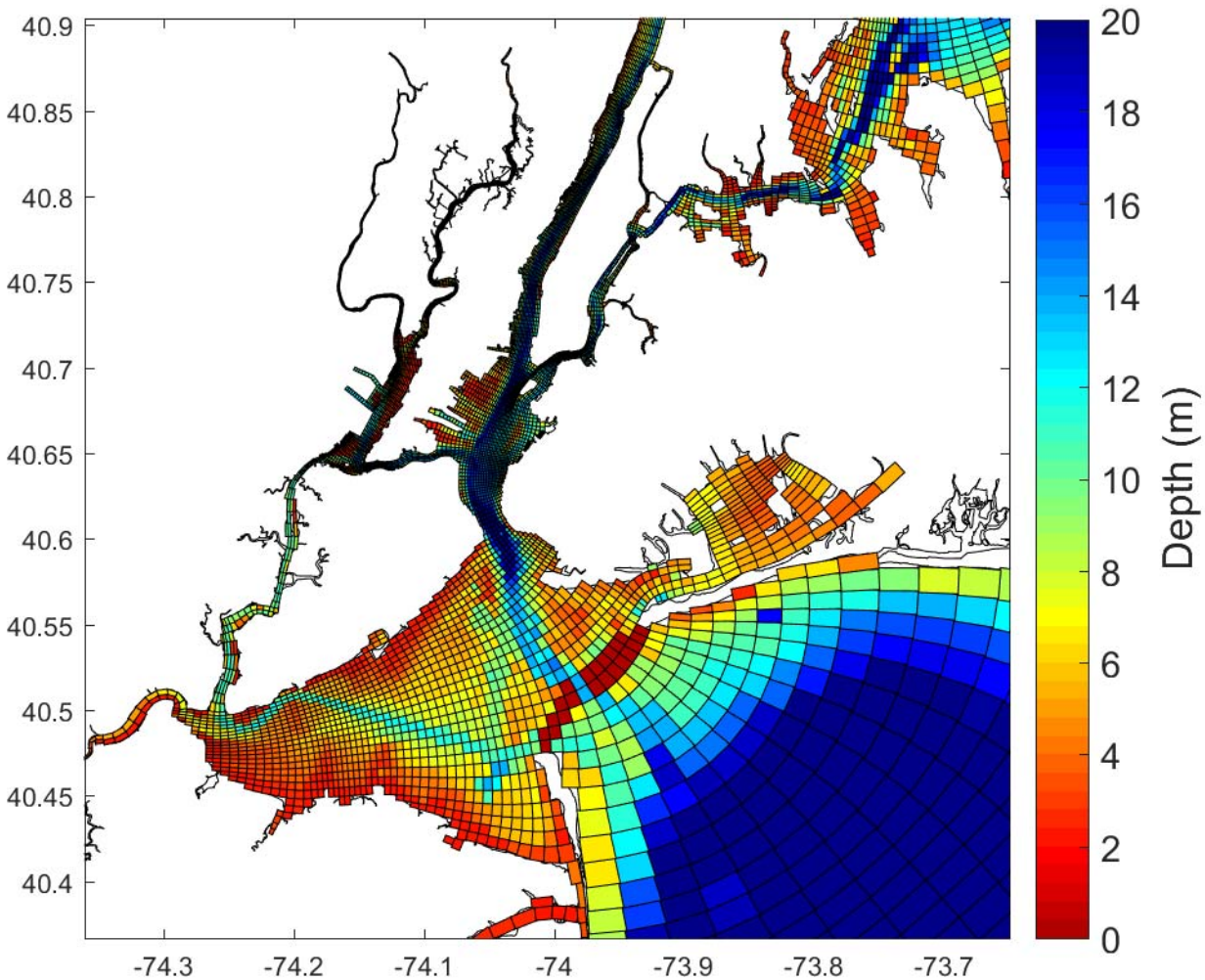
sECOM Case C: Porosity 44%



sECOM Case D: Porosity 34%



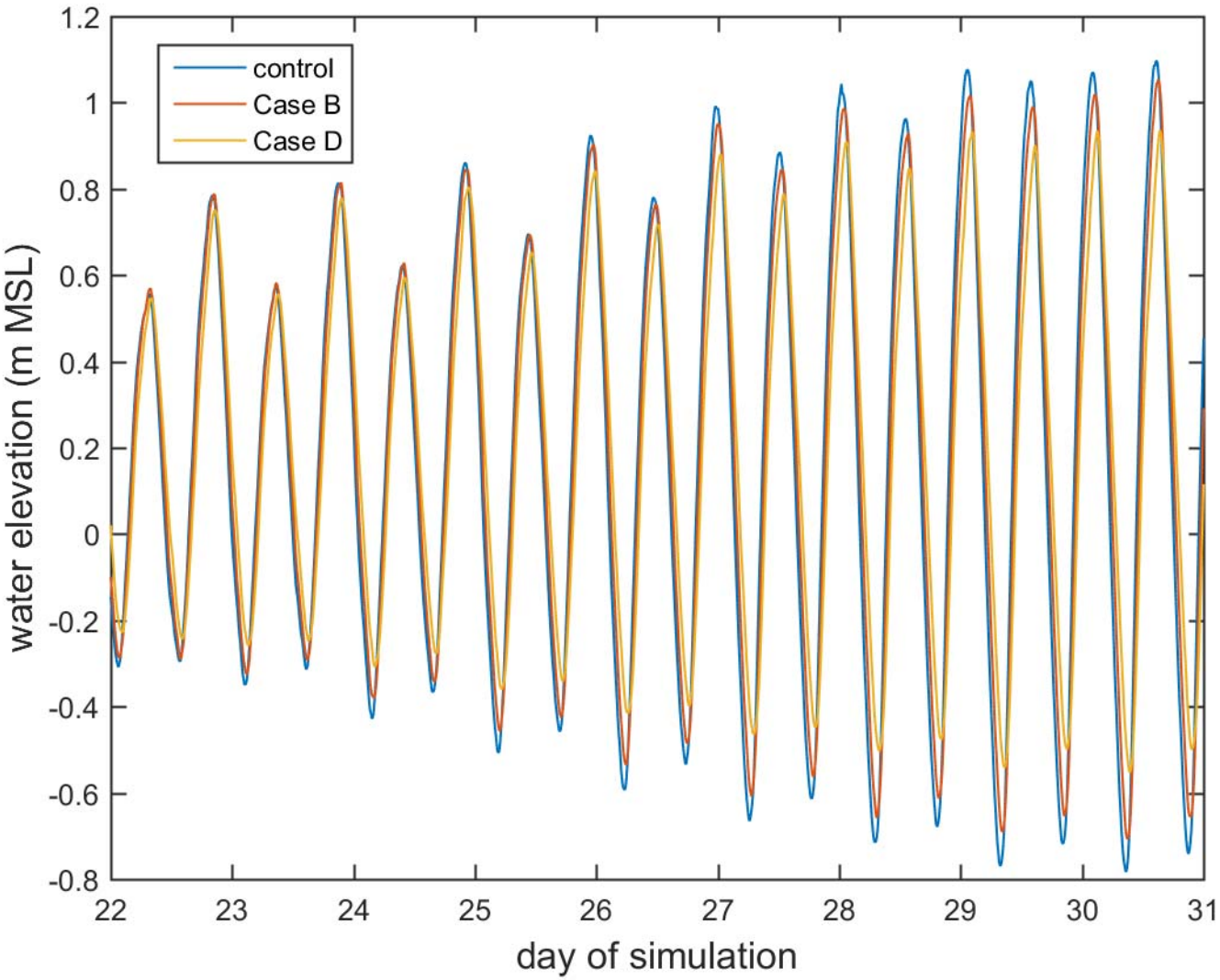
sECOM Case E: Porosity 15%



Shortcomings of sECOM Here

- Very coarse resolution at barriers – likely has a bias for tidal currents through poorly resolved gates

Tides: Control (P=100%), Case B (P=62%) & D (34%)



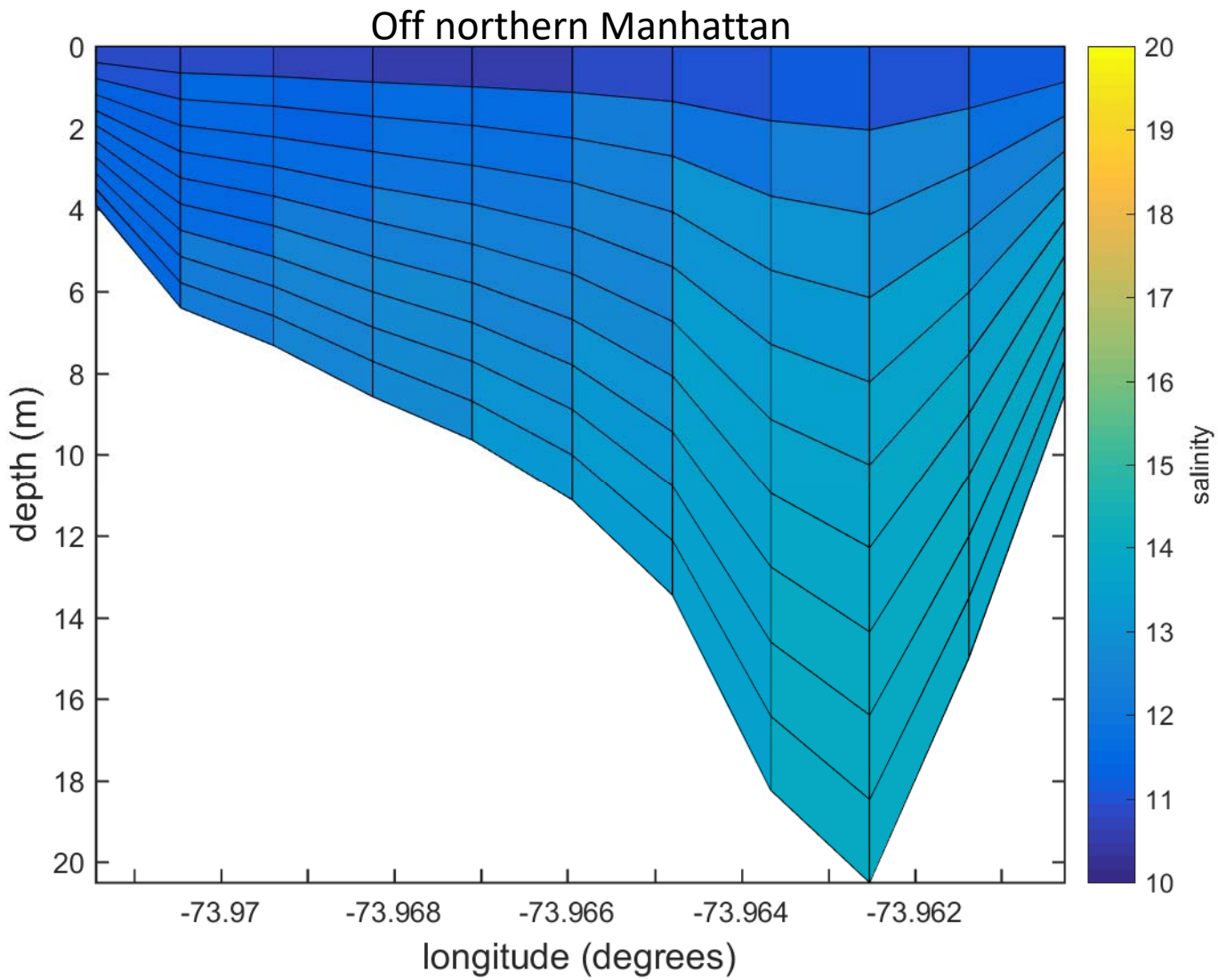
Control tide range over final tidal month was 1.35 m.

Case B tide range is 1.28 → 95% tide range conveyance

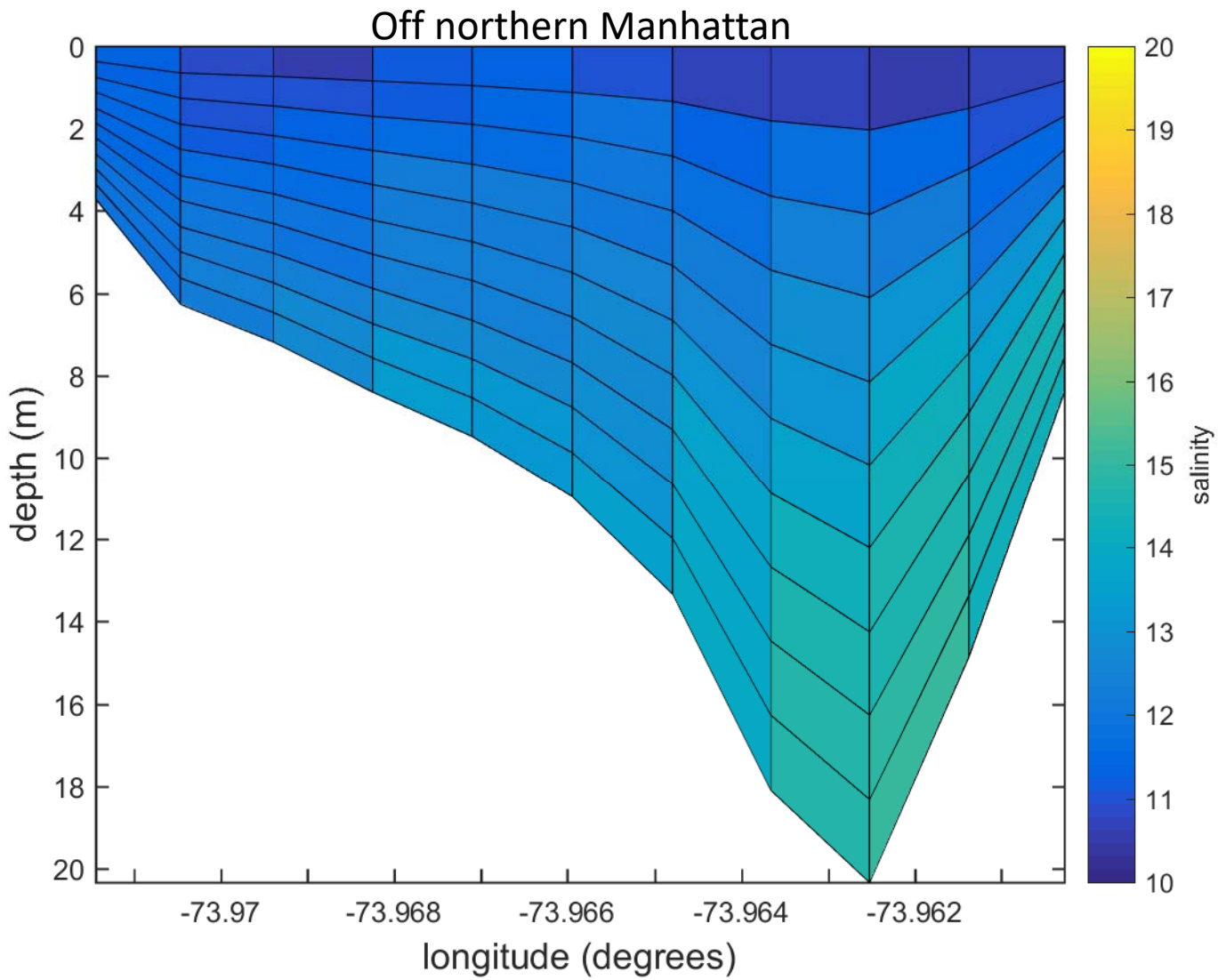
In contrast
Case D tide range is 1.12 m → 83%

Later, we'll look at a synthesis of all results

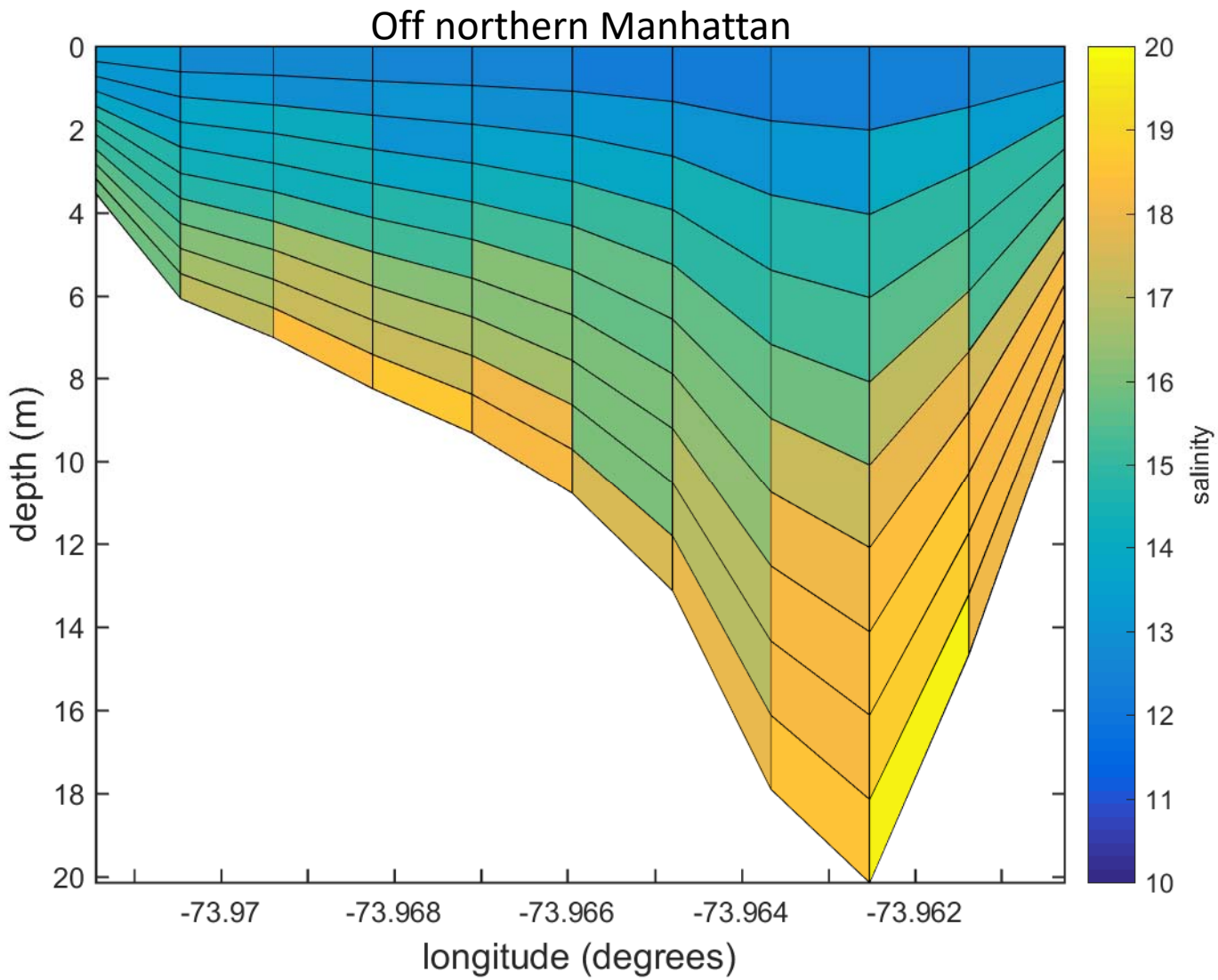
Spring Tide Cross-section: Control (P=100%)



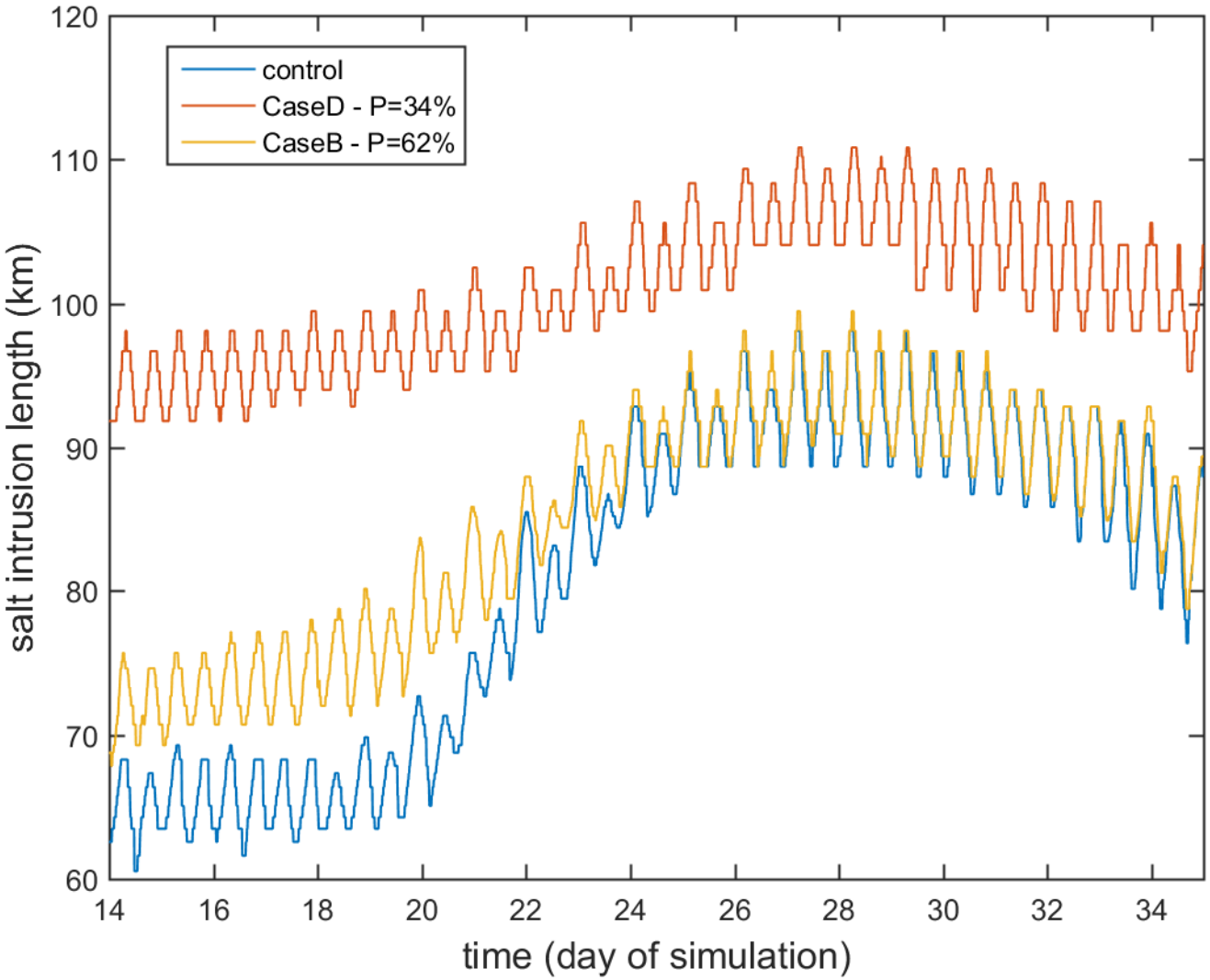
Spring Tide Cross-section: Porosity 62%



Spring Tide Cross-section: Porosity 34%



Salt Front Location (0.1 psu)

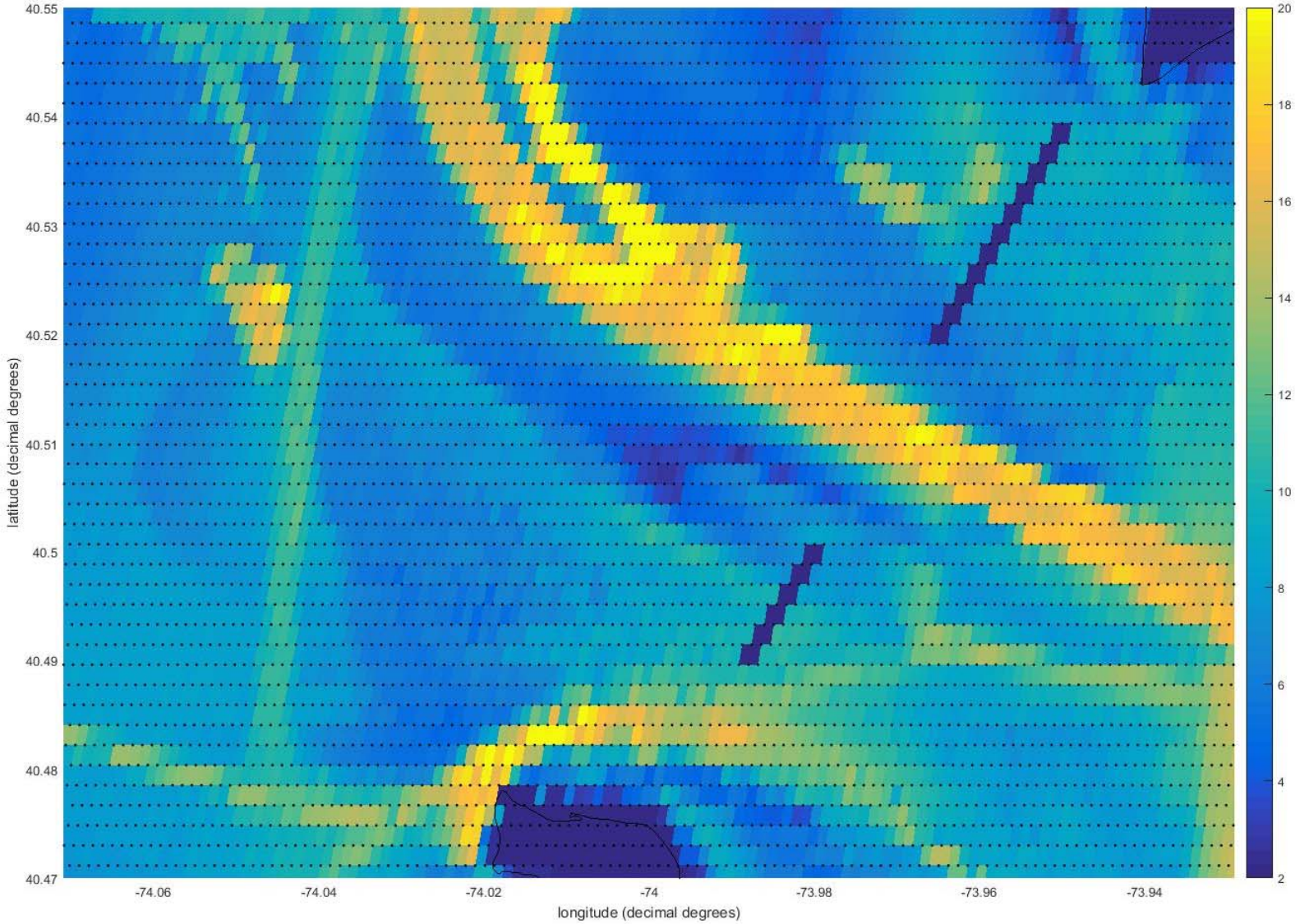


ROMS-3D Modeling

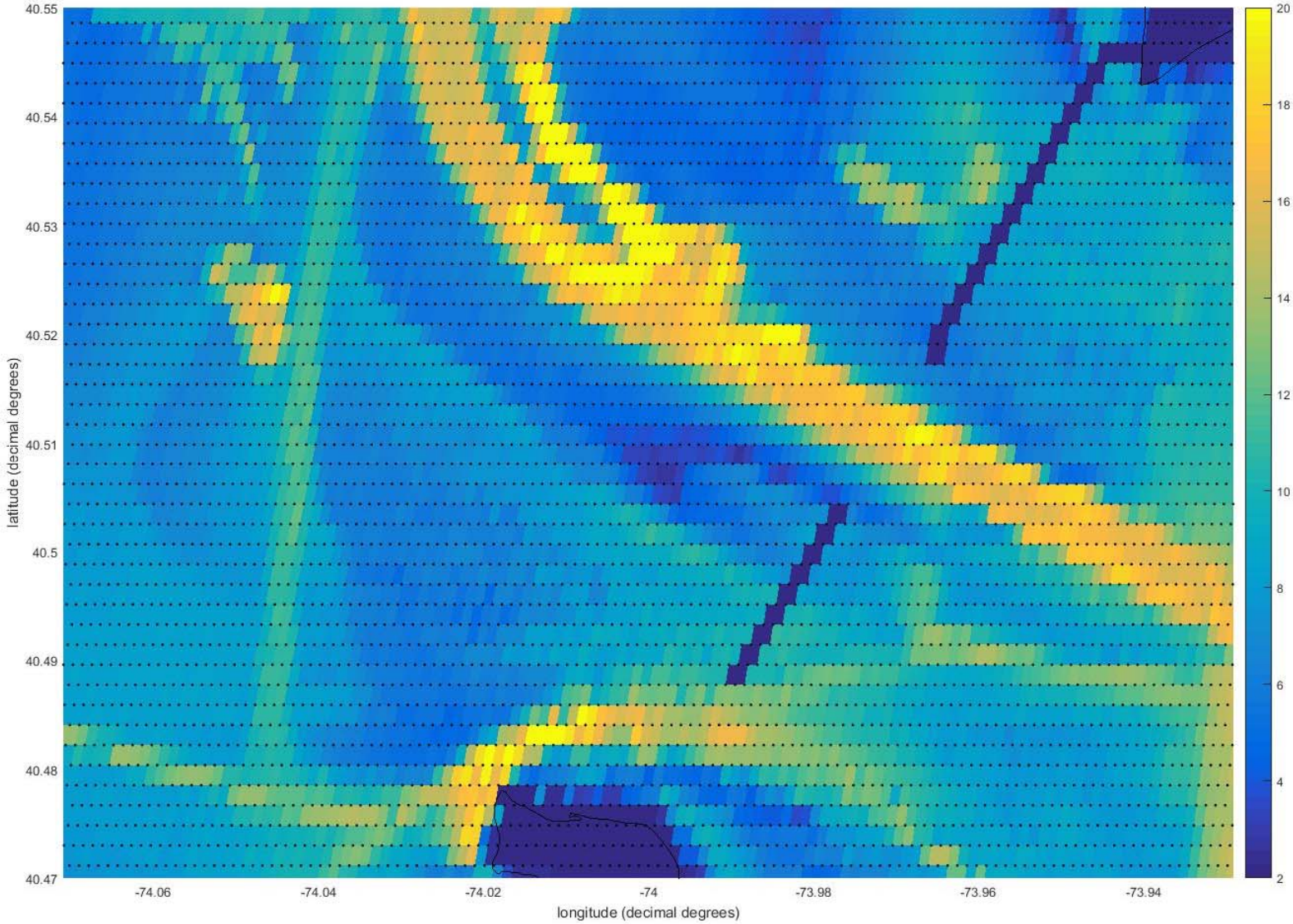
ROMS Model Set-Up (Simulations by Dave Ralston)

- Rectangular cells of resolution 100x300m
- 60-day simulation
- Tide forcing only; no wind
- Streamflows steady at Green Island 550 m^3/s
- Cold start with modified DEM to create tall flow barriers
- Dry cell masking in u, v, tracers
- East River is completely open – assumed to have many gates at Throgs Neck for strong flushing

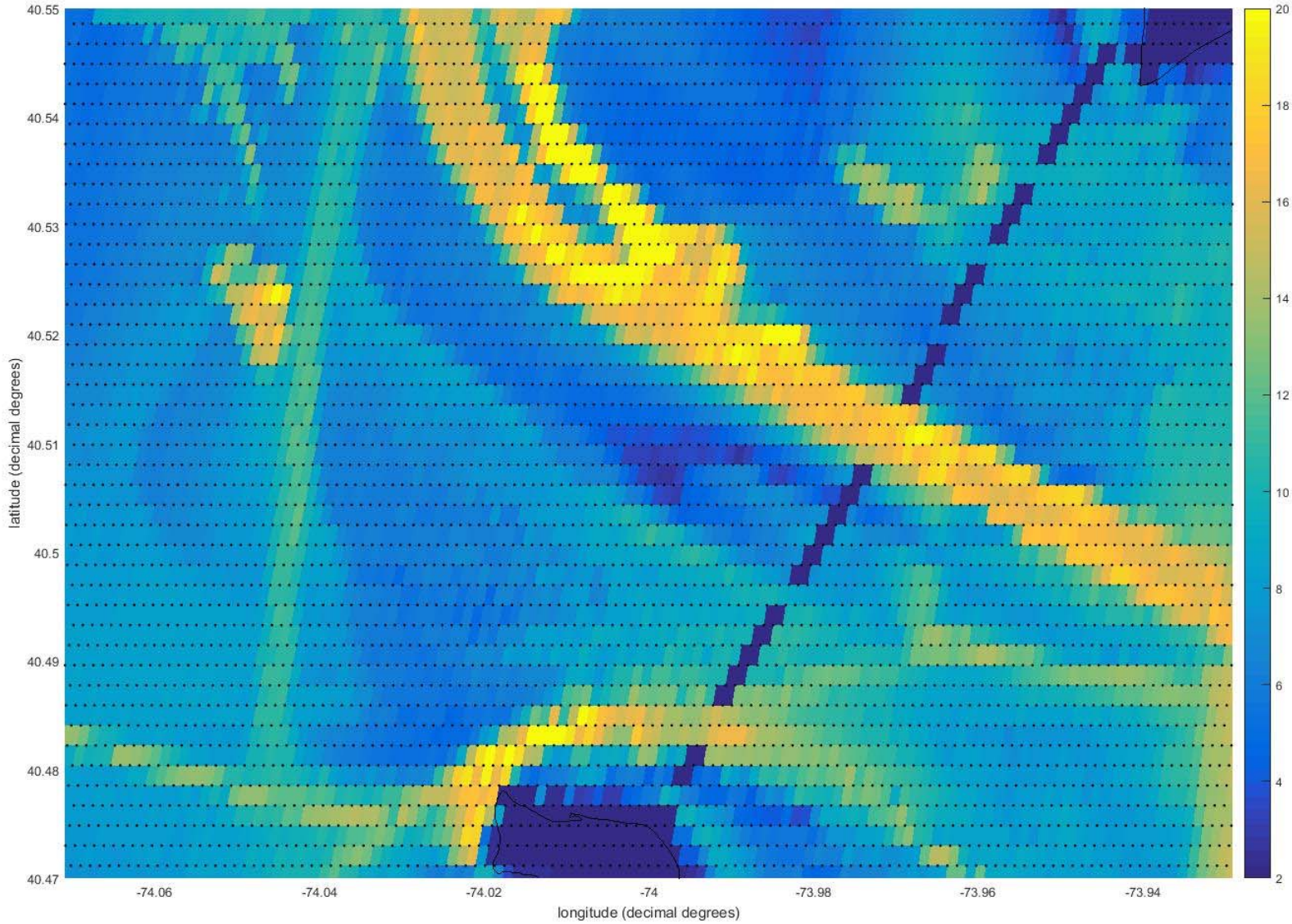
ROMS Porosity 58%



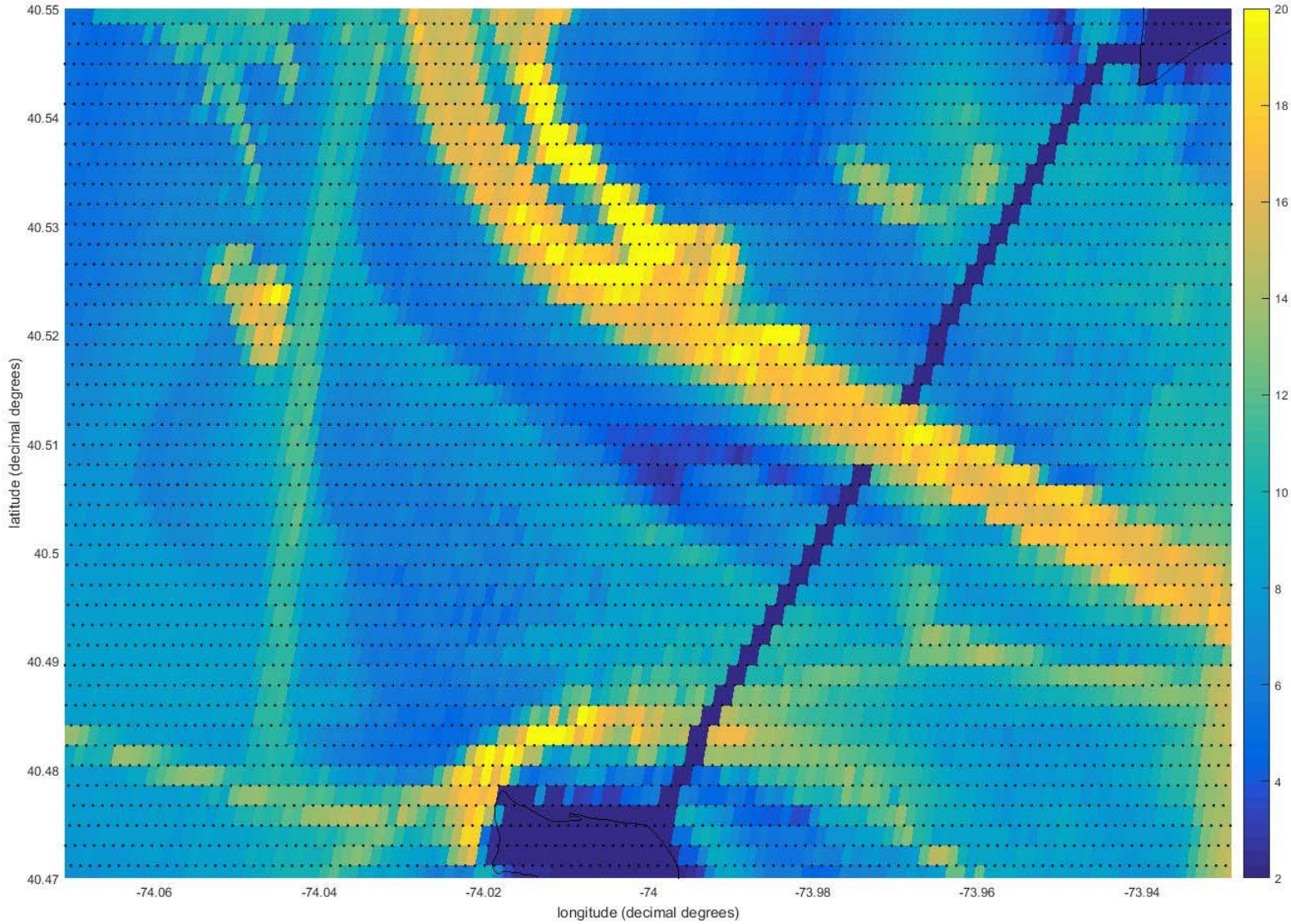
ROMS Porosity 43%



ROMS Porosity 24%



ROMS Porosity 12%

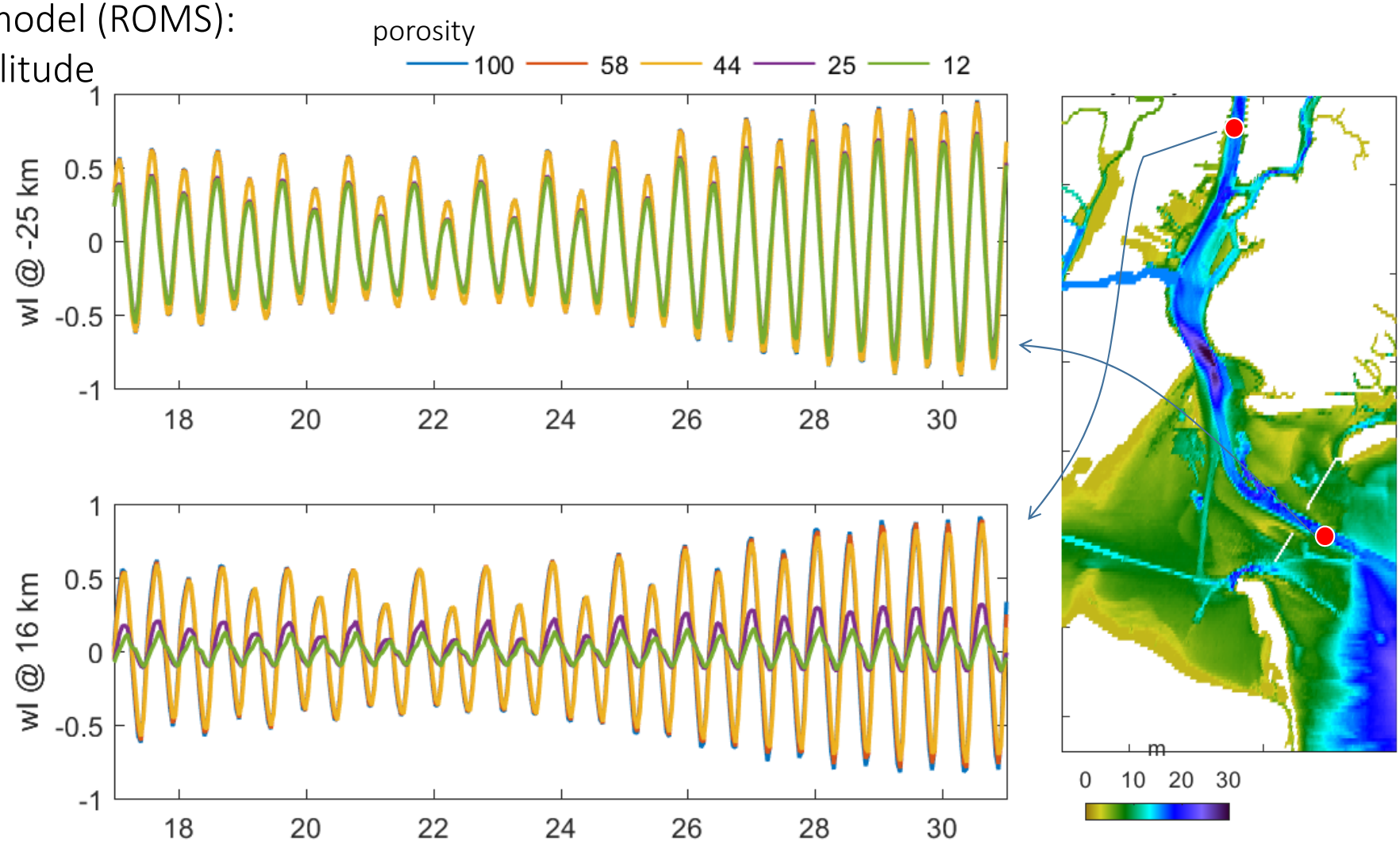


Shortcomings of ROMS Here

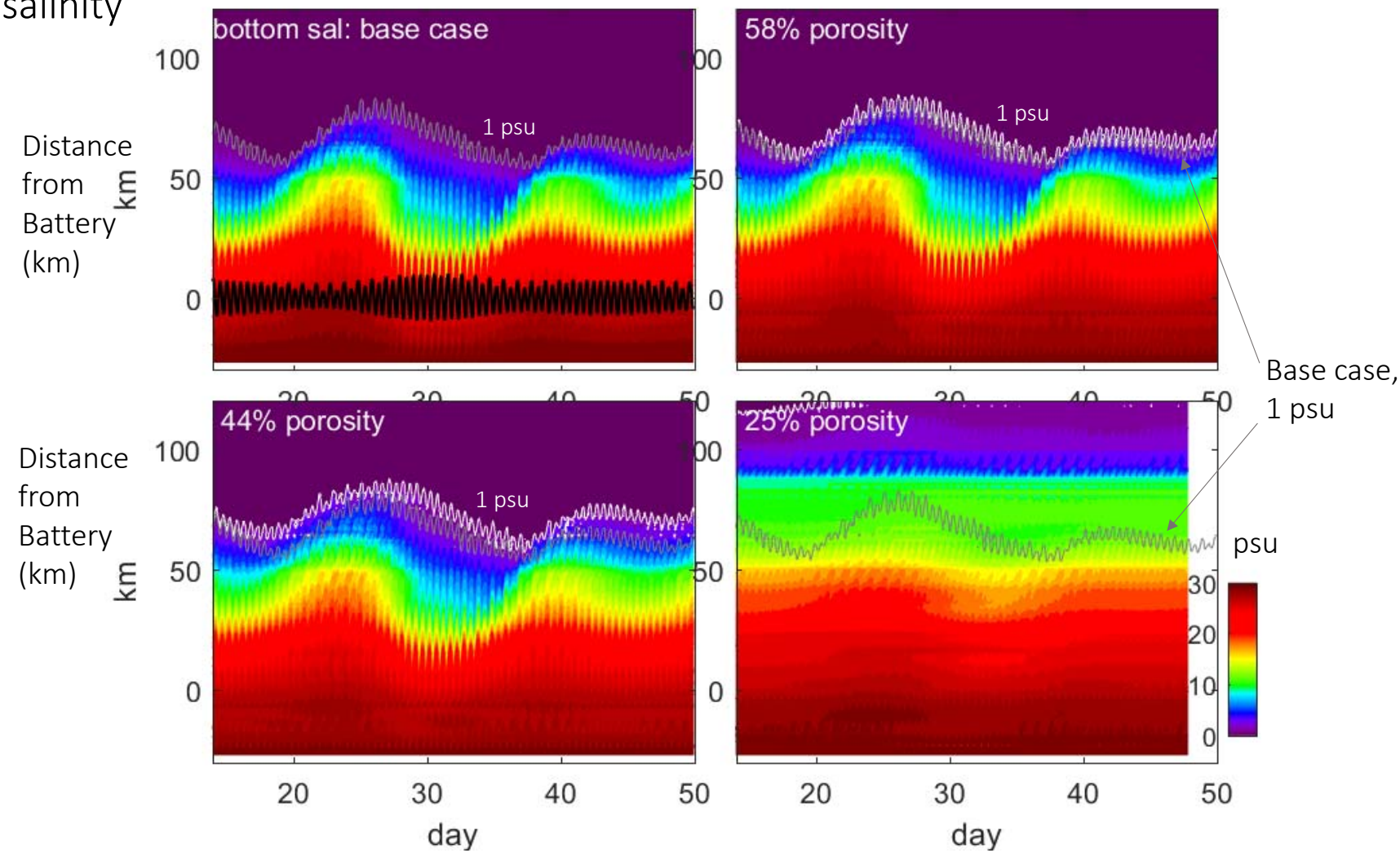
- Coarse resolution at the barrier – likely has a bias for tidal currents through smaller gates
- Moderate rotation of cells relative to flow, combined with masking of U, V at barriers – may underestimate tidal flushing for smaller gates

ROMS Results

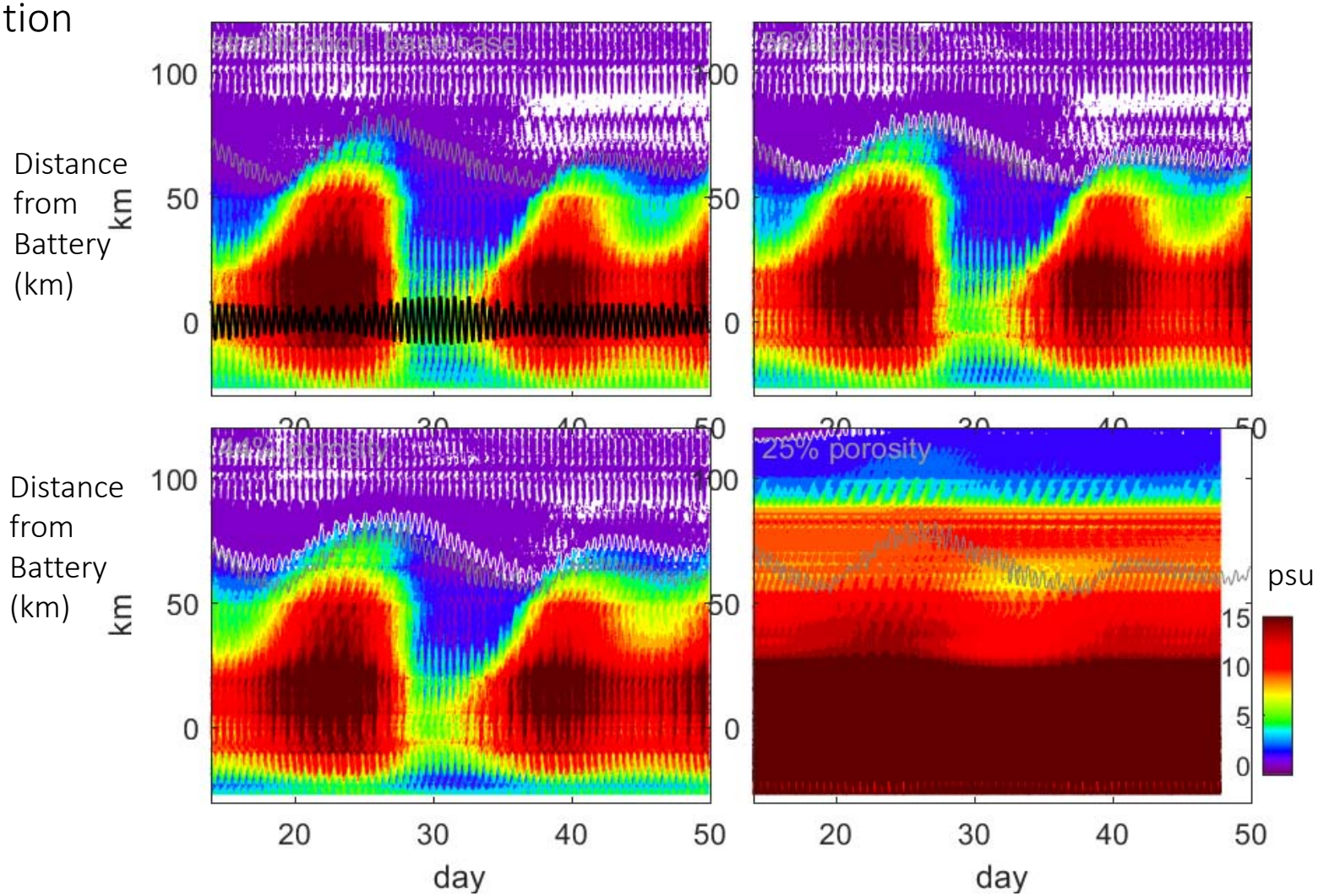
Hudson model (ROMS):
tidal amplitude



Hudson model (ROMS):
bottom salinity



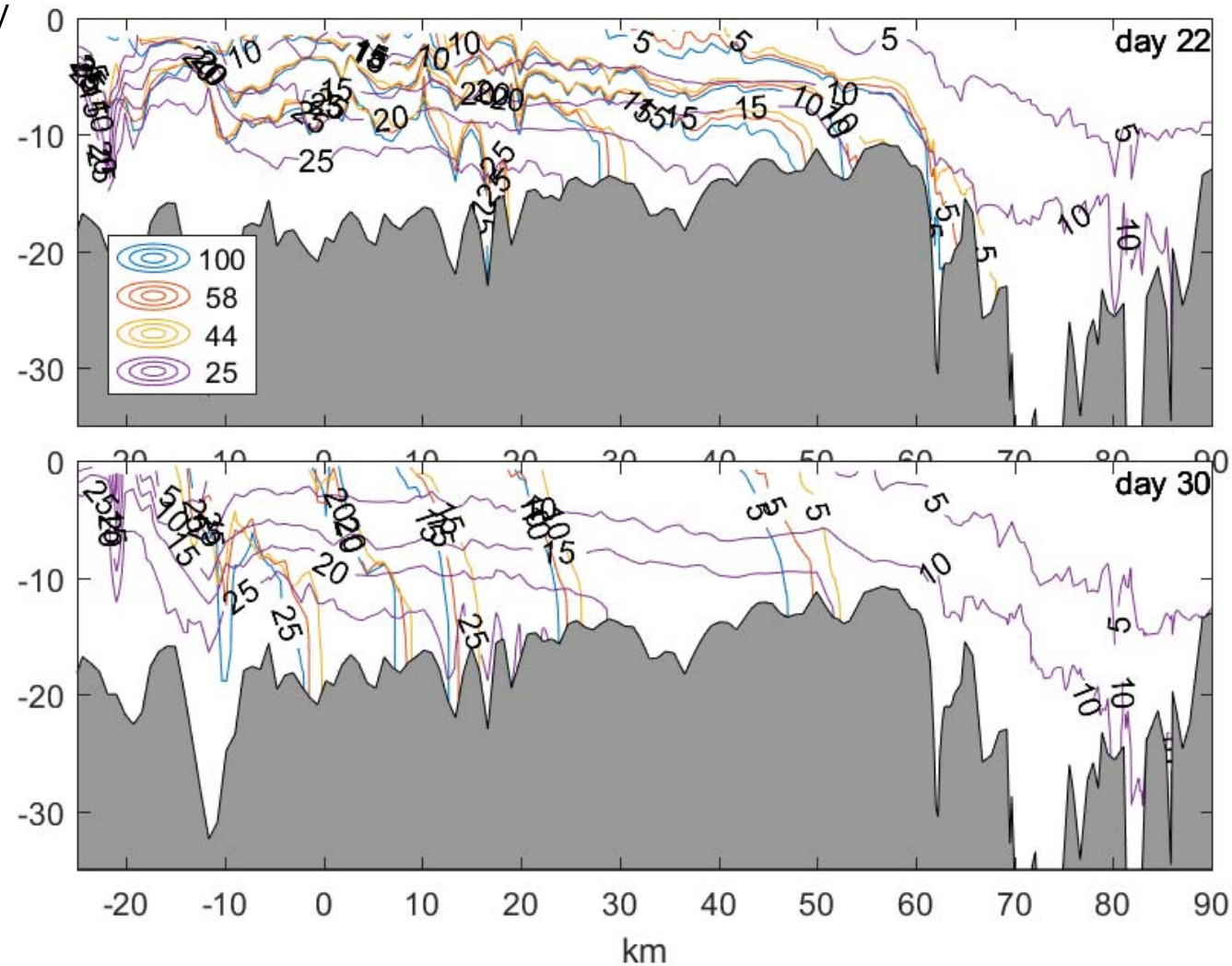
Hudson model (ROMS): stratification



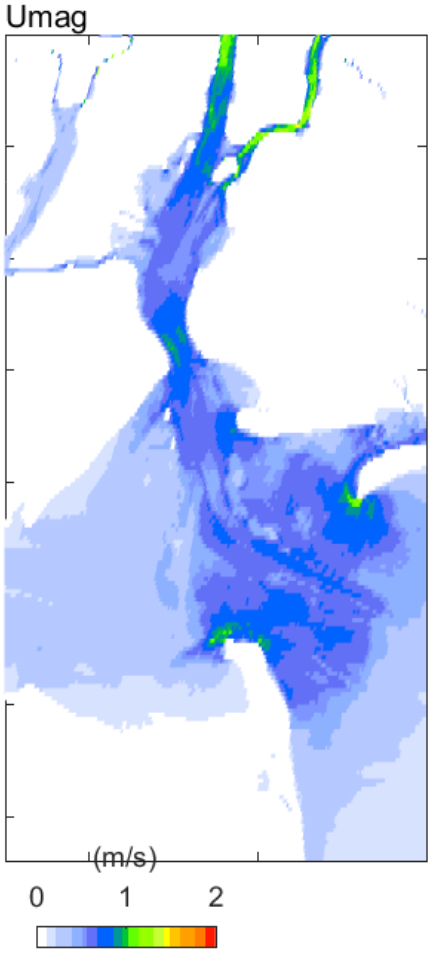
Hudson model (ROMS):
along-channel salinity

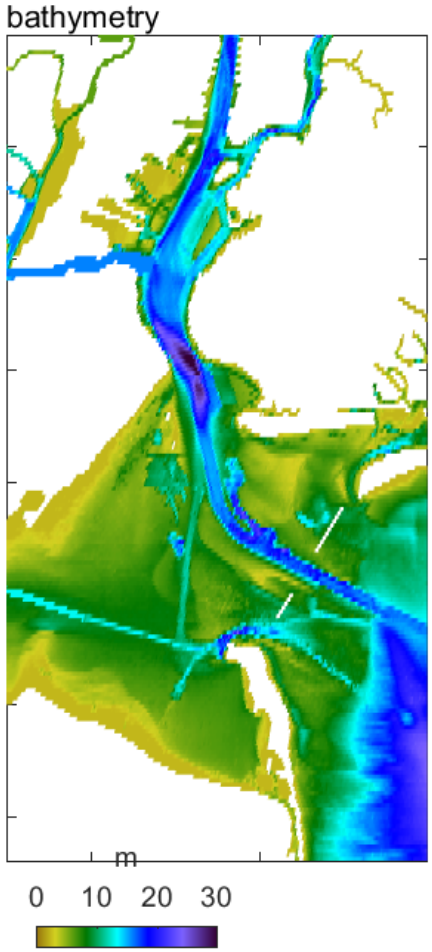
Neap tide

Spring tide

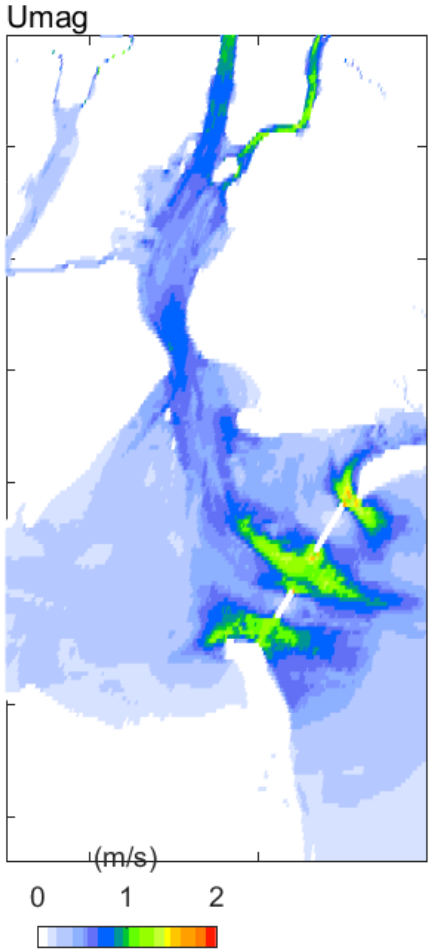


Hudson model (ROMS): max tidal velocity

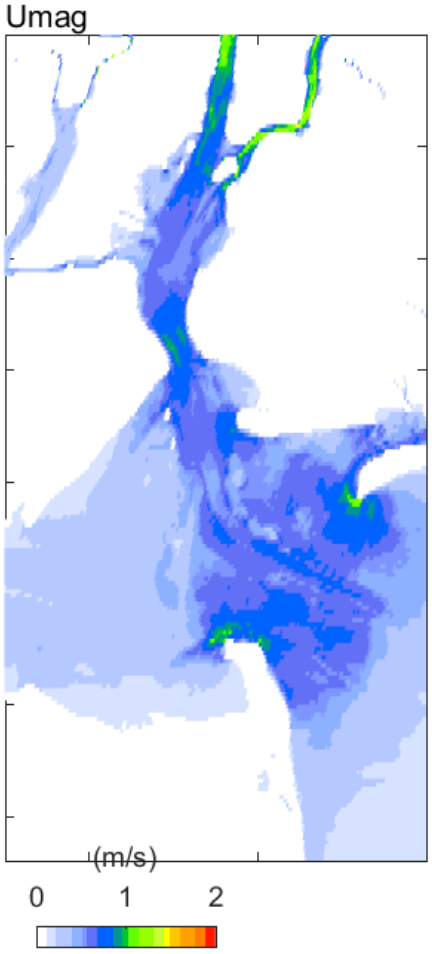


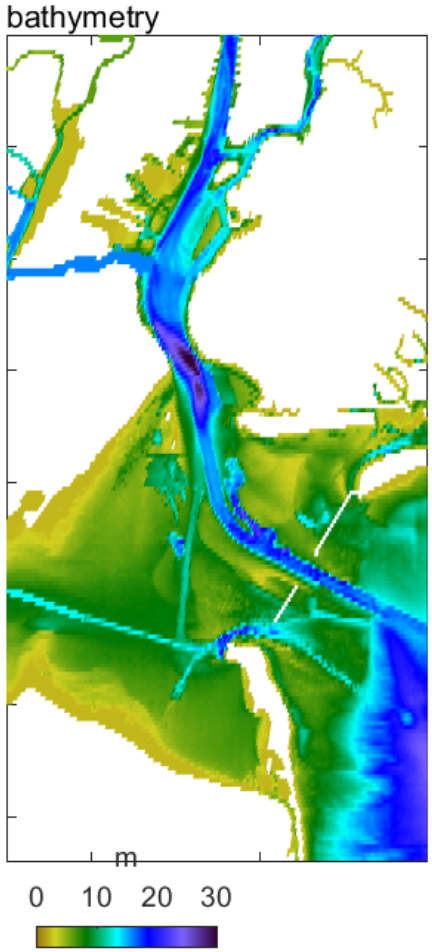


58% porosity

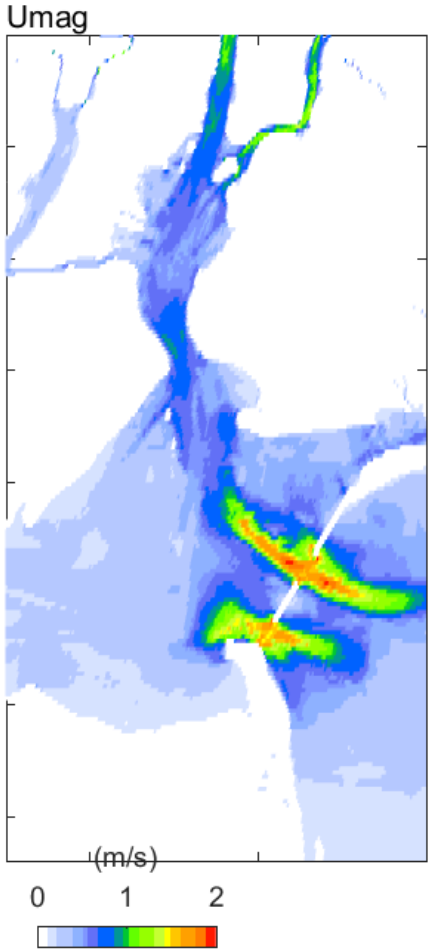


Hudson model (ROMS): max tidal velocity





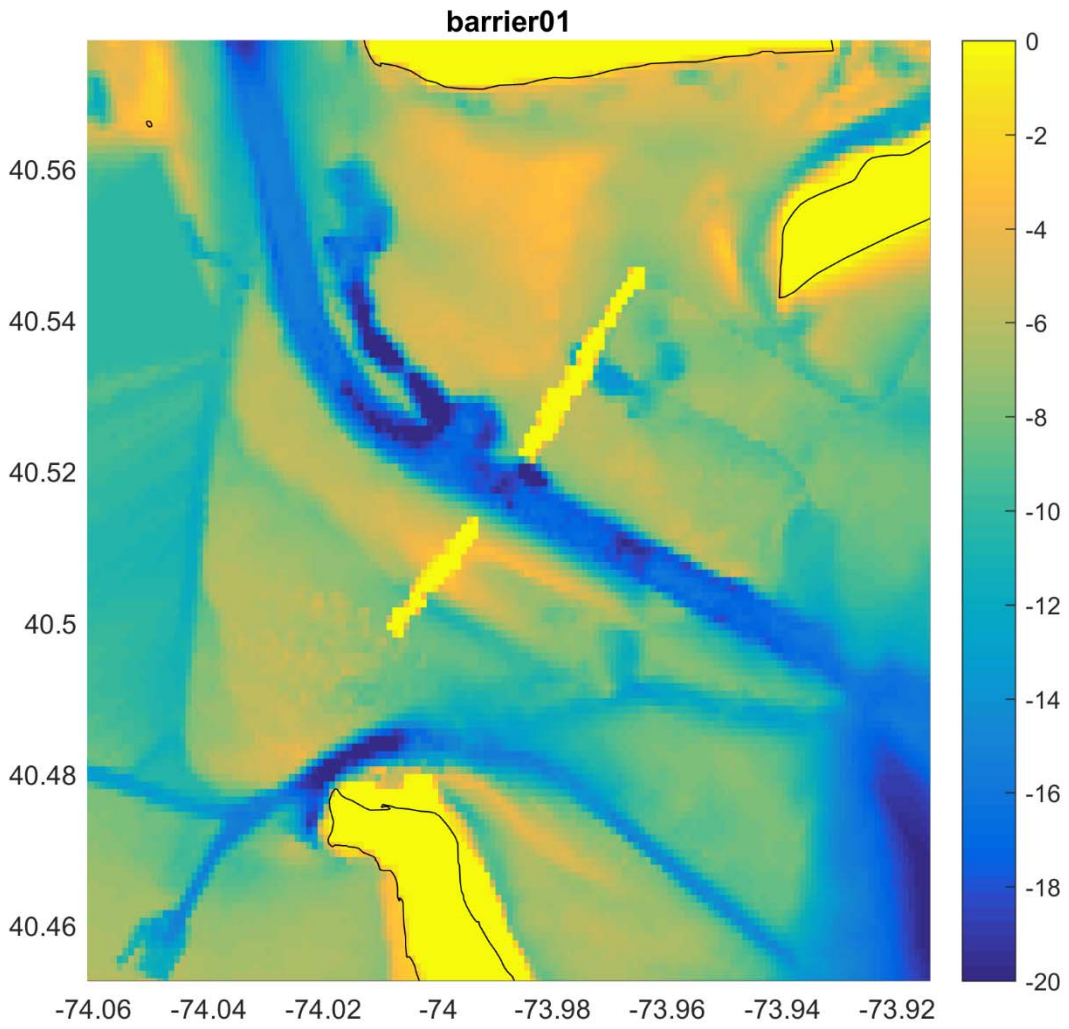
44% porosity

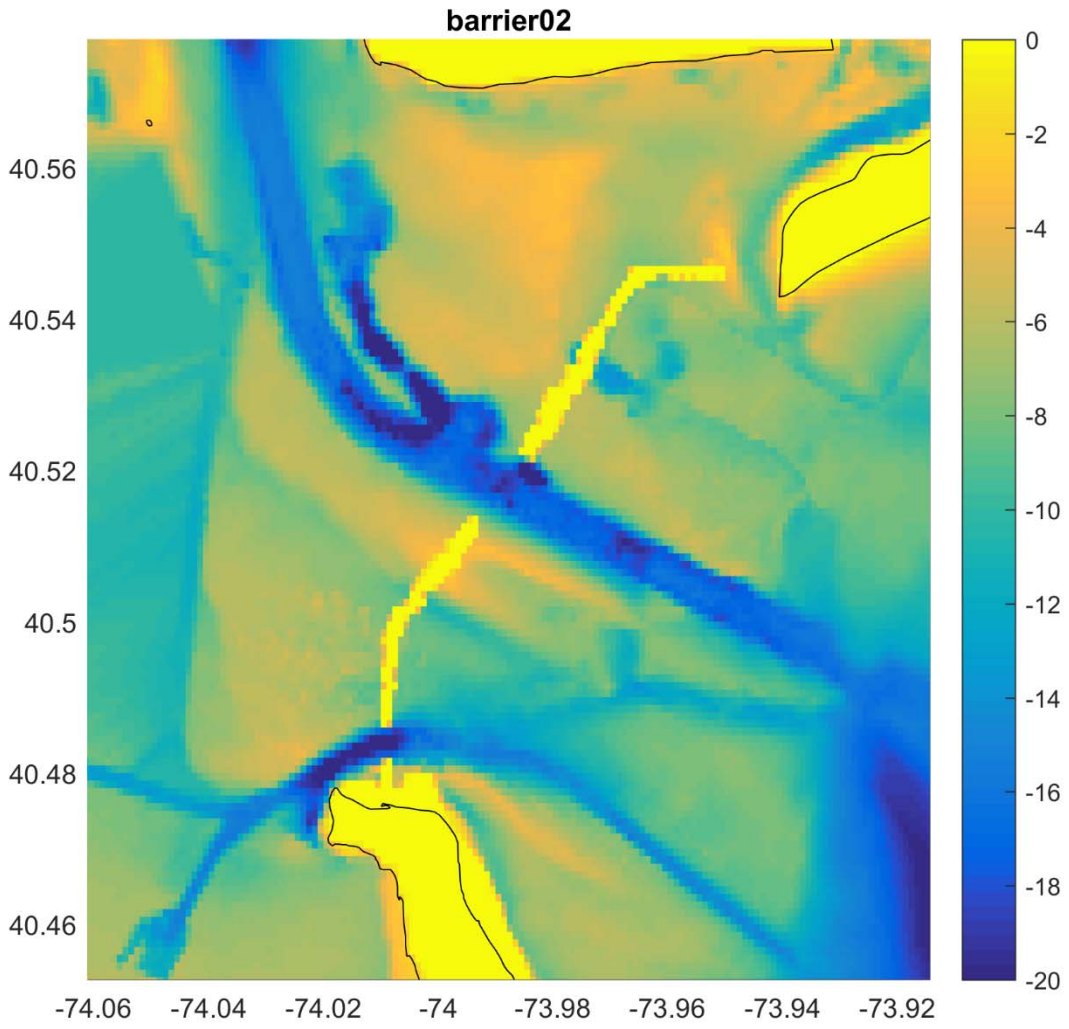


ADCIRC-2D Modeling

ADCIRC-2D Model Set-Up (Highly preliminary - added this week)

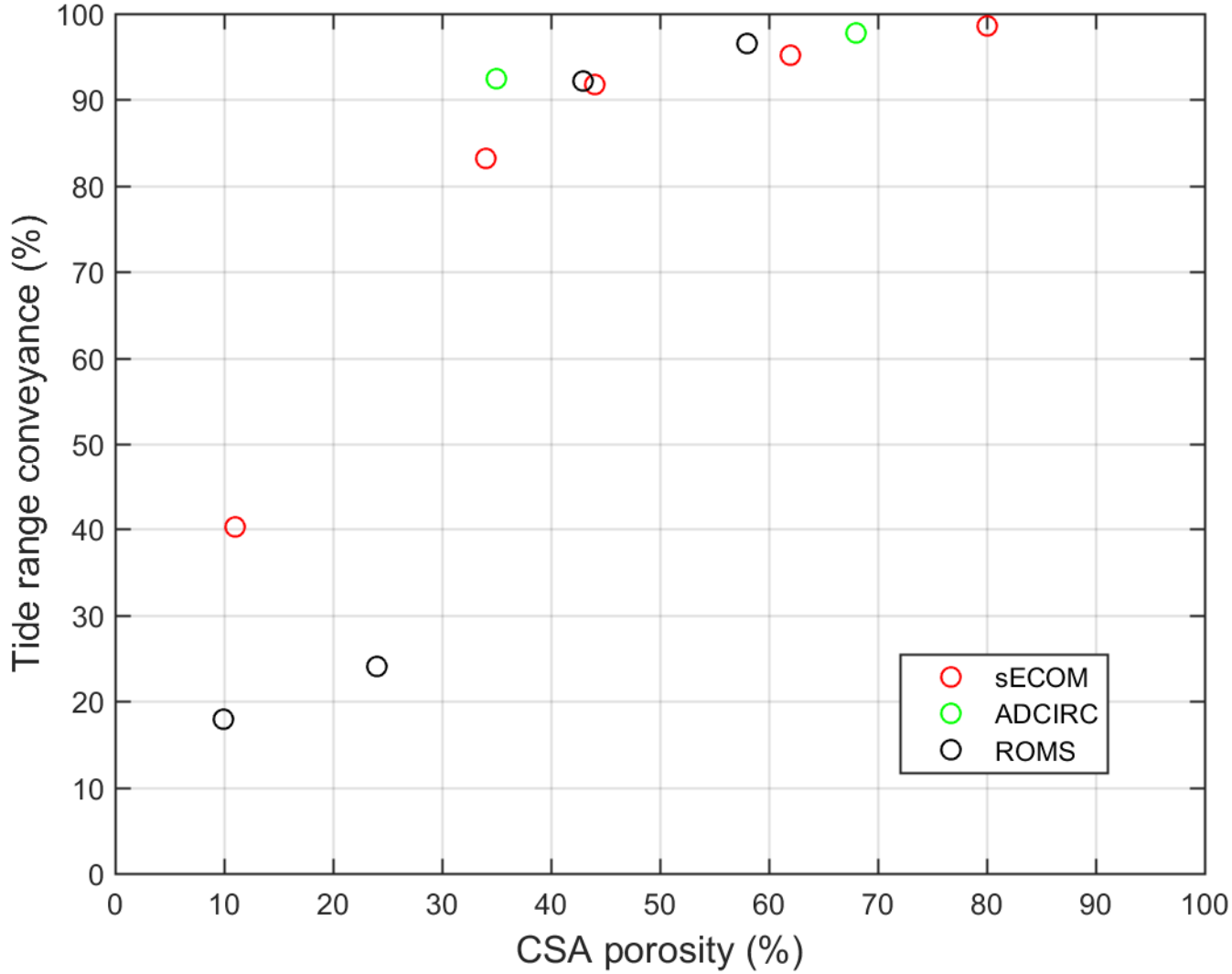
- FEMA Region II coastal flood study grid
- Unstructured mesh
- Triangular cells of resolution ~70m at inlet
- 15-day simulation
- Tide forcing only; no wind
- No streamflows
- Cold start with modified DEM to create tall flow barriers
- No cell masking at barrier
- East River is completely open


barrier01
40.56
40.54
40.52
40.5
40.48
40.46
-74.06
-74.04
-74.02
-74
-73.98
-73.96
-73.94
-73.92
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20

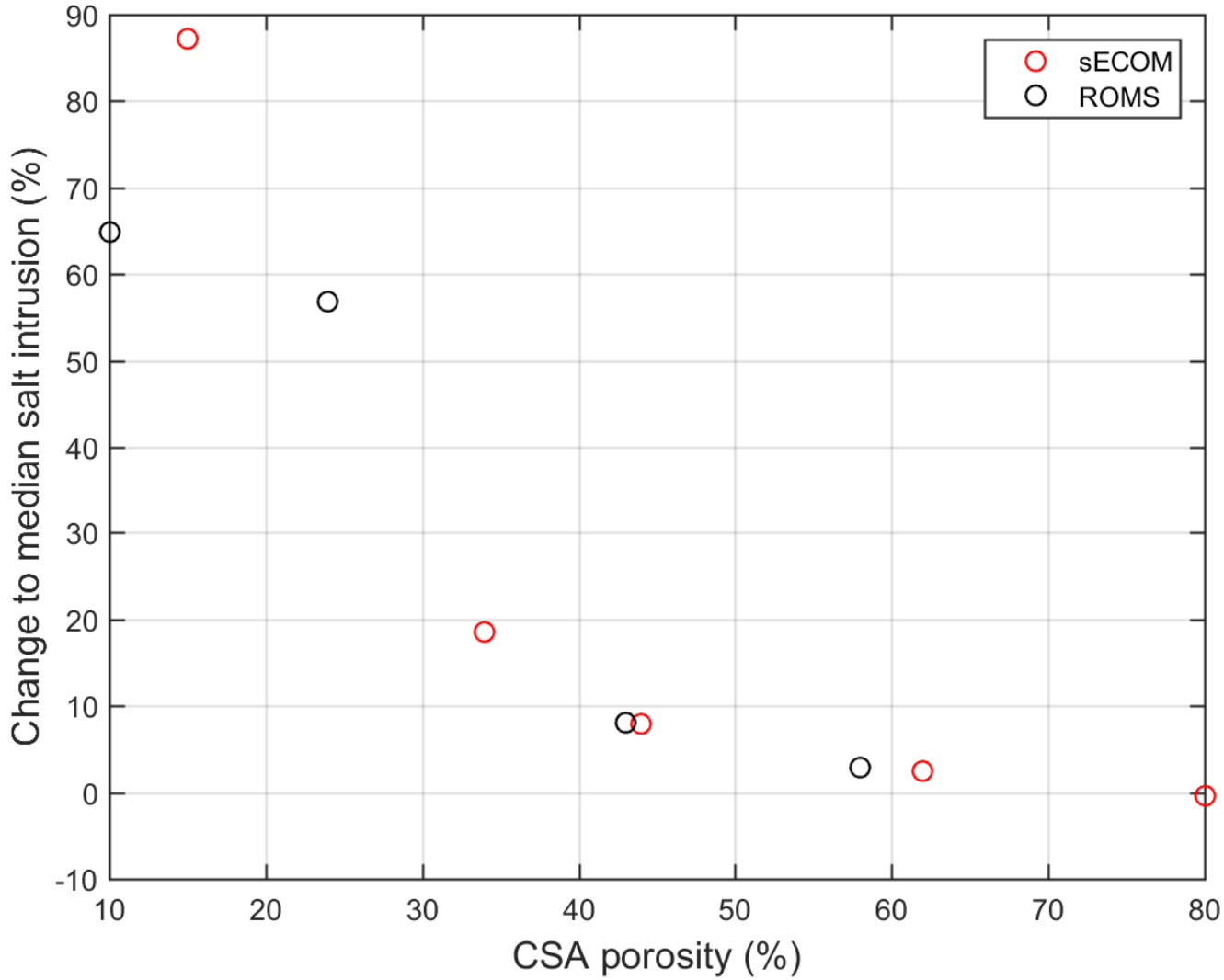

barrier02
40.56
40.54
40.52
40.5
40.48
40.46
-74.06
-74.04
-74.02
-74
-73.98
-73.96
-73.94
-73.92
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20

Preliminary Synthesis Plots

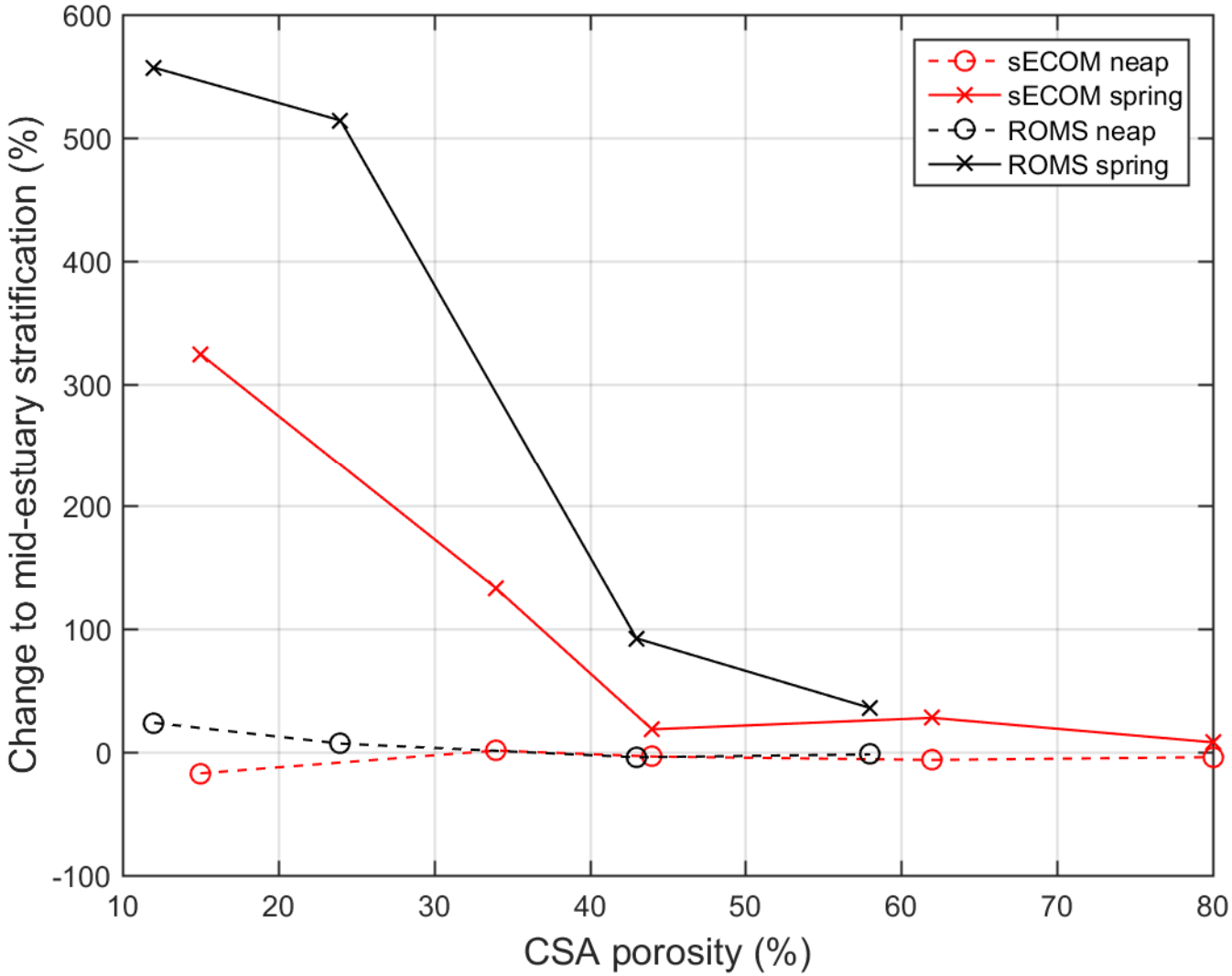
Porosity vs Tide Conveyance



Porosity vs Salt Intrusion Length



Porosity vs Delta-S (stratification)



Conclusions and Future Study

- Results are highly preliminary – they qualitatively agree on effects for porosities >40% but **diverge** for low porosities
- Lower porosity leads to:
  - Greater stratification and salt intrusion, likely due to weaker currents and mixing
  - Stratification increases – most prominent on spring tides
  - Salt intrusion variability is reduced
- This ongoing research provides a baseline for more in-depth physical studies or for interdisciplinary studies
  - A one-year study funded by NOAA (Orton, PI) will have multiple workshops and enable more physical modeling and analyses, as well as interdisciplinary interactions

Recommendations for Further Work

- Continue with 3D estuary modeling of estuary conditions and surge barrier-induced changes
- Conduct resolution sensitivity studies – are results stable to increasing resolution through gates?
- Do a more detailed comparison of ADCIRC-2D and the 3D models
- Continue to develop a more detailed set of parameters describing influences of barriers on estuaries
- Find/fund studies of built barriers for similar estuaries – what do models predict and was it realized?