Non-Tidal Residual Current and Water Level Response to Storm Events in a Micro-Tidal Estuary

Midshipman 1/C Siena N. Hall, USN, Class of 2024

Advisor(s): Dr. Joseph P. Smith, Dr. Liliana Velásquez-Montoya, Instructor Alexander R. Davies, and Mr. Benjamin Hickman

Abstract

Forcing from episodic storm events can result in non-tidal residual water levels and currents that are significantly higher or lower that those observed under tide dominated conditions in microtidal estuaries like the Severn River. In this study, observed water levels and tidal-scale currents in the lower Severn Estuary during significant coastal flooding events were compared to values from a hydrodynamic model to evaluate the capability to accurately simulate such events.

Study Area and Methods

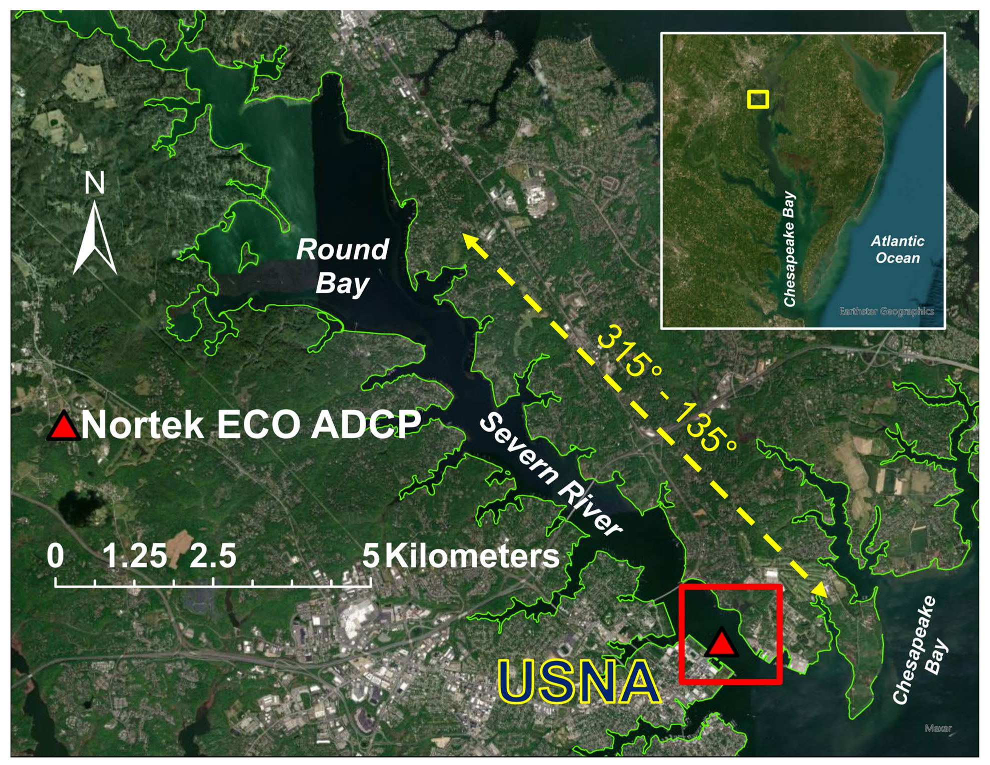

Figure 1. Map of study area showing the deployment location for a 1 MHz Nortek ECO 3-beam Acoustic Doppler Current Profiler (ADCP) at the mouth of the Severn River. The Severn River is a microtidal sub-estuary in the mesohaline Chesapeake Bay with semi-diurnal tides. It has a mean tidal range of ~0.30 m and a diurnal range of ~0.44 m. Three separate deployments were conducted: 24 August – 08 September 2023 (minor flooding events); 22 – 28 September 2023 (minor and moderate flooding event); and 08 – 18 January 2024 (minor and major flooding events). The 315° - 135° axis of the Severn River is shown by a yellow dashed line (*Davies et al., 2022*).

A 1 MHz Nortek ECO (www.nortekgroup.com/products/eco) 3-beam Acoustic Doppler Current Profiler (ADCP) was deployed in a bottom-mount buoy system with a timed release at ~ 7.0 m depth in the main channel near the mouth of the Severn River near the U.S. Naval Academy (USNA). The ADCP to collect current and before a forecasted storm in January 2024. The ADCP was programmed to collect pressure and current data in three depth averaged bins (surface, middle, and bottom; **Fig. 2**) every 6 minutes coincident with predicted and observed water level data and meteorological data (6 minute) recorded at the NOAA/NOS/CO-OPS Annapolis, MD (ID: 8575512) tide gauging station located at USNA (www.tidesandcurrents.noaa.gov/stationhome.html?id=8575512). Mean sea level pressure data from the NOAA Annapolis gauging station was used to barometrically correct water levels recorded by the ECO. All water levels were referenced in meters to the North American Vertical Datum of 1988 (NAVD 88). Surface, middle, and bottom current data collected by the ECO was averaged and normalized to the main 315°-135° axis of the Severn River (*Davies et al., 2022)* to determine bulk water column axial and longitudinal current speeds. Measured water level and current data was compared to 5 minute modeled water level and bulk axial currents from a Delft3D FM model for the Severn River initially developed by *Brennan (2022)* and modified by *Velásquez-Montoya (2023).* The model is being used to simulate flooding at USNA and the hydrodynamics of the Severn River. The model extends 3 km across the river from Greenbury Point while the upriver boundary is located approximately 18 km to the northwest into the Severn River headwaters. The model has a grid resolution of 100 m upstream and 50 m near USNA. Bathymetry and topography for the model were built from LIDAR-based digital elevation models from 2019 and a compilation of NOAA's historical surveys of the Severn River. The model is forced with water level data taken from NOAA Station 8575512 in the seaward boundary and discharge data from U.S. Geological Survey South Fork Jabez Branch gauging station at Millersville, MD - 01589795 (https://waterdata.usgs.gov/monitoring-location/01589795). The 5 minute model data was interpolated to a 6-minute time step to match measured ADCP data using the *MATLAB R2023a retime* function with spline fit and normalized to the axis of the Severn River.

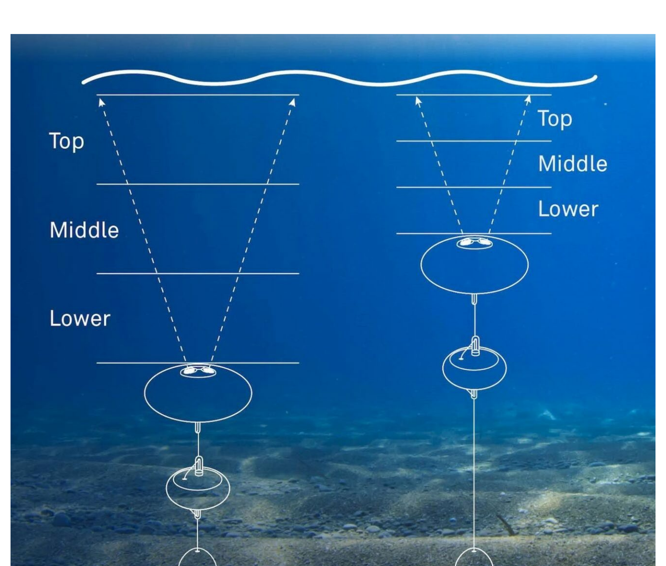

Figure 2. The 1 MHz Nortek ECO 3-beam ADCP (https://www.nortekgroup.com/info/eco) is a bottom-mounted system made for waters up to 50 m with a 20 m range. It can deployed for up to a month depending on the sampling frequency. It has a blanking distance of 0.1 m. It has an onboard GPS and compass and uses a pressure sensor to time-average a tidally-varying water column into three equal depth layers above the blanking distance and the records horizontal currents speeds and true current directions for each layer. It has an accuracy of +/- 0.5 cm/s.

Acknowledgements: This work was funded by the U.S. Defense Threat Reduction Agency (DTRA). Special thanks to Richard Fry and Bruce Trask (DTRA).

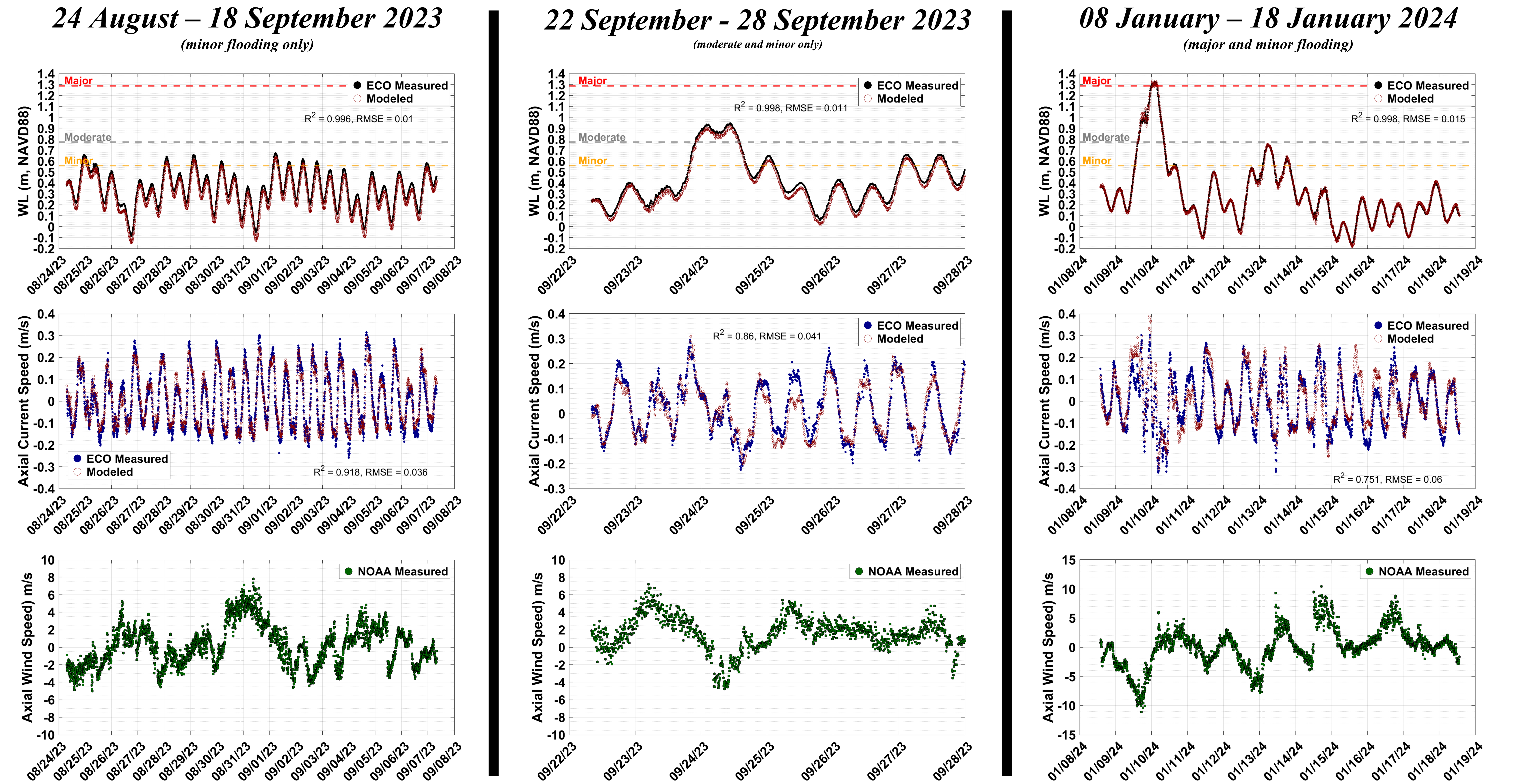

Figure 3. (*top-to-bottom*) Measured and modeled water levels (WL, m referenced to NAVD88); measured and modeled axial current speeds (m/s, + = down estuary towards mouth) and; axial wind speed (m/s, + = down estuary towards mouth) for (*left-to-right*) 24 August – 18 September 2023; 22 September - 28 September 2023 and; 08 January – 18 January 2024. The dashed lines on the WL plots show local Annapolis coastal flooding thresholds: minor flooding = NAVD88 +0.56 m (MLLW +2.6ft.); moderate flooding = NAVD88 +0.77 m (MLLW +3.3 ft.) and; major flooding = NAVD88 +1.29 m (MLLW+5.0 ft.). The R2 value for the linear fit of measured to model data for WLs and axial current speeds are shown on each plot for each date range.

The Delft3D FM model for the Severn River (*Brennan, 2022*) takes its Chesapeake Bay side forcing from water levels at the NOAA Annapolis, MD (ID: 8575512) tide gauging station located at USNA, so it is not surprising that water levels derived from Nortek ECO ADCP pressure sensor match well with modeled water levels ($R^2 > 0.99$; Root Mean Squared Error (RMSE) < 0.015 m) regardless of whether minor, moderate, or major flooding is occurring. Assuming that the Nortek ECO ADCP provides an accurate measure of bulk water column currents, then a comparison of measured to modeled axial current speeds (m/s, with + values indicating flow down-estuary towards the mouth) over the three deployment periods of 24 August – 08 September 2023, 22 – 28 September 2023 and 08 – 18 January 2024 shows that the model predicts the phase of the axial currents well, but the fit for measured to modeled current speed decreases and the RMSE increases with increasing severity of coastal flooding (minor flooding only, $R^2 = 0.92$, RMSE = 0.036 m/s; moderate and minor flooding, $R^2 = 0.86$, RMSE = 0.041 m/s; major and minor flooding, $R^2 = 0.75$, RMSE = 0.060 m/s). If one looks at axial winds speed up (- value) and down (+) the estuary, minor, moderate, and major flooding events tend to be associated with sustain negative values prior to the flooding peak (**Fig. 3**). This is consistent with the findings of *Davies at al. (2022)* which associated WLs in Annapolis with wind direction along the axis of the Severn River. The model has higher uncertainty in predicting tidal current response in the Severn during and around moderate to major coastal flooding events (**Fig. 4a**). **Figure 4b** shows a wind rose (histogram) wind speed and direction (degrees true) occurrences during the 3 deployment periods. The largest differences between measured and modeled axial current speed tend to be associated with 6-hour average wind speed along the axis of the Severn River. Assuming measured and modeled currents are in phase, more positive values with winds from SE indicate measured currents over-represent ebb or modeled currents overestimate flood. More negative values with winds from NW indicate that measured currents over-represent flood or modeled currents overestimate ebb (**Fig. 4c**). Results show that sustained wind speed and direction relative to the axis of the Severn River influences WLs and suggest that inertial effects associated with higher (or lower) WLs during flooding events influences tidal current response in the Severn River.

The Severn River Delft3D FM model developed by Brennan (2022) accurately predicts WLs at USNA under normal and coastal flooding conditions observed in this study. The model does a good job at predicting tidal current response near USNA but could be improved by including sustained wind forcing prior to moderate and major flooding events.

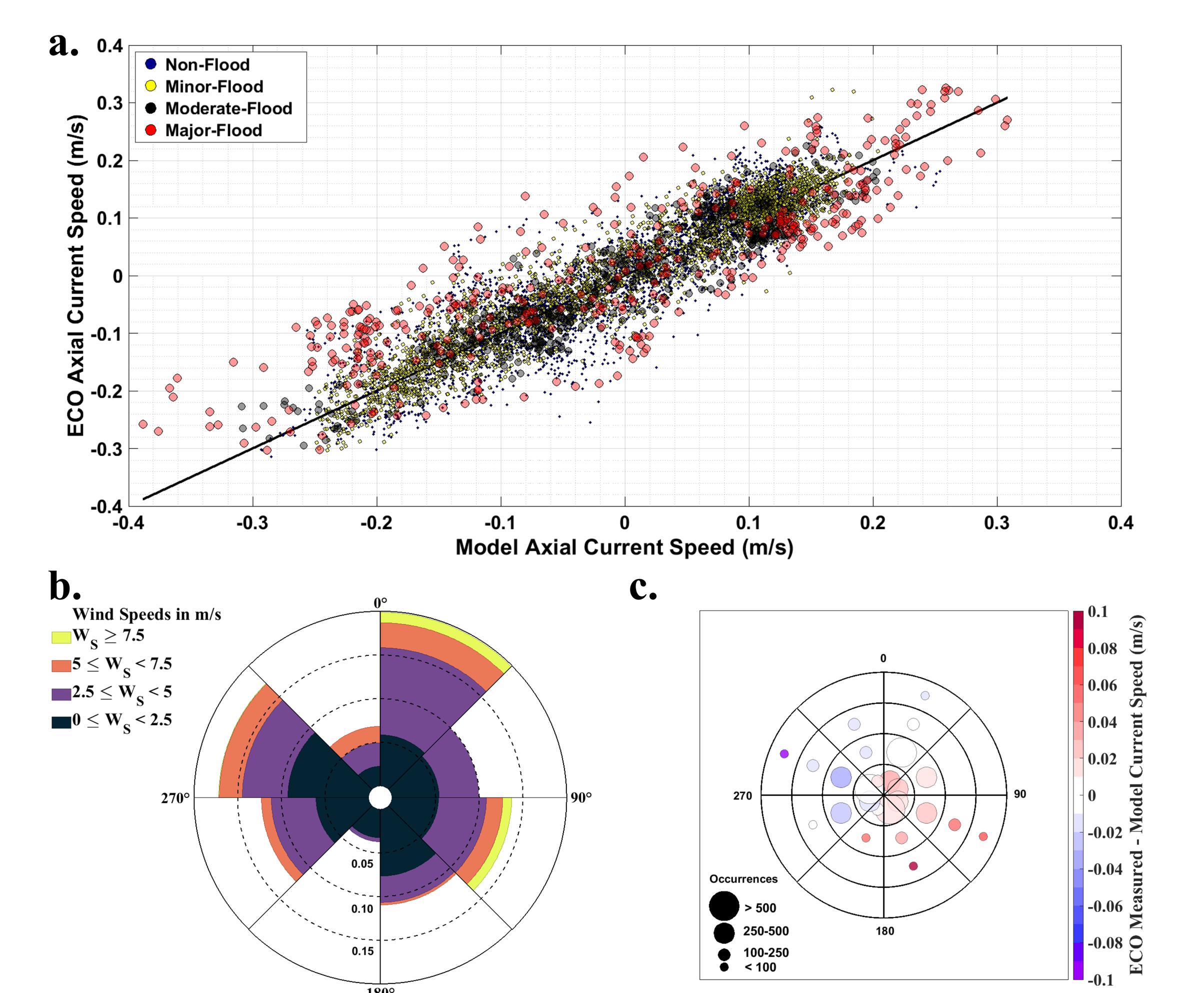

Figure 4. (**a**) Scatterplot of all ECO measured axial currents vs. modeled axial currents with values during minor, moderate, and major flooding highlighted; (**b**) histogram of wind speed and direction during the study averaged by sector (true degrees from); and (**c**) histogram of ECO measured axial currents - modeled axial current plotted against sectors for 6-hour averaged wind speed and direction.

References: Velásquez-Montoya (2023), *USNA;* Brennan (2022), *NPS*; Davies et al. (2022), *Earth Interactions* 26