Coastal Texas Protection and Restoration Feasibility Study
Final Feasibility Report

Appendix D – Annex 6:

ERDC Letter Report Summarizing the Galveston Bay Larval Transport Study

August 2021

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DEPARTMENT OF THE ARMY
U.S. ARMY CORPS OF ENGINEERS, ENGINEER RESEARCH AND DEVELOPMENT CENTER
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VICKSBURG, MISSISSIPPI 39180-6199

CEERD-HFC 10 August 2020

MEMORANDUM FOR Commander, U.S. Army Corps of Engineers, Galveston District (ATTN: Mr. Jeff Pinsky), 2000 Fort Point Rd, Galveston, TX 77550

SUBJECT: Letter Report Summarizing the Galveston Bay Larval Transport Study

1. The enclosed Letter Report (ERDC/CHL LR-20-9) details the application of the Adaptive Hydraulics (AdH) model and the Particle Tracking Model (PTM) to determine the impact of proposed storm surge protection measures at Galveston Bay, Texas. Although the additional structures will provide storm surge protection for the nearby population, the potential impact to the diverse marine life within Galveston Bay must also be considered. The AdH model was utilized to develop hydrodynamic conditions for initial analyses and input into PTM. Hydrodynamic results show the structures will change the flow speeds and patterns at the barriers but will not greatly impact the tidal prism. The PTM was used to simulate the transport of particles with associated characteristic transport behaviors attributed to local larval marine species. Results of the time series of recruitment and recruitment rate for the with and without project conditions are used to investigate the potential impact of the structures on larval transport. Recruitment analyses show similarities between the recruitment with current conditions and the predictive conditions with the proposed storm surge protection measure.

2. If you have questions or comments, please email the Letter Report's main author, Dr. Tahirih Lackey at Tahirih.C.Lackey@usace.army.mil or by phone at 601-634-3552.

Encl

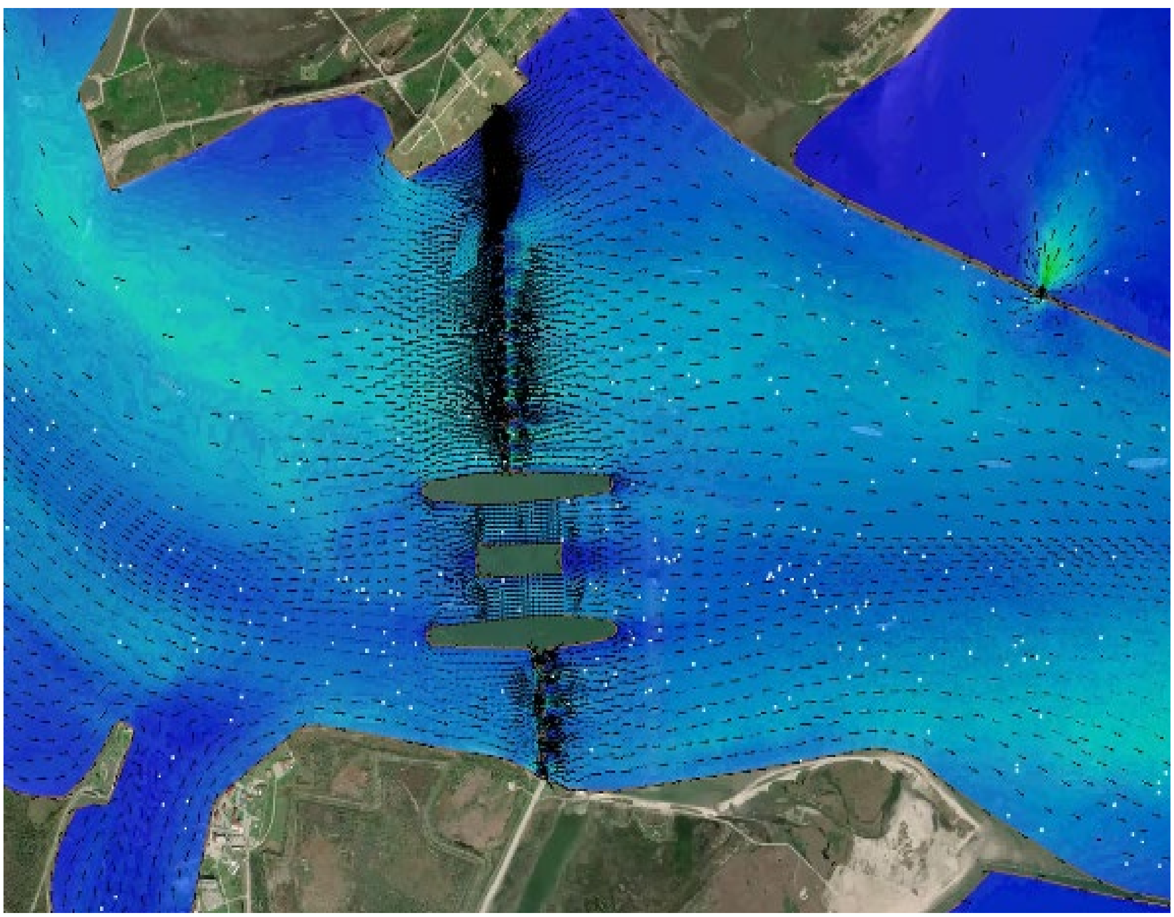
TY V. WAMSLEY, PhD, SES
Director

ERDC/Coastal and Hydraulics Laboratory

Galveston Bay Larval Transport Study

Tahirih Lackey and Jennifer McAlpin

August 2020



ERDC/CHL LR-20-9
August 2020

Galveston Bay Larval Transport Study

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Final Letter Report

Prepared for U.S. Army Corps of Engineers, Galveston District
Galveston, TX 77553-1229

Abstract: Galveston Bay is the seventh largest estuary in the United States, encompassing major Ports which promote significant economic progress in the region. Currently proposed storm surge protection measures within the area are being investigated. Navigation capacity must be maintained within Galveston Bay while providing storm surge protection for the impacted population. In addition, the potential impact to the diverse marine life within Galveston Bay must also be considered. The US Army Engineer District, Galveston (SWG) requested the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to perform particle tracking analyses to determine impacts on the recruitment of larval species due to proposed storm surge protection measures at the Bolivar Inlet. The 3D Adaptive Hydraulics Model was utilized to model circulation and assess the impacts to salinity, currents, and water surface elevation. The Particle Tracking Model (PTM), a Lagrangian model, is used to simulate the transport of particles with associated characteristic transport behaviors attributed to local larval marine species. Recruitment analyses resulting from PTM simulations show similarities between the current conditions and the predictive conditions with the proposed storm surge protection measures.

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1 Introduction

Background

Since the early 1800s, vessels have transited Galveston Bay both to and from Galveston and Houston (Galveston Bay Estuary Program 2002). Galveston Bay is a tidal estuary such that the effect of the tide on the water surface elevation is observed from the Gulf of Mexico to locations near Houston, TX. The Houston Ship Channel (HSC) is a deep-draft navigation channel that allows for vessel passage from the Gulf to the city of Houston, approximately 53 miles upstream. Given the large volume of vessel traffic along the HSC, any modifications to the channel dimensions or design must not adversely affect navigation. Figure 1-1 shows the HSC as it passes through Galveston Bay from its entrance at Bolivar Roads to the Port of Houston.

Figure 1-1. HSC area map.

The HSC entrance at Bolivar Roads is a critical pathway for navigation but also a means for storm surge to propagate into the bays, up the HSC and into the urban areas from Galveston to Houston, TX. Storm surge protection measures are being considered for areas surrounding and along the HSC. These alternatives allow for closing the waterway for some period to prevent storm surge from moving inland. Several proposed storm surge barrier alternatives were tested in a validated hydrodynamic, salinity and sediment transport model (McAlpin et al., 2019 a and b).

Objective

In 2016, the US Army Engineer District, Galveston (SWG) requested the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to perform hydrodynamic and salinity transport modeling of proposed storm surge protection measures (see Figure 1-2). The modeling results are necessary to provide data for hydrodynamic and salinity analysis as well as ecological models to determine impacts on aquatic habitat. The model results of project year zero (2035) and project year 50 (2085) with and without project results are documented in McAlpin et al. (2019 a and b). Particle Tracking Model (PTM) analyses are now requested to study the project's impact on the behavior of larval species. A modified barrier is proposed as well, requiring additional hydrodynamic and salinity numerical modeling.

Figure 1-2. Tentatively Selected Plan - Proposed Coastal Protection (figure from SWG).

Approach

The previously developed and validated 3D Adaptive Hydraulics (AdH) model was modified to represent the adjusted storm surge barrier structure which will be discussed in Chapter 2. Although the base condition (present without project condition) was simulated previously (as documented in McAlpin et al. 2019b) it will be re-run for these analyses for consistency. The base condition and the alternative are run for 2 years. The first year is a spin up period to obtain an accurate initial salinity field and the second year is used for all analyses. The model development and boundary condition definitions for the hydrodynamic, salinity, and sediment transport model as well as model calibration/validation to water surface elevation, velocity, salinity, and HSC dredge volumes are documented in McAlpin et al. (2019a).

A five-week period was extracted from the second year of the AdH simulation during the months of February and March. The hydrodynamic results at 30-minute intervals provide input to the PTM model. This model tracks particles that are given characteristic transport behaviors to mimic transport of larval species representative to the area. Recruitment analysis resulting from the PTM simulations is used to determine the impact of the proposed structures.

2 Plan Alternative

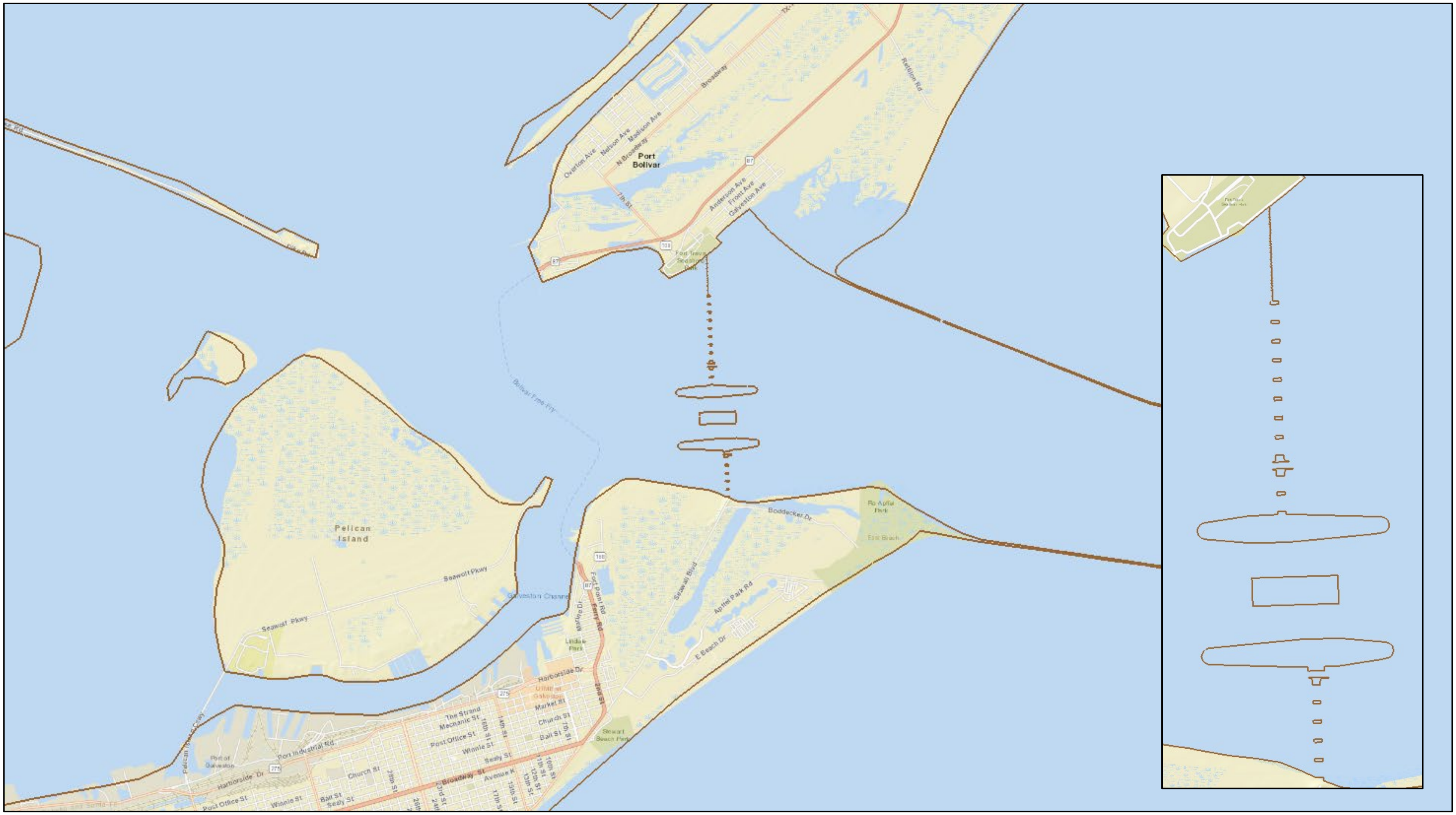
The plan alternative includes the geometric modifications to the system, defined as *project*, as well as the input conditions for the present project year zero (2035). No future conditions were simulated.

Project Modifications

SWG previously developed several potential storm surge protection plans. These plans were analyzed for cost/benefit based on construction, mitigation for habitat impacts, and other factors. The final Tentatively Selected Plan (TSP) analyzed with the AdH model includes a beach and dune system along Bolivar Peninsula and Galveston Island, improvements to the Galveston seawall, a ring barrier around the city of Galveston, and several gate closure structures – across the HSC at Bolivar Roads, High Island, Offatts Bayou, Dickinson Bayou, and Clear Creek. Figure 1-2 shows the initial TSP. Based on stakeholder inputs, modifications are made to this TSP. SWG requested that the modified TSP, defined as (2019 present with project) *2019PWP*, should be used for the PTM analysis and evaluate impacts on salinity and velocity.

In the revised TSP, the surge barrier system at Bolivar Roads includes two, 650 ft wide, -60 ft sill elevation navigation gates at the ship channel. Two additional 125 ft wide, -40 ft sector gates along with 15, 300 ft wide vertical lift gates (7 having a -40 ft sill elevation and 8 having a -20 ft sill elevation) lie to the north and south of the ship channel. The northernmost section of the barrier consists of 16 shallow water environmental gates, each with 6 openings 16 ft wide with a -5 ft sill elevation. All elevations are referenced to Mean Lower Low Water (MLLW). Figure 2-1 shows the surge barrier system defined as the 2019PWP alternative.

Figure 2-1. Modified structure (2019PWP) to be included in the AdH model domain.



Input Conditions

Input conditions include freshwater river inflows, tide elevation, ocean salinity, and wind. All model input conditions match those for the present condition as referenced in McAlpin et al. (2019b). No sediment was included in these simulations.

For this project, the 2010 validation year was determined suitable as a base or starting point for the year zero (present – 2035). (For details of the 2010 model boundary conditions, see McAlpin et al. (2019a)). The tidal water surface elevation is the only model input that will vary from the 2010 base condition as it is modified to account for intermediate sea level rise at 2035 (0.49 ft). All simulations are made for a 2-year period with the first year-long simulation serving to generate an accurate initial salinity field.

3 Larval fish transport methodology and model input conditions

Larval fish transport was modeled using the Particle Tracking Model (PTM) (MacDonald et al. 2006, Lackey and Smith 2008, Tate et al. 2010, Gailani et al. 2016). PTM is a Lagrangian particle tracker designed to allow the user to simulate particle transport processes. PTM has been developed for applications to coastal projects which focus on a range of particle types: water particles, sediment, and biological particles. The model contains algorithms that appropriately represent transport, settling, deposition, mixing, and resuspension processes in nearshore wave/current conditions (McDonald et al 2006, King and Lackey 2015).

PTM uses hydrodynamics developed through other models and input directly to PTM as forcing functions. In this work, as has been described in detail, AdH hydrodynamic output was used as model input for PTM. A five-week period was extracted from the year-long AdH simulation during the months of February and March. The need to select a five to six-week period was discussed with state and federal resource agencies (Agency Meeting, 24 June 2019). The five-week period during the months of February and March was chosen to capture a time when several commercially important species that exhibit various larval behaviors migrate into the Galveston Bay system.

Behaviors

PTM models larval marine species particles as neutrally buoyant (passive particles) with added characteristic behaviors. Neutrally buoyant particles move based solely on the flow field. The particle velocity is interpolated from the hydrodynamic velocity at the surrounding nodes in the computational grid. The particle is then transported over a distance based on the equation

$$\overrightarrow{X_{n+1}} = \overrightarrow{X_n} + \Delta t * \overrightarrow{V_n} \qquad \text{Eq (1)}$$

The new location of the particle X is determined based on the previous location and an added distance dependent on the interpolated velocity and the time step. The characteristic behaviors are added either to a component of the velocity vector V or added as a restriction to the location of the particle X.

Six larval marine species characteristic behaviors were modeled in this work. These behaviors correspond to the suspected dominant transport characteristic behavior of a variety of marine species native to the area. These behaviors were derived from the field data provided in Hartman et al. (1987) for the Keith Lake Fish Pass Larval Transport study

1. Tidal Lateral (move to center of channel during incoming tide)

2. Diel Vertical (move up during day)

3. Tidal Vertical (move up during incoming tide)

4. Bottom movers (particles remain 1 m from bottom)

5. Surface movers (particles remain 1 m from top)

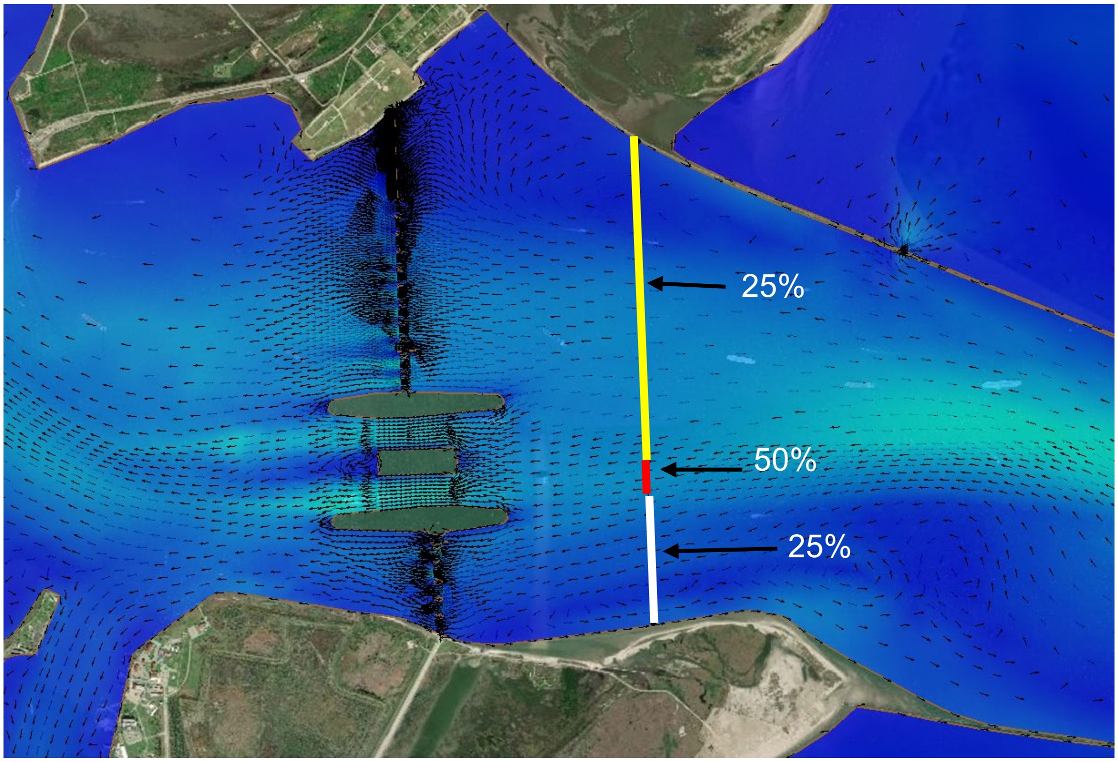
6. Passive (neutrally buoyant particles)

In each behavior that requires the particle to move at a specific swimming speed towards an area, the velocity that particles move in these simulations was 0.01 cm/s determined based on interagency team consultation.

Larval Initial Release

Particles are initiated at a location upstream on the gulf-side of the planned gate structure (Figure 3-1). Approximately 7400 particles are released over the five-week simulation. Fifty percent of the particles are released uniformly across the channel in the section shown in red. Twenty-five percent of the particles are released on either side of the channel in the white and yellow sections respectively. The particles are initiated in the upper one meter of the water column.

Figure 3-1. Initial release location and percentage of total particles.



Recruitment of larvae

Larval recruitment is defined as the date/time at which particles reach one of four designated recruitment areas (Figure 3-2) defined by the inter-agency group. During transport, once particles reach a recruitment area, the particle identification, recruitment location, and date/time of recruitment are denoted by the PTM model. This information is later post-processed to determine statistics and time series of recruitment.

The recruitment areas were chosen to represent larval recruitment to three sections of Galveston Bay known to contain important nursery habitats for marine species. Those sections of Galveston Bay are East Bay, West Bay, and Trinity Bay. A fourth recruitment area was added to ensure that particles that were created in the channel and were pushed offshore would not be counted if they entered East Bay through Rollover Pass which is now closed. These recruitment areas were agreed upon and refined in an inter-agency meeting held on 24 June 2019.

Figure 3-2. Recruitment areas (defined by the interagency group).

Model Limitations and Assumptions

Larval transport utilizing PTM has been previously performed and published (Tate et al. 2010) for transport of larval fish into Lake Pontchartrain. The six behaviors used in this simulation are consistent with this previous work. It is important to note that this method for understanding larval fish transport is simplistic in the fact that it focuses on modeling "characteristic" transport. That is, the particle transport method included in this work does not suggest that it contains all the intricate behaviors of an alive biological larvae. However, the focus is on simple characteristic behaviors, defined by experts, which potentially dominate transport of larvae. In addition it should be noted that the behavior for specific species may change based on the lifecycles of individual species. Therefore, in this work the focus is applied to the impact of the behavior on transport of particles that have characteristic behaviors. Extrapolation of the impact of the structures to the population of a specific species is not within the scope of work of this project.

4 Hydrodynamic Model Results

The two alternatives – present without project (PWOP) and present with project (2019PWP) – were simulated using the 3D AdH model as stated in the previous chapters. Present condition is referenced at year 2035. The results include changes in salinity, velocity, and water level throughout the model domain under the alternative conditions. The results provided in this section are for a one-year analysis period.

Several locations were identified for specific analysis such as time history, percent less than, and maximum/minimum/average computations of salinity and velocity magnitude. These locations are also used to analyze tidal amplitude changes. These locations are shown in Figure 4-1 and labeled in Table 4-1. A subset of these locations, the circled points and the shaded rows in Table 4-1, are included in this report text. Analysis plots and images for all locations are included in the appendices.

Figure 4-1. Point analysis locations. Circled locations discussed in this section.

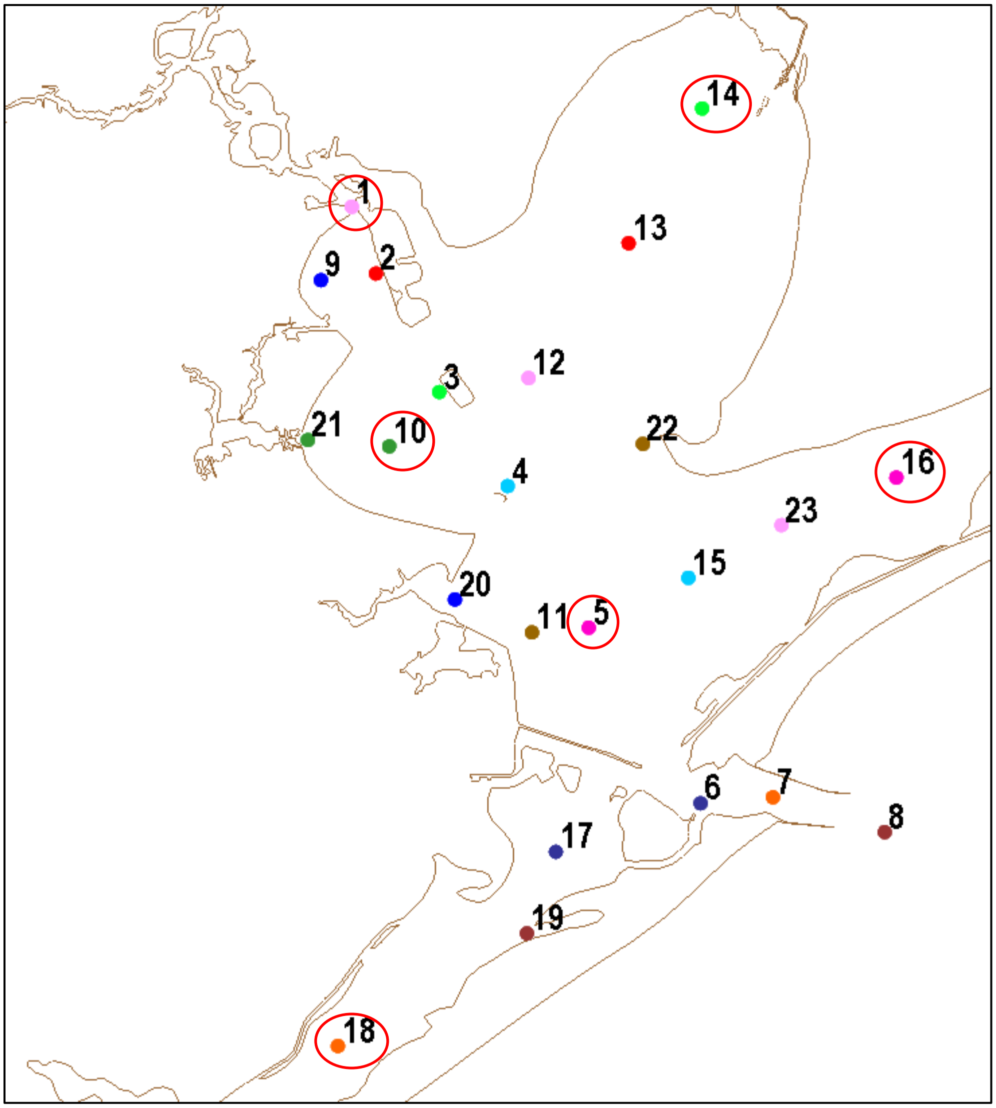


Table 4-1. Point analysis location names. Highlighted locations discussed in this section.

Point #	Name
1	HSC at Morgan's Point
2	HSC at Atkinson Island
3	HSC at Mid Bay Marsh
4	HSC at Red Fish Reef
5	HSC at Lower Galveston Bay
6	HSC at Bolivar Roads
7	HSC at Entrance
8	HSC at Gulf
9	Upper Galveston Bay 1
10	Upper Galveston Bay 2
11	Lower Galveston Bay
12	Lower Trinity Bay

Point #	Name
13	Mid Trinity Bay
14	Upper Trinity Bay
15	Western East Bay
16	Eastern East Bay
17	Eastern West Bay
18	Mid West Bay
19	Offatts Bayou
20	Dickinson
21	Clear Creek
22	Smith Point
23	Mid East Bay

Tidal Prism and Amplitude

Changes to the system geometry can impact the tidal exchange in a bay environment such as Galveston and Trinity Bays. The modified TSP alternative impacts the cross-sectional area of the entrance channel which has the potential to cause changes in the volume of flow being exchanged through the inlets. The tidal prism is the difference in water volume between high and low tide. This volume is computed over the analysis year and the average tidal prism is then determined. Table 4-2 shows the volume of the average tidal prism for each alternative as well as the percentage change in the with project alternative as compared to the without project alternative. This approach has been taken at several representative locations.

Results show that the reduction of tidal prism stands between 3% and 7%– indicating that the structures are restricting the flow in and out of the HSC at Bolivar Roads. This analysis assumes that only the structure at Bolivar Roads is in place; therefore, the reduction at the bayous is due to the restriction created by the large structure at Bolivar Roads.

Table 4-2. Average tidal prism volume for analysis year.

	2019PWP (m^3)	PWOP Re-Run (m^3)	2019PWP % change from PWOP
Bolivar Roads	509,068,923	526,009,862	-3.22
Offatts Bayou	1,211,965	1,261,998	-3.96
Dickinson Bayou	535,201	572,211	-6.47
Clear Creek	3,411,910	3,541,595	-3.66

The tidal amplitude is the change in the water level from low tide to high tide and vice versa. The tidal prism gives an overall impact on the water exchange whereas the tidal amplitude may vary at locations depending on changes in the flow patterns within the system and where the system modifications are made. Figure 4-2 and Table 4-3 show the percentage change between present with and without project alternatives for all locations shown in Figure 4-1.

The tidal amplitude comparisons between with and without project range between +3% and -6%. The Gulf of Mexico location shows unchanged tidal amplitudes and the HSC entrance location shows an increase in the with project amplitude – expected since the restriction in the flow area will force water to pile up on the Gulf side of the project. The greatest impact is at Bolivar Roads, which is the location closest to the project site on the bay side. All bay side locations show a decrease in the tidal amplitude for the project condition as compared to the without project.

Figure 4-2. Percentage change in tidal amplitude for 2019PWP from PWOP.

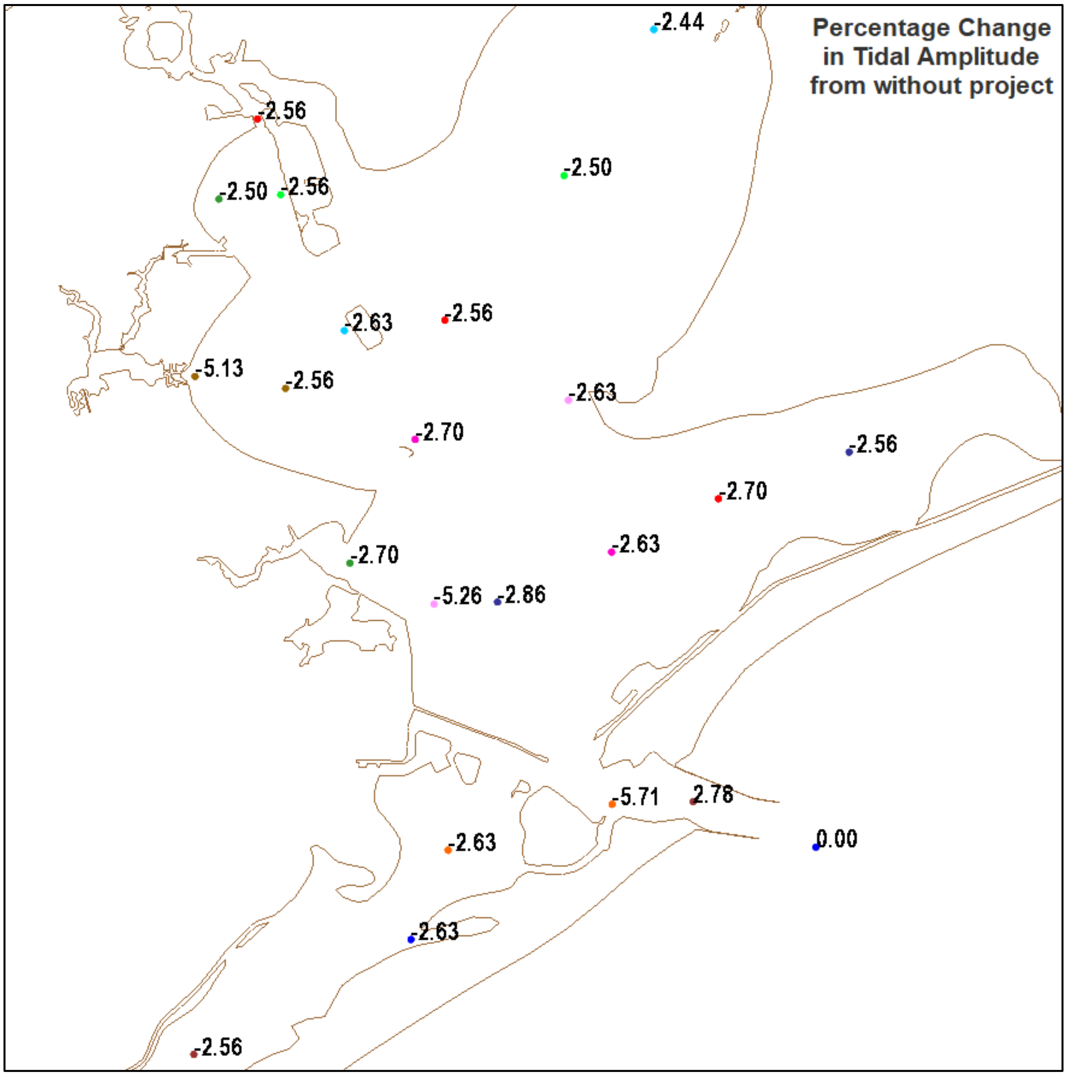


Table 4-3. Tidal amplitude and percent change from the without project alternatives.

	PWOP Rerun Amplitude (m)	2019PWP Amplitude (m)	2019PWP % change from without project
HSC at Morgan's Point	0.39	0.38	-2.56
HSC at Atkinson Island	0.39	0.38	-2.56
HSC at Mid Bay Marsh	0.39	0.37	-5.13
HSC at Red Fish Reef	0.37	0.36	-2.70
HSC at Lower Galveston Bay	0.35	0.34	-2.86
HSC at Bolivar Roads	0.35	0.33	-5.71
HSC at Entrance	0.36	0.37	2.78
HSC at Gulf	0.42	0.42	0.00
Upper Galveston Bay 1	0.4	0.39	-2.50
Upper Galveston Bay 2	0.39	0.38	-2.56
Lower Galveston Bay	0.38	0.36	-5.26
Lower Trinity Bay	0.39	0.38	-2.56
Mid Trinity Bay	0.4	0.39	-2.50
Upper Trinity Bay	0.41	0.4	-2.44
Western East Bay	0.38	0.37	-2.63
Eastern East Bay	0.39	0.38	-2.56
Eastern West Bay	0.38	0.37	-2.63
Mid West Bay	0.39	0.38	-2.56
Offatts Bayou	0.38	0.37	-2.63
Dickinson	0.37	0.36	-2.70
Clear Creek	0.39	0.37	-5.13
Smith Point	0.38	0.37	-2.63
Mid East Bay	0.37	0.36	-2.70

Salinity Point Analysis

Time history of salinity is shown for several points within the HSC and several in the bays. Also provided are plots showing the maximum, average, and minimum salinity at each location for the year-long analysis period. The salinity shown in the plots are bottom values which will be larger than or equal in magnitude to the surface values due to the density stratification of salt water. For all plots of salinity, present with project (2019PWP) is blue, present without project is orange (PWOP).

Additionally, percent less than plots are provided to show how the bottom salinity varies over the year-long analysis period. The maximum salinity value is given at 100% and the minimum value at 0%. The 50% salinity value indicates that the salinity is less than this value for 50% of the analysis time and greater than this value 50% of the time.

Figure 4-3 and Table 4-4 give the mean bottom salinity for the analysis locations as well as the change in the mean salinity due to the project conditions. Figure 4-4 through Figure 4-27 show the point salinity analysis at the six selected locations. The results for all 23 locations are provided in Appendix A: Salinity Point Analysis.

The variation in salinity between with and without project alternatives is fairly small for most locations over the simulation year – generally less than 2 ppt. The salinities are almost identical near the HSC entrance but begin to diverge further into the system at Mid Bay Marsh and Morgan’s Point. However, the change in the mean salinity between with and without project remains within 2 ppt. The maximum salinity comparisons between with and without project are slightly higher for some locations but still less than a 5 ppt difference. The time history of salinity includes dotted lines for 10 ppt and 15 ppt thresholds. The with project conditions generally maintain the same pattern of the salinity over time as the without project, but salinity does increase above these thresholds for short periods of time at some locations.

Figure 4-3. Change in mean bottom salinity from PWOP condition.

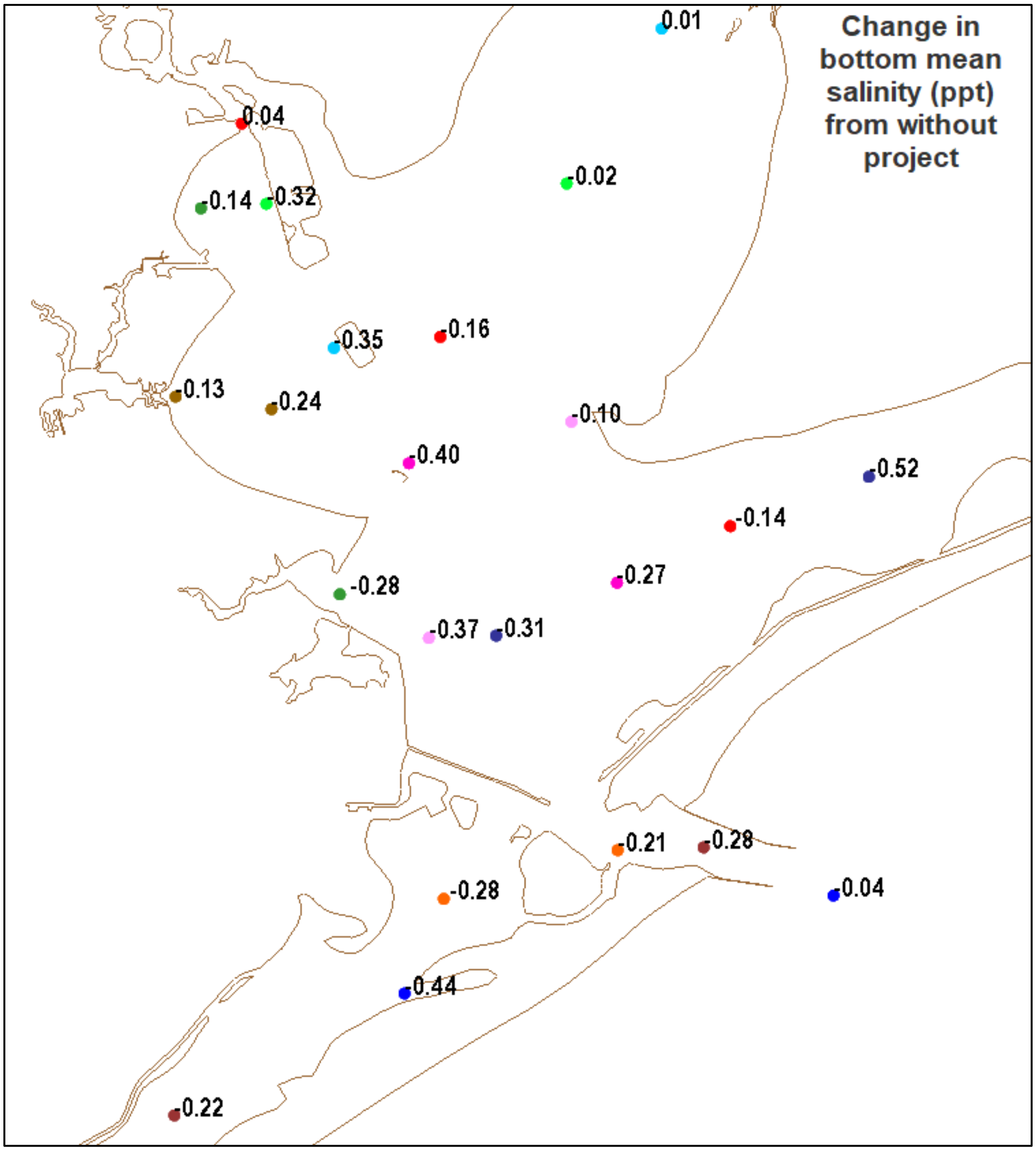


Table 4-4. Mean bottom salinity and absolute change from the without project alternative.

	PWOP Rerun Mean Bottom Salinity (ppt)	2019PWP Mean Bottom Salinity (ppt)	2019PWP change (ppt) from without project
HSC at Morgan's Point	21.04	21.07	0.04
HSC at Atkinson Island	22.18	21.86	-0.32
HSC at Mid Bay Marsh	23.67	23.32	-0.35
HSC at Red Fish Reef	25.38	24.98	-0.40
HSC at Lower Galveston Bay	26.79	26.48	-0.31
HSC at Bolivar Roads	27.66	27.45	-0.21
HSC at Entrance	28.24	27.96	-0.28
HSC at Gulf	29.98	29.94	-0.04
Upper Galveston Bay 1	17.84	17.70	-0.14
Upper Galveston Bay 2	18.70	18.46	-0.24
Lower Galveston Bay	18.00	17.62	-0.37
Lower Trinity Bay	14.99	14.82	-0.16
Mid Trinity Bay	9.46	9.45	-0.02
Upper Trinity Bay	3.22	3.24	0.01
Western East Bay	11.71	11.43	-0.27
Eastern East Bay	6.60	6.08	-0.52
Eastern West Bay	21.66	21.38	-0.28
Mid West Bay	21.17	20.95	-0.22
Offatts Bayou	21.64	21.20	-0.44
Dickinson	13.41	13.13	-0.28
Clear Creek	13.92	13.79	-0.13
Smith Point	7.38	7.28	-0.10
Mid East Bay	5.73	5.59	-0.14

Figure 4-4. Salinity time history at HSC at Morgan's Point.

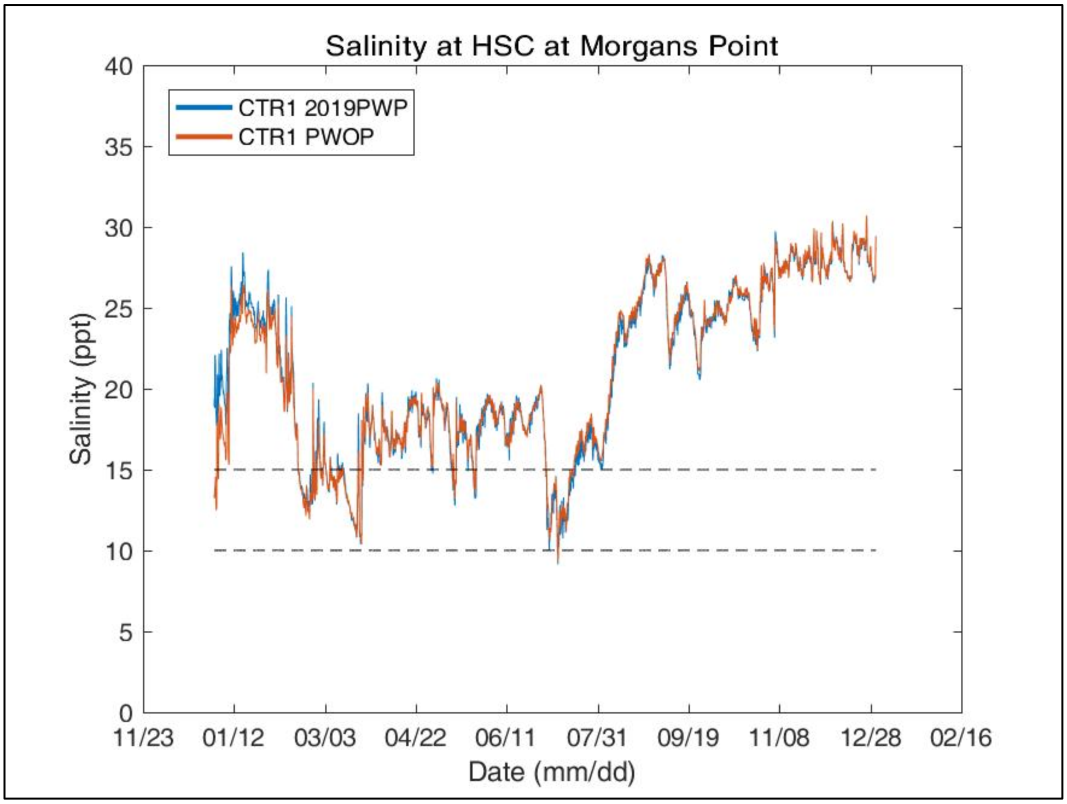


Figure 4-5. Maximum, mean, and minimum salinity at HSC at Morgan's Point.

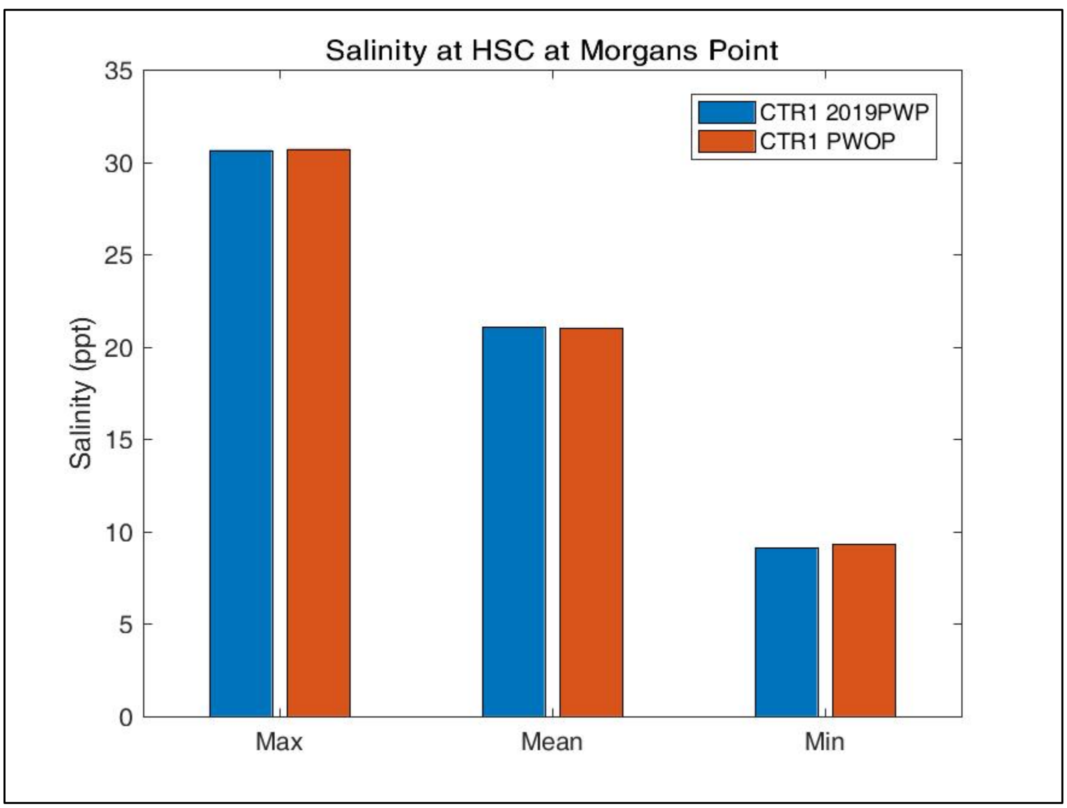


Figure 4-6. Percent less than salinity at HSC at Morgan's Point.

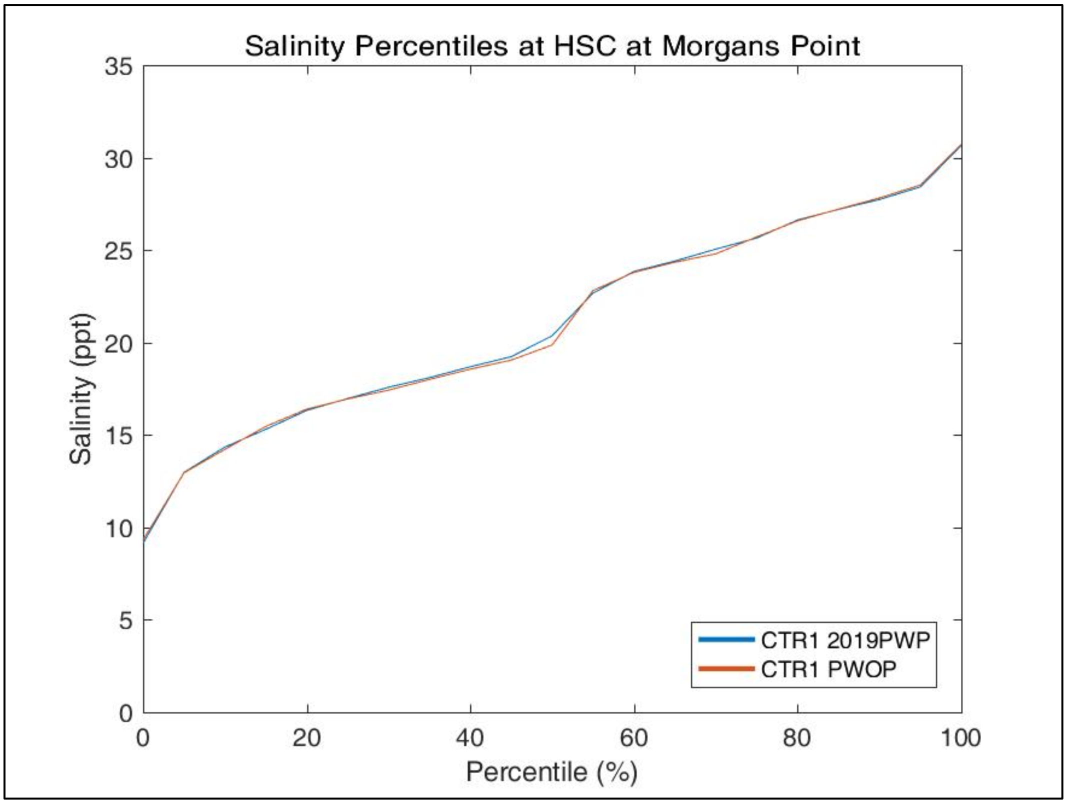


Figure 4-7. Vertical salinity profile at HSC at Morgan's Point.

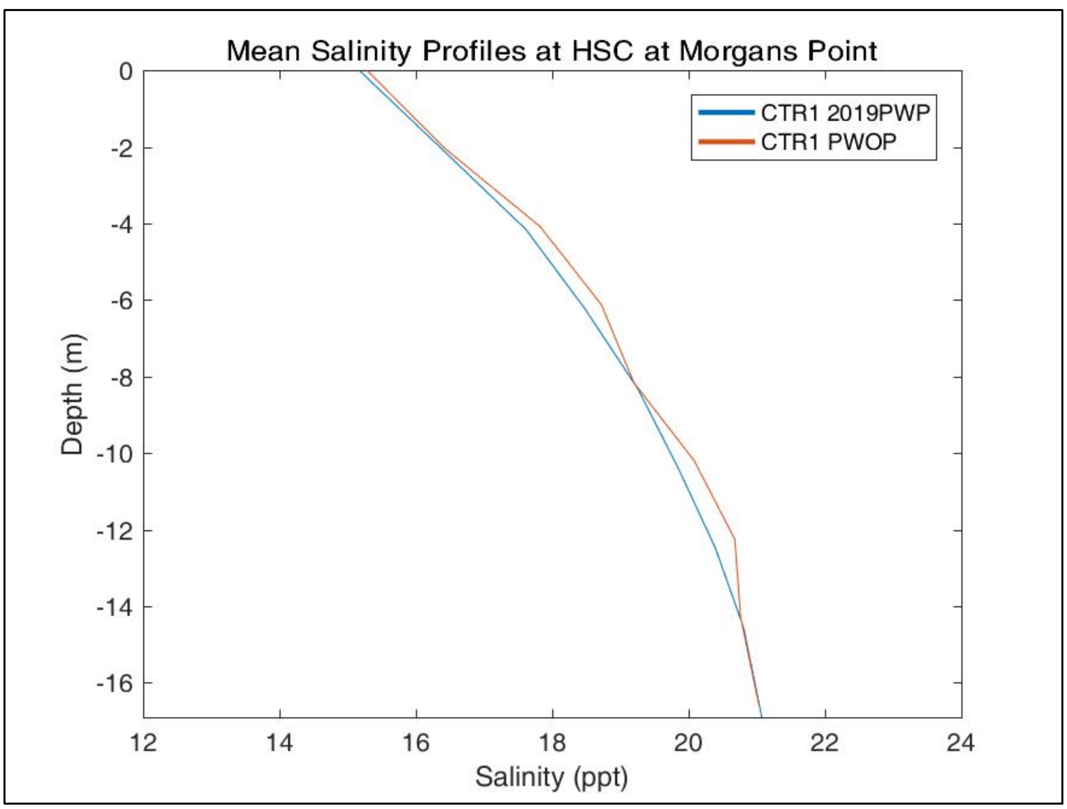


Figure 4-8. Salinity time history at HSC at Lower Galveston Bay.

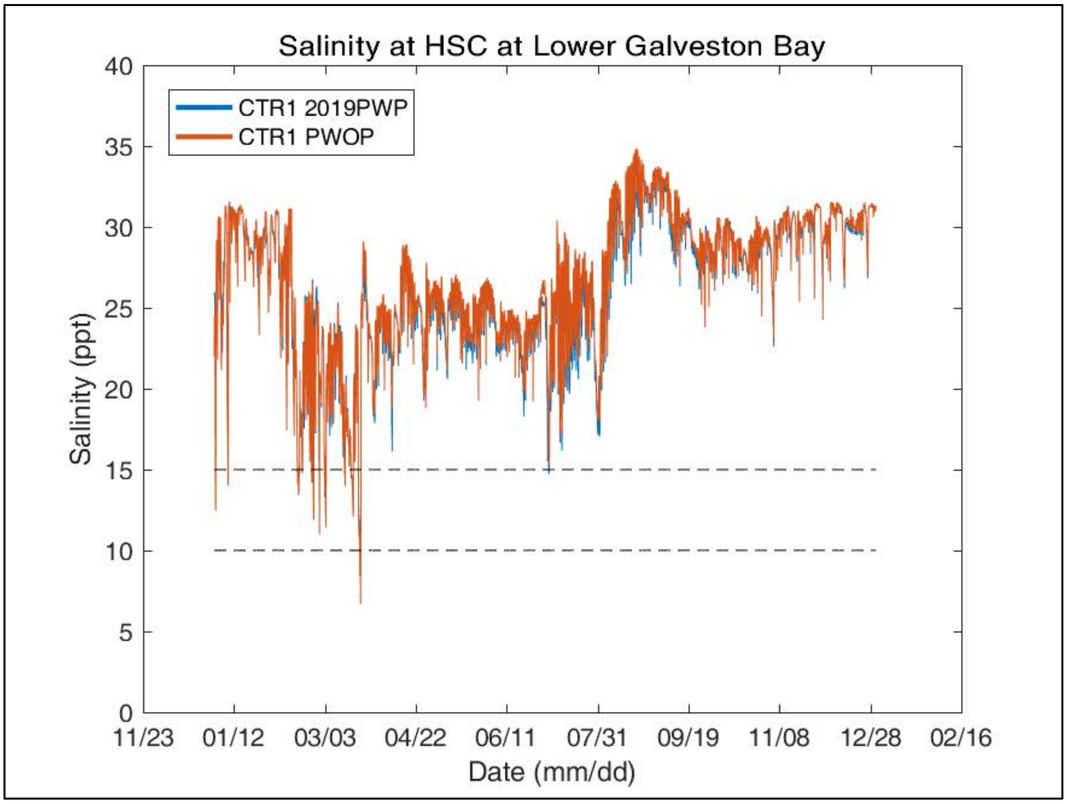


Figure 4-9. Maximum, mean, and minimum salinity at HSC at Lower Galveston Bay.

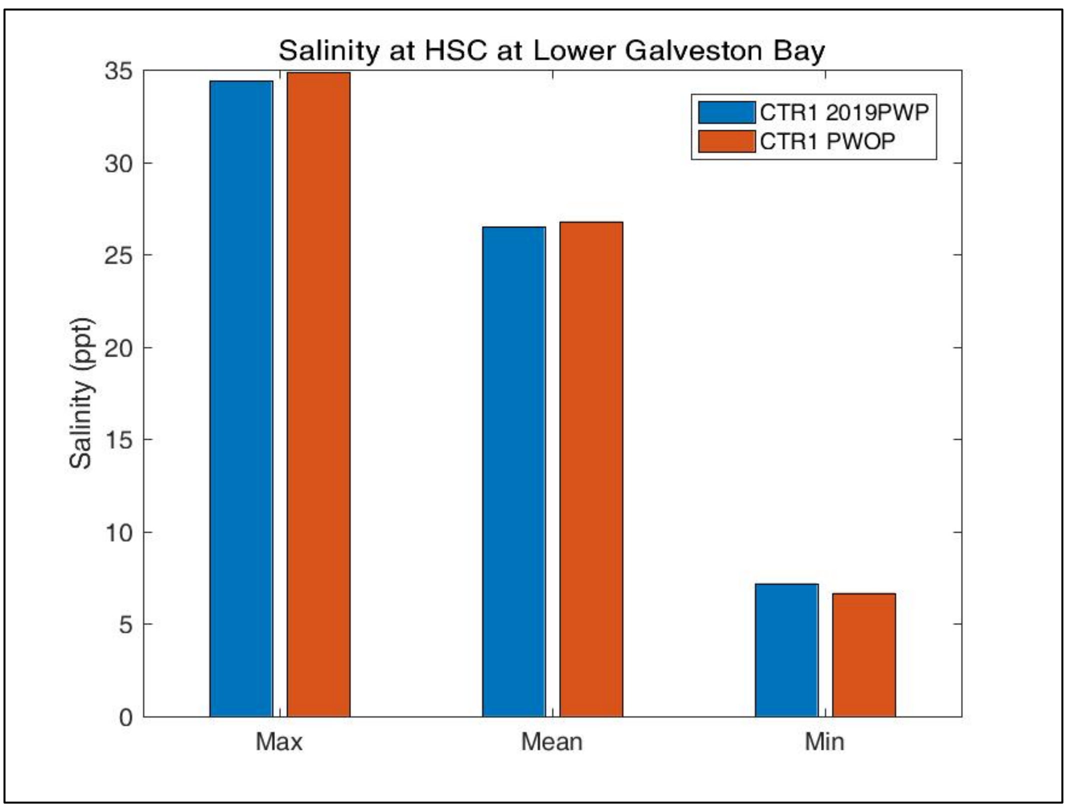


Figure 4-10. Percent less than salinity at HSC at Lower Galveston Bay.

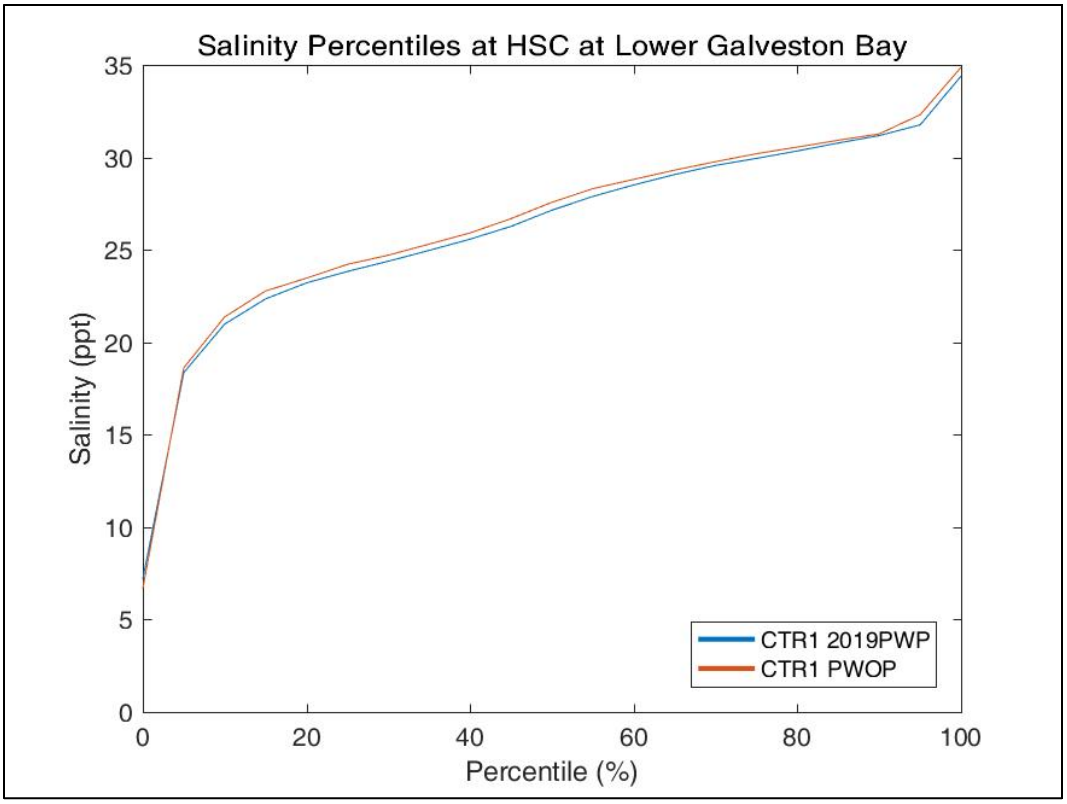


Figure 4-11. Vertical salinity profile at HSC at Lower Galveston Bay.

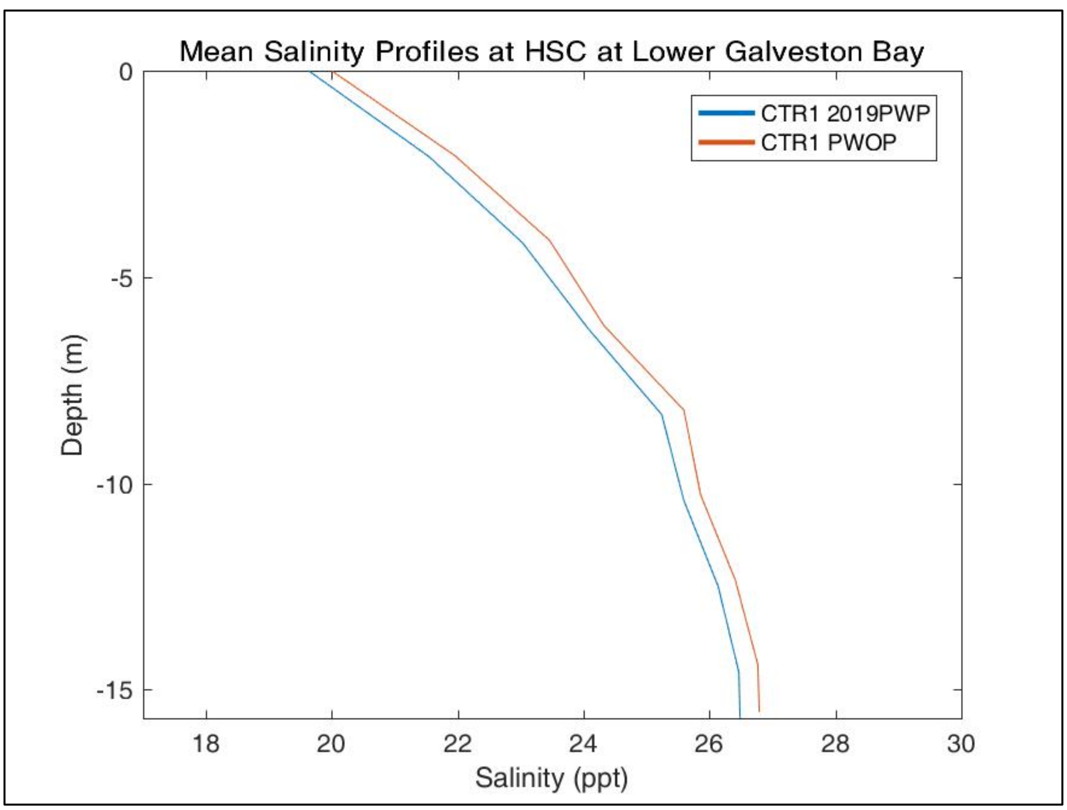


Figure 4-12. Salinity time history at Upper Galveston Bay 2.

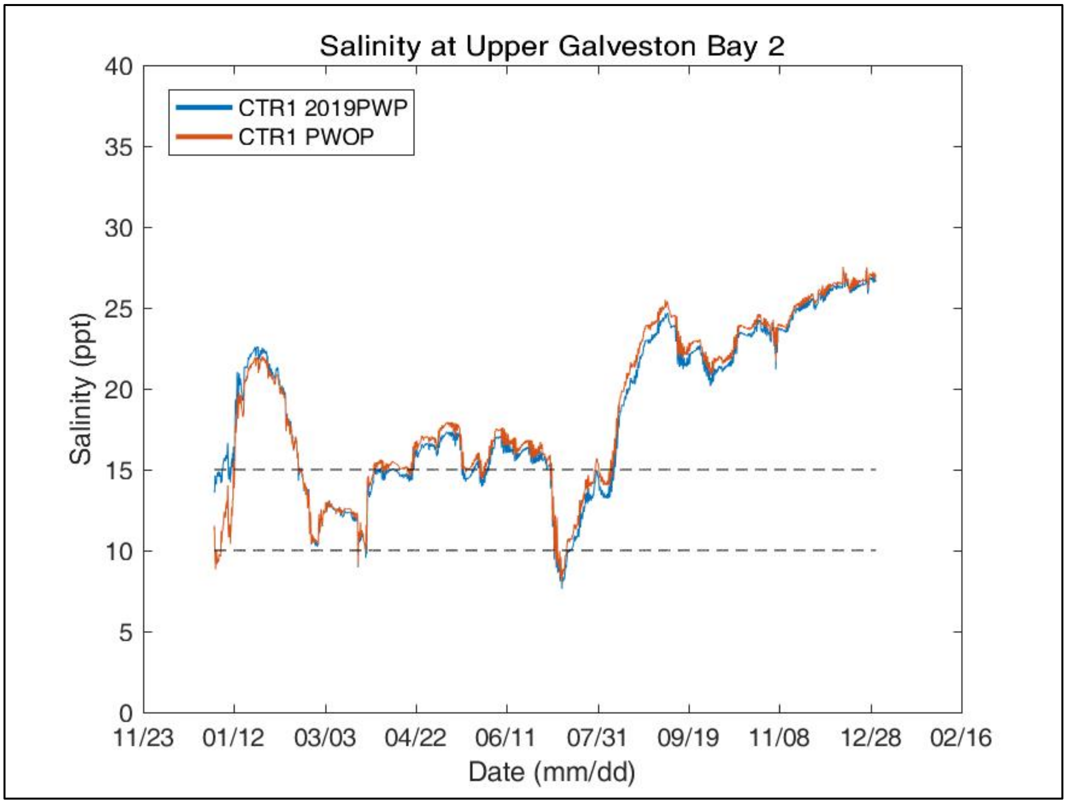


Figure 4-13. Maximum, mean, and minimum salinity at Upper Galveston Bay 2.

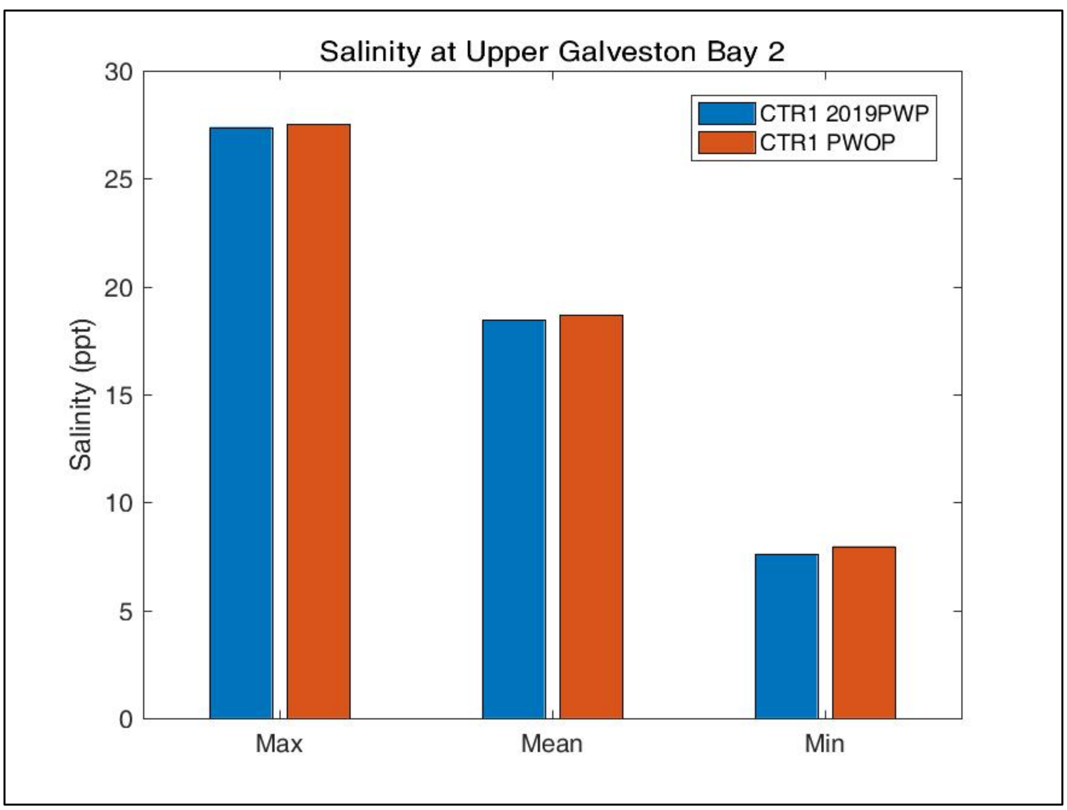


Figure 4-14. Percent less than salinity at Upper Galveston Bay 2.

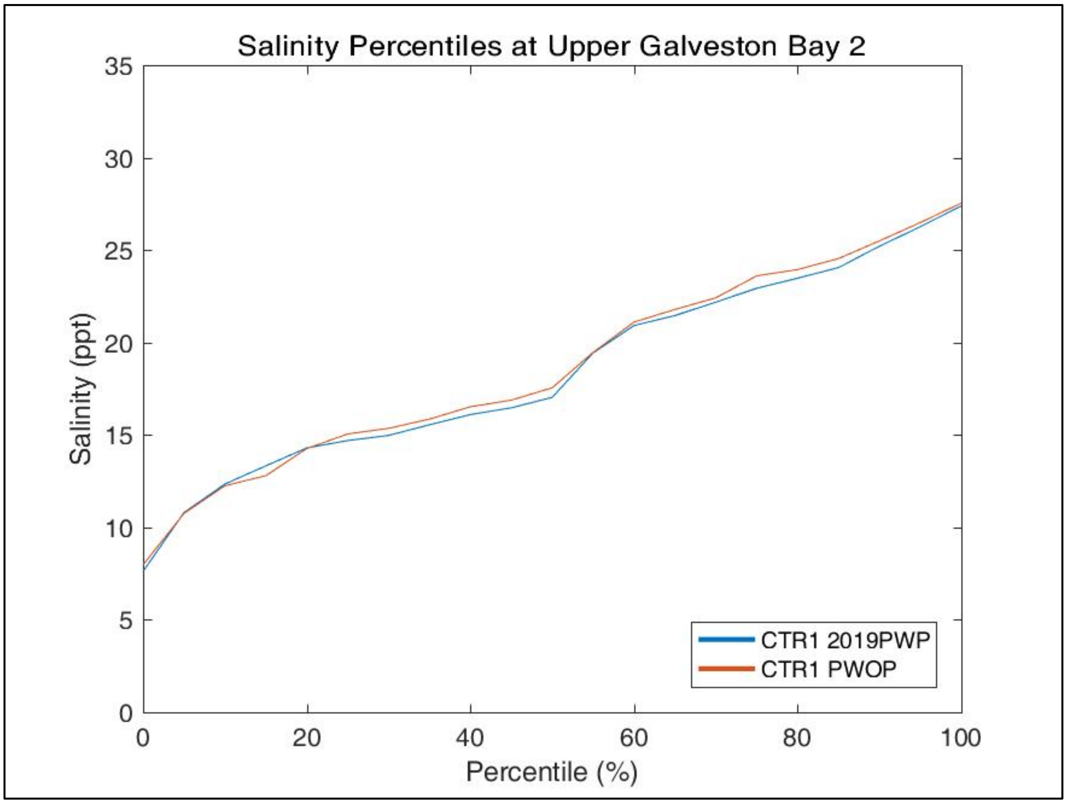


Figure 4-15. Vertical salinity profile at Upper Galveston Bay 2.

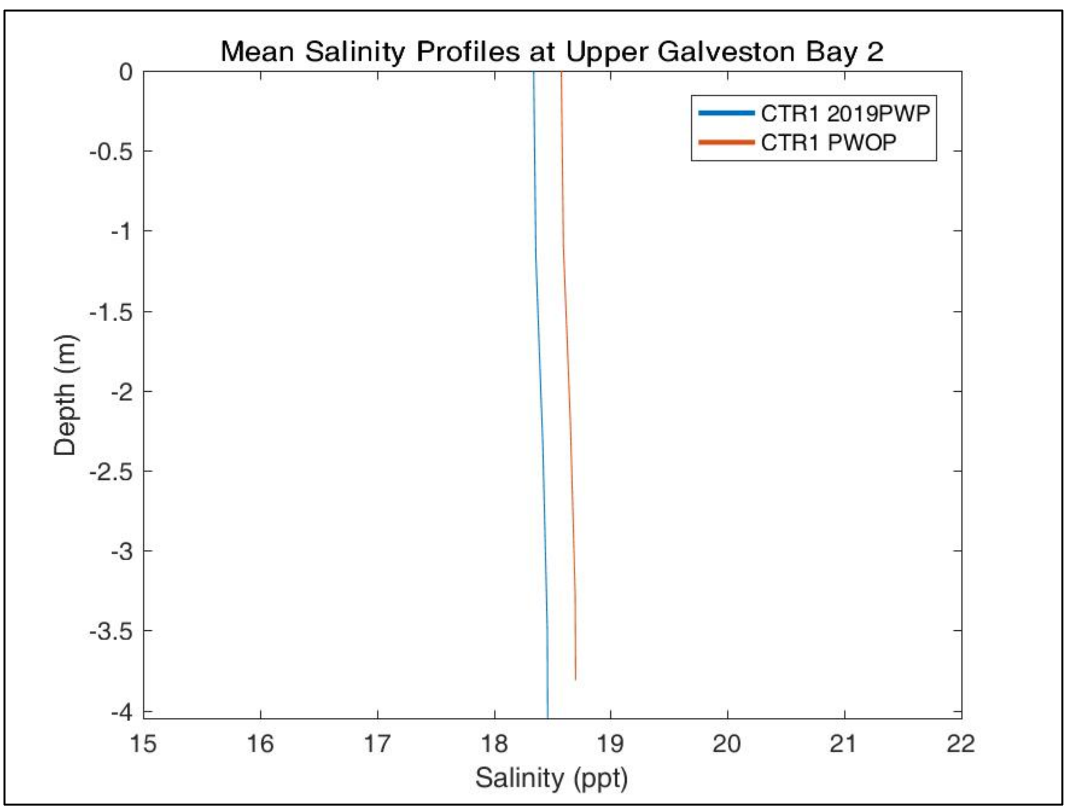


Figure 4-16. Salinity time history at Upper Trinity Bay.

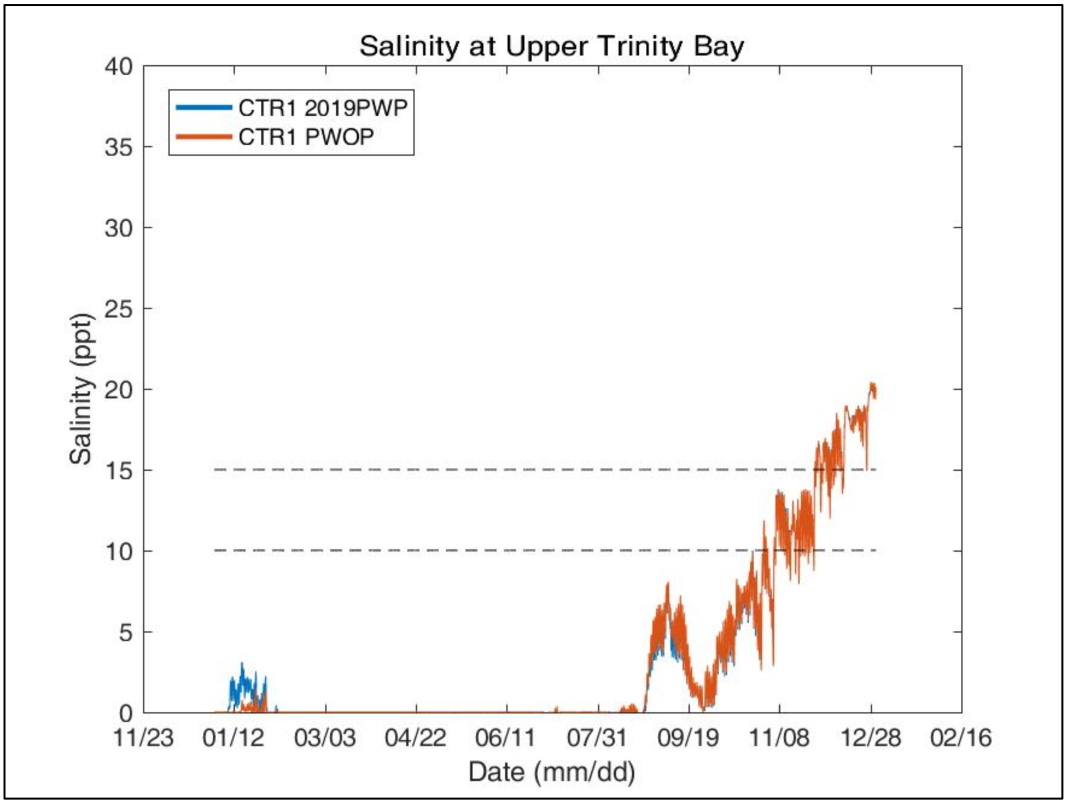


Figure 4-17. Maximum, mean, and minimum salinity at Upper Trinity Bay.

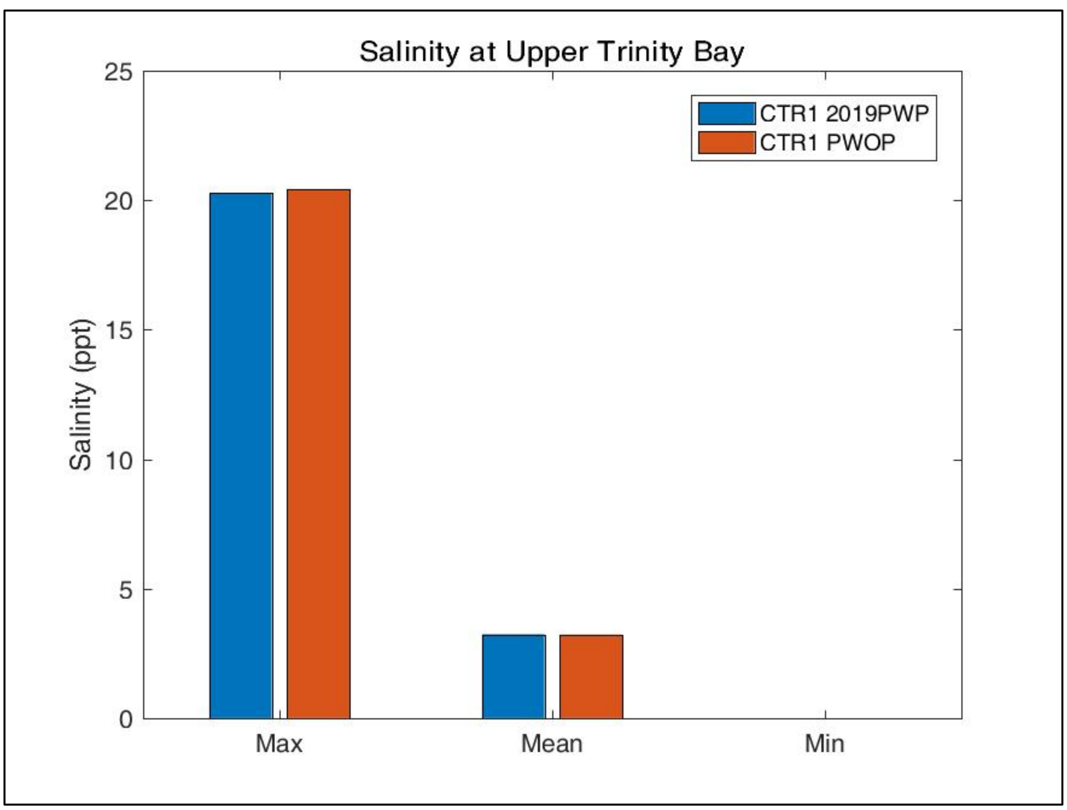


Figure 4-18. Percent less than salinity at Upper Trinity Bay.

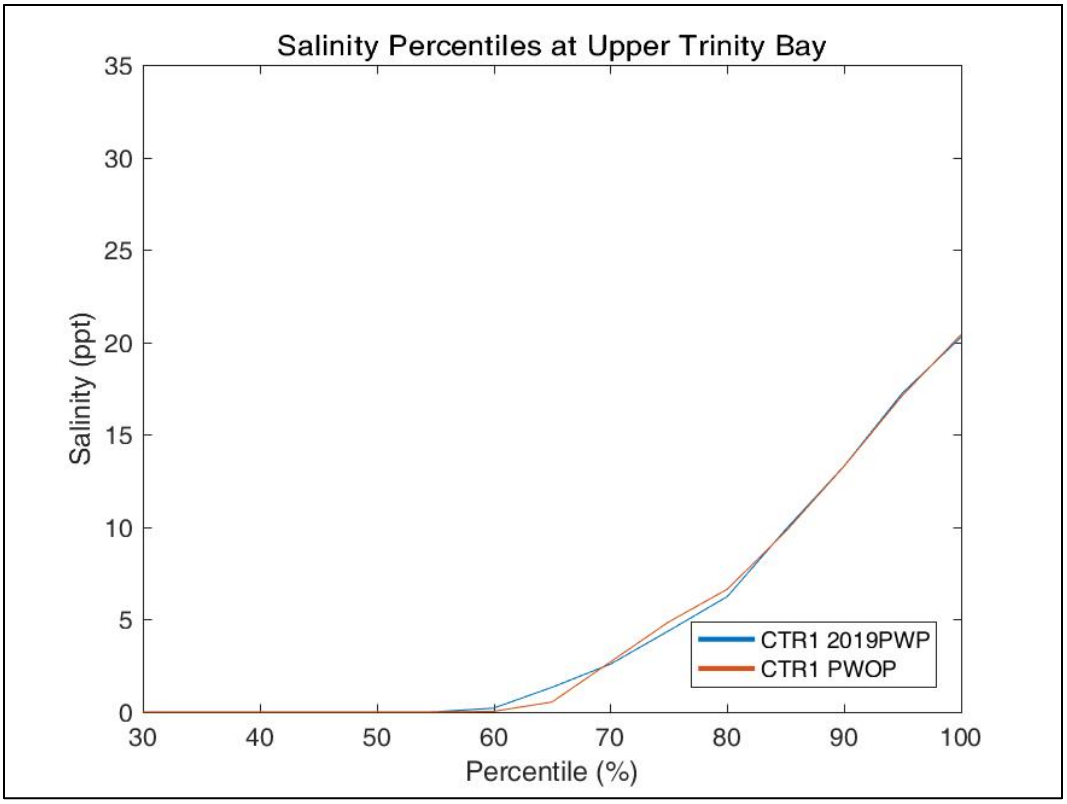


Figure 4-19. Vertical salinity profile at Upper Trinity Bay.

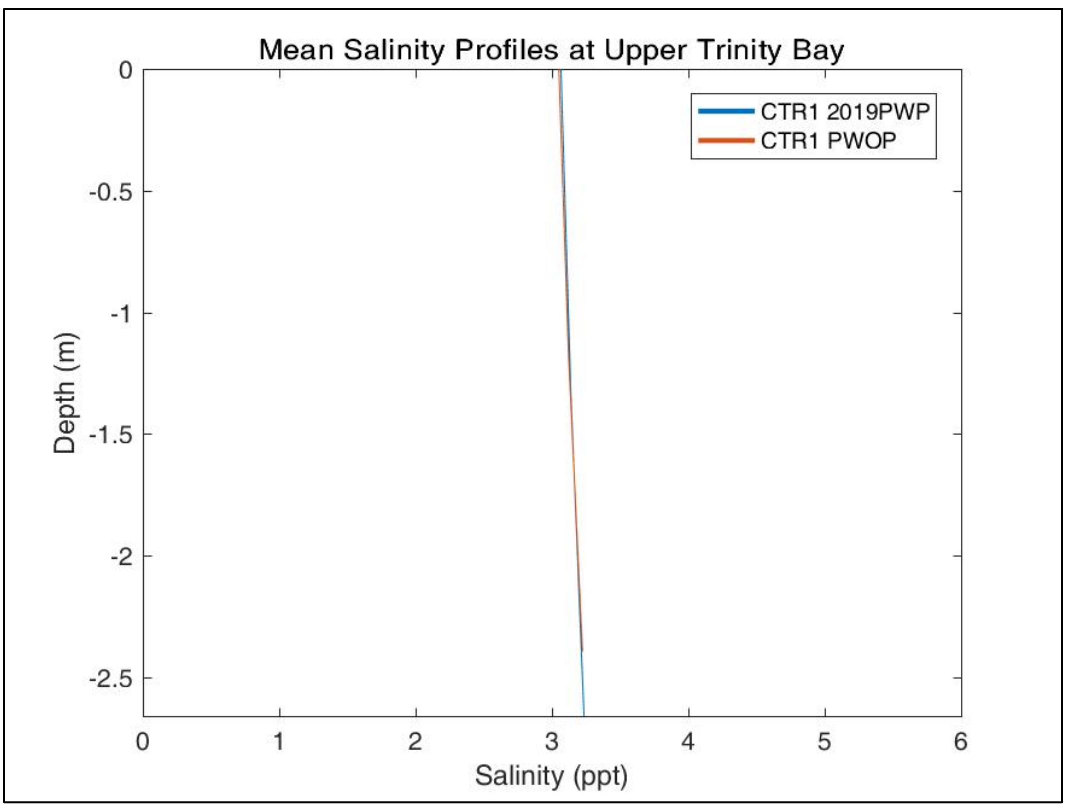


Figure 4-20. Salinity time history at Eastern East Bay.

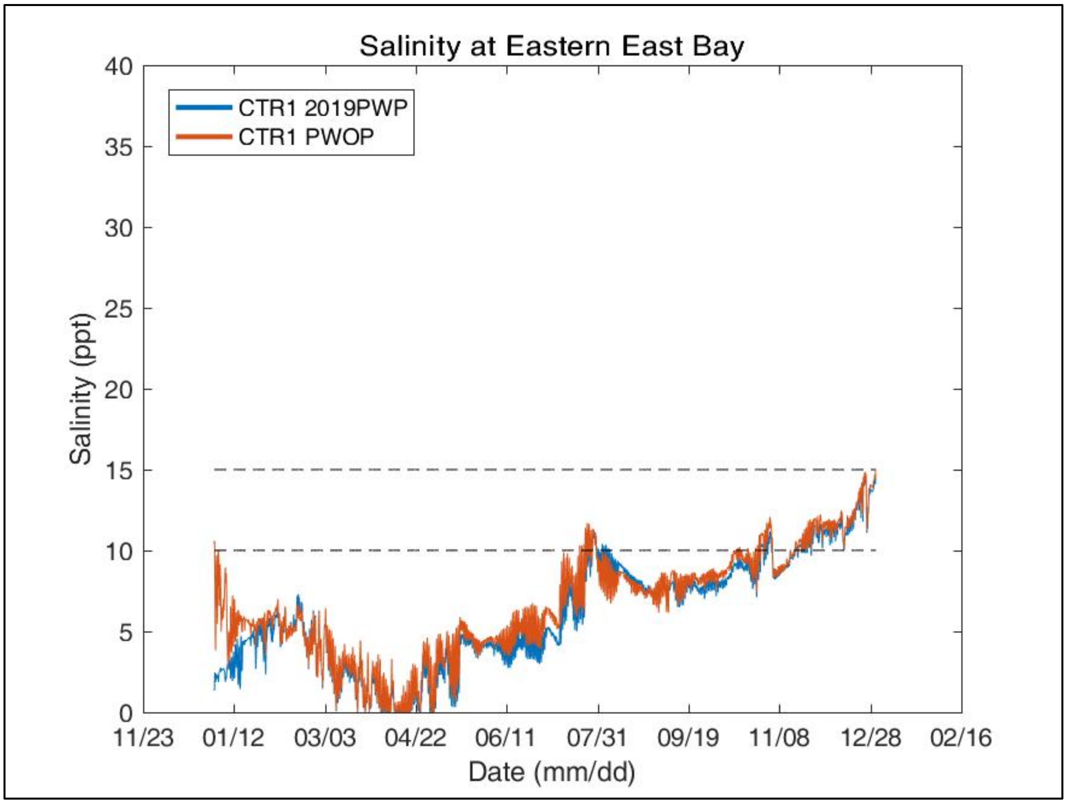


Figure 4-21. Maximum, mean, and minimum salinity at Eastern East Bay.

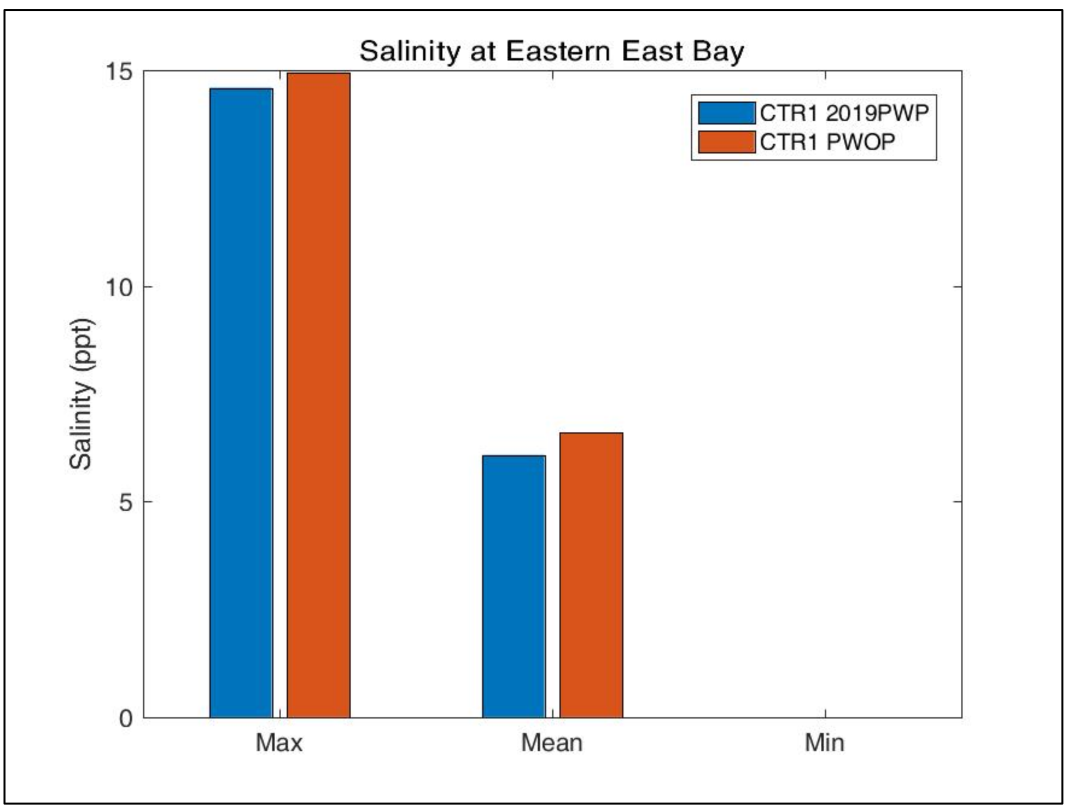


Figure 4-22. Percent less than salinity at Eastern East Bay.

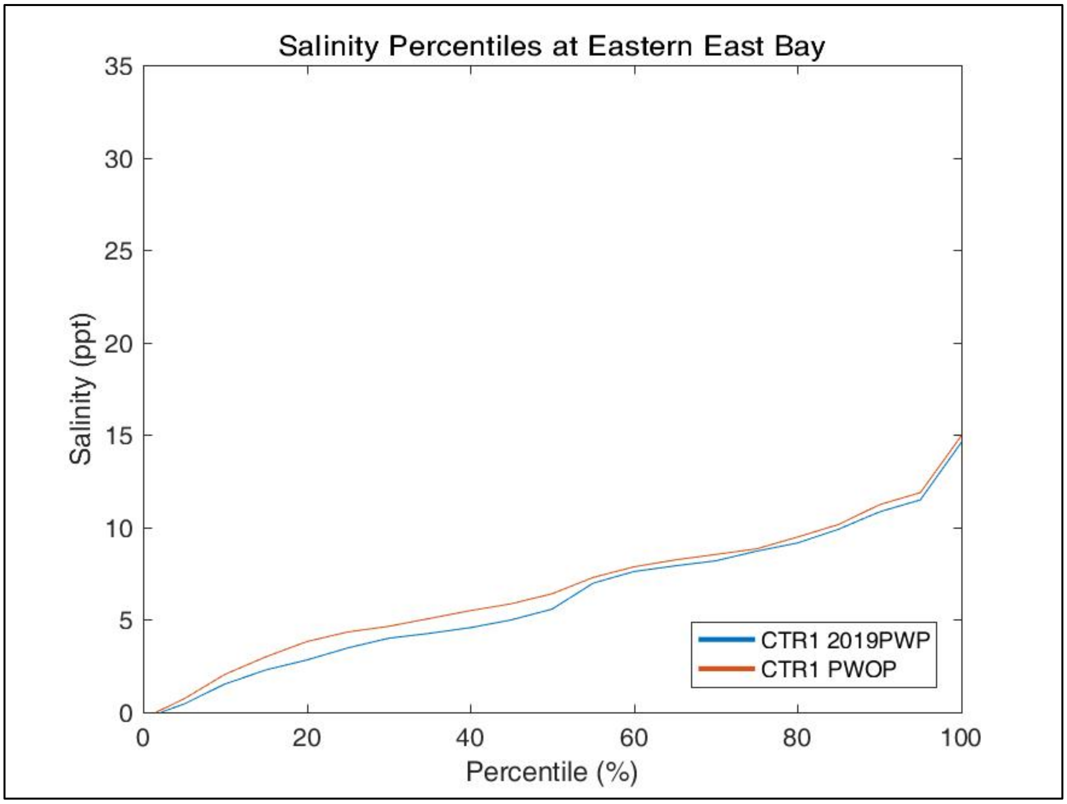


Figure 4-23. Vertical salinity profile at Eastern East Bay.

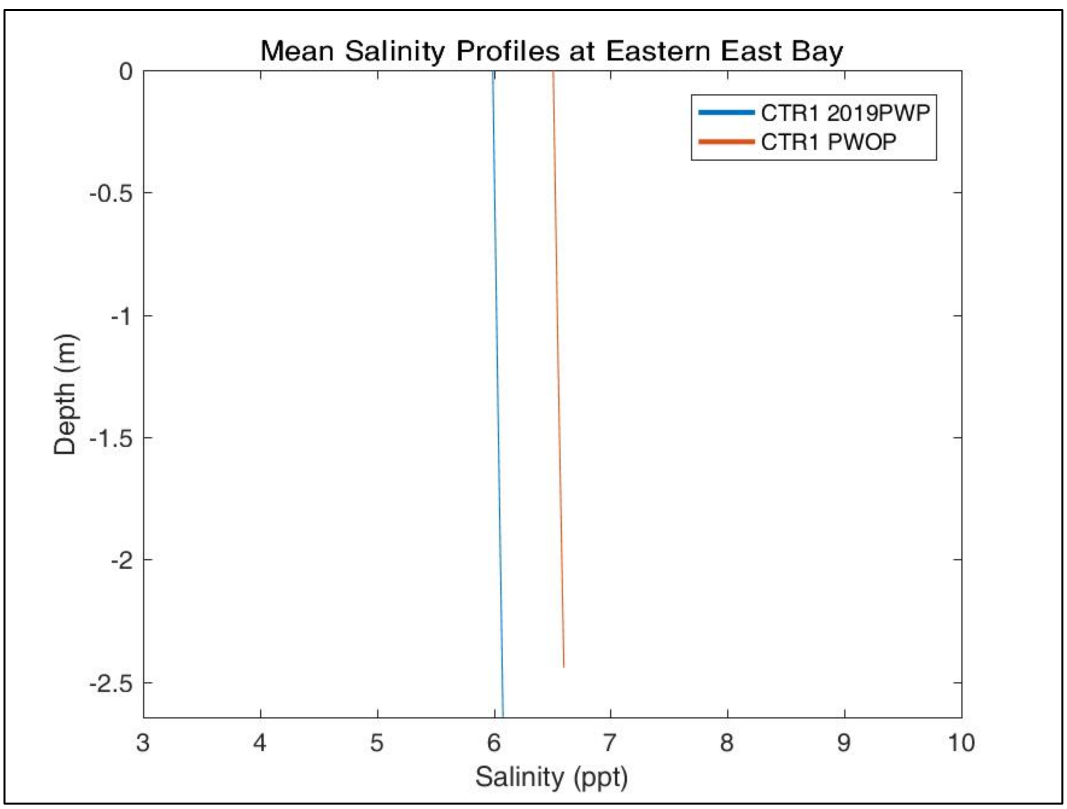


Figure 4-24. Salinity time history at Mid West Bay.

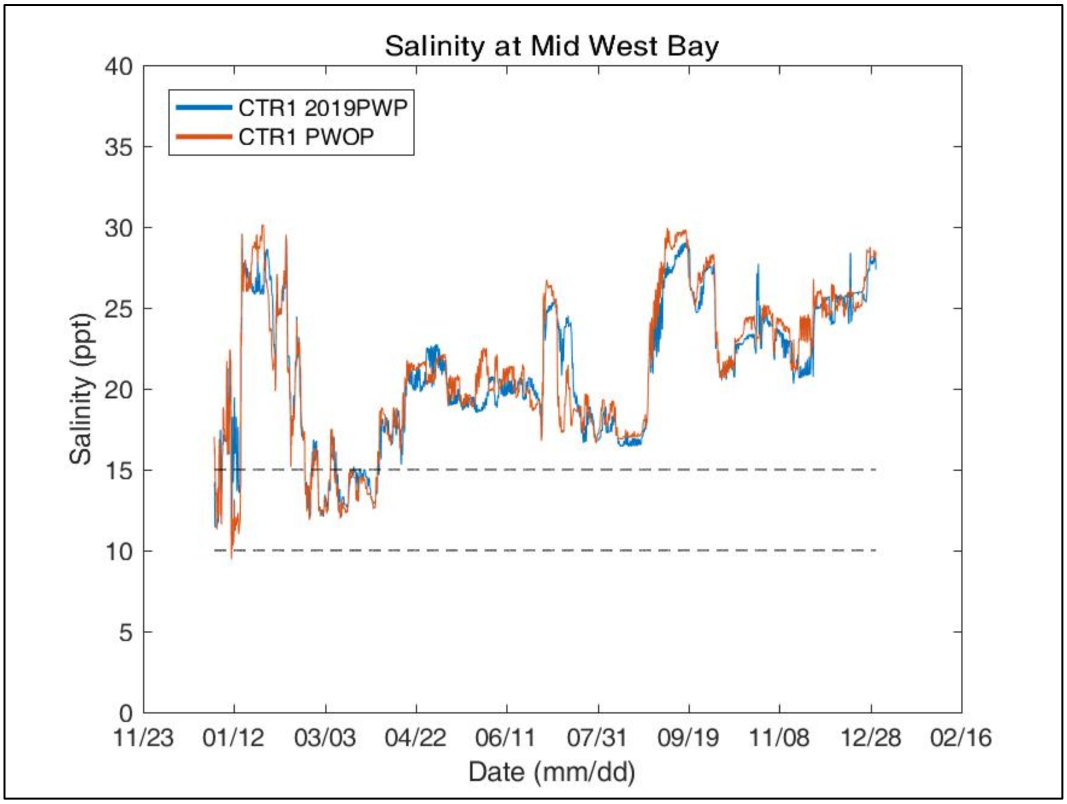


Figure 4-25. Maximum, mean, and minimum salinity at Mid West Bay.

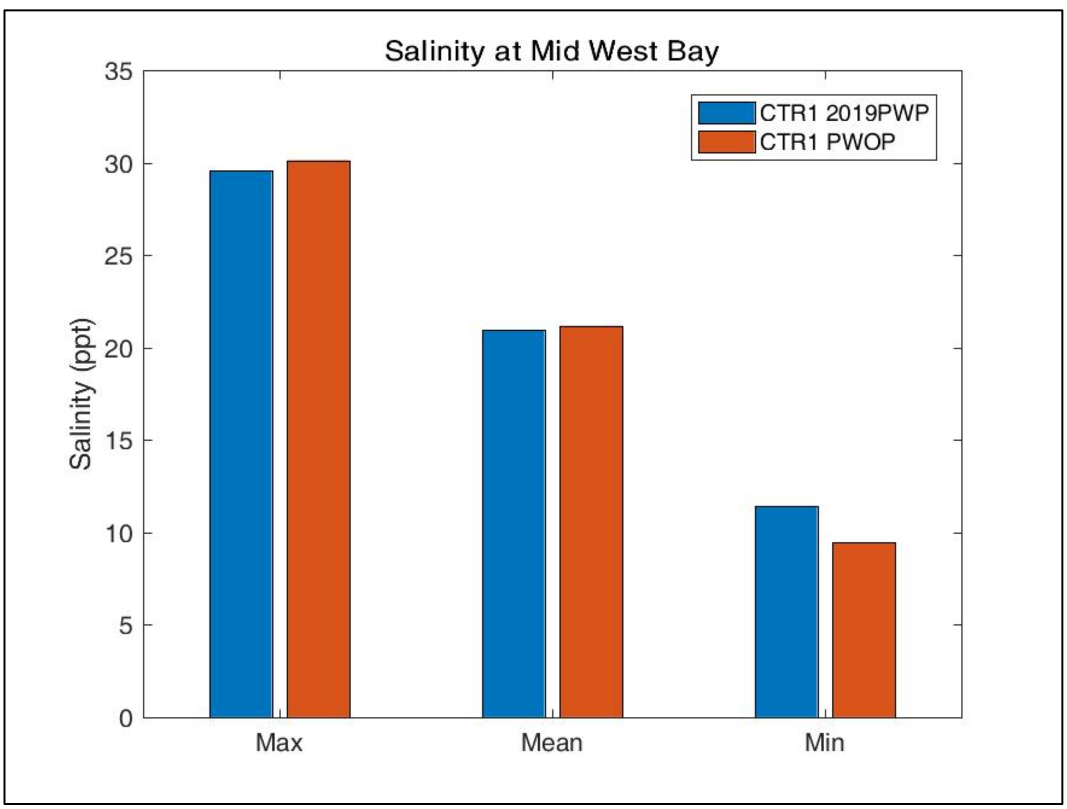


Figure 4-26. Percent less than salinity at Mid West Bay.

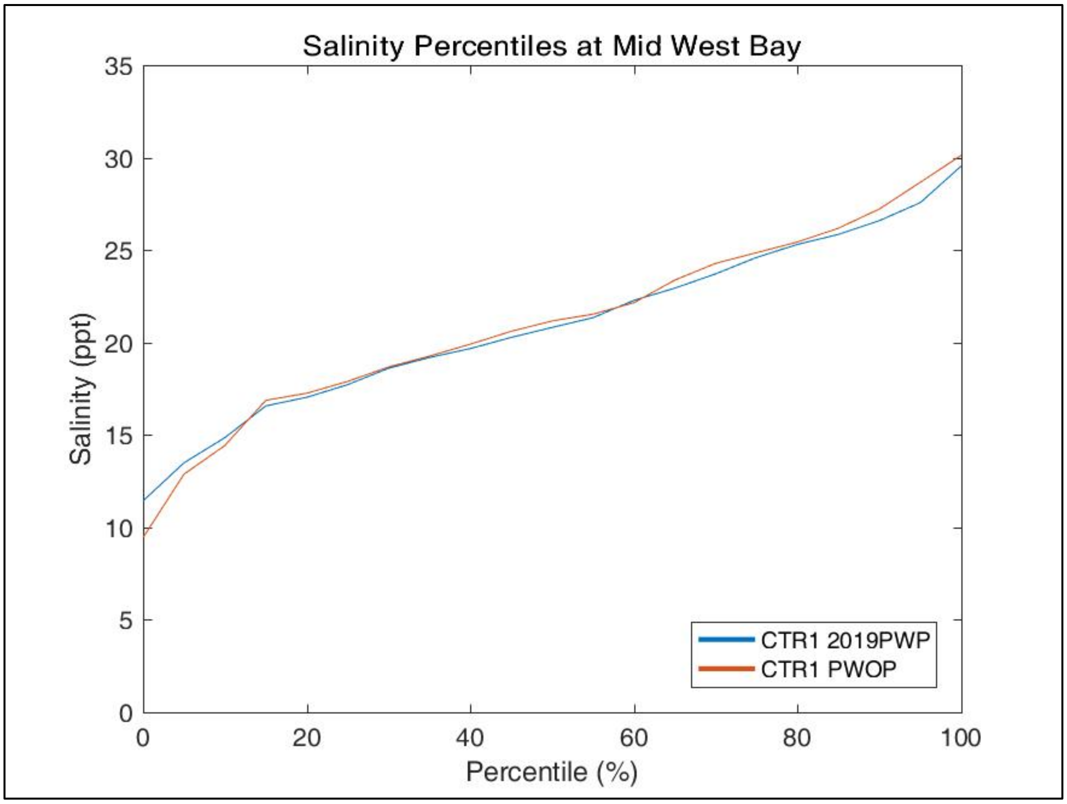
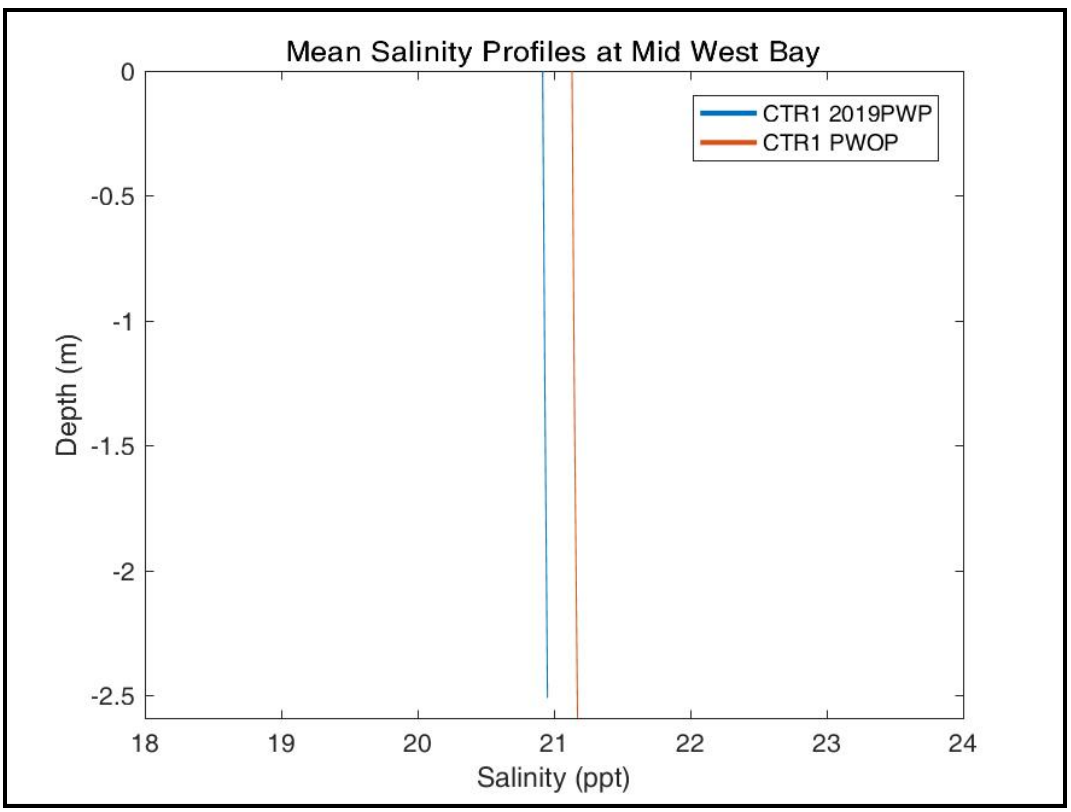


Figure 4-27. Vertical salinity profile at Mid West Bay.



Velocity Magnitude Point Analysis

Time history of velocity over the year-long analysis period is difficult to view graphically. However, the maximum, average, and minimum velocity magnitude and percent less than velocity magnitude for both surface and bottom values at each location for the year-long analysis period are provided. For all plots of velocity magnitude, present with project (PWP) is blue, present without project is orange (2019PWOP).

The percent less than plots are provided to show how the velocity magnitude varies over the analysis period. The maximum velocity magnitude value is given at 100% and the minimum value at 0%. The 50% velocity magnitude value indicates that the magnitude is less than this value for 50% of the analysis time and greater than this value for 50% of the time.

Figure 4-28 and Table 4-5 give the mean bottom velocity magnitude for the analysis locations as well as the change in the velocity magnitude due to the project conditions. Figure 4-29 and Table 4-6 give the same for the mean surface velocity magnitude. Figure 4-30 through Figure 4-53 show the point velocity magnitude analysis at the six selected locations. The results for all 23 locations are provided in Appendix B: Velocity Magnitude Point Analysis.

As with the salinity analysis, the velocity magnitudes for the with project condition do not vary greatly at different locations in the bays. The velocity magnitudes do drop at most locations for both surface and bottom but this reduction in the mean velocity magnitude is less than 0.1 m/s and typically more on the order 0f 0.05 m/s or less. Locations in West Bay and on the western perimeter of Galveston Bay show a slight increase in velocity magnitude for surface or bottom but, again, the change in the mean velocity magnitude is less than 0.1 m/s. The change in maximum velocity magnitude is often greater than that for the mean; however, the percent less than plots support that these large values are not experienced much during the analysis year (shown by the steep slope in the lines between 95% and 100%).

Figure 4-28. Change in mean bottom velocity magnitude from PWOP condition.

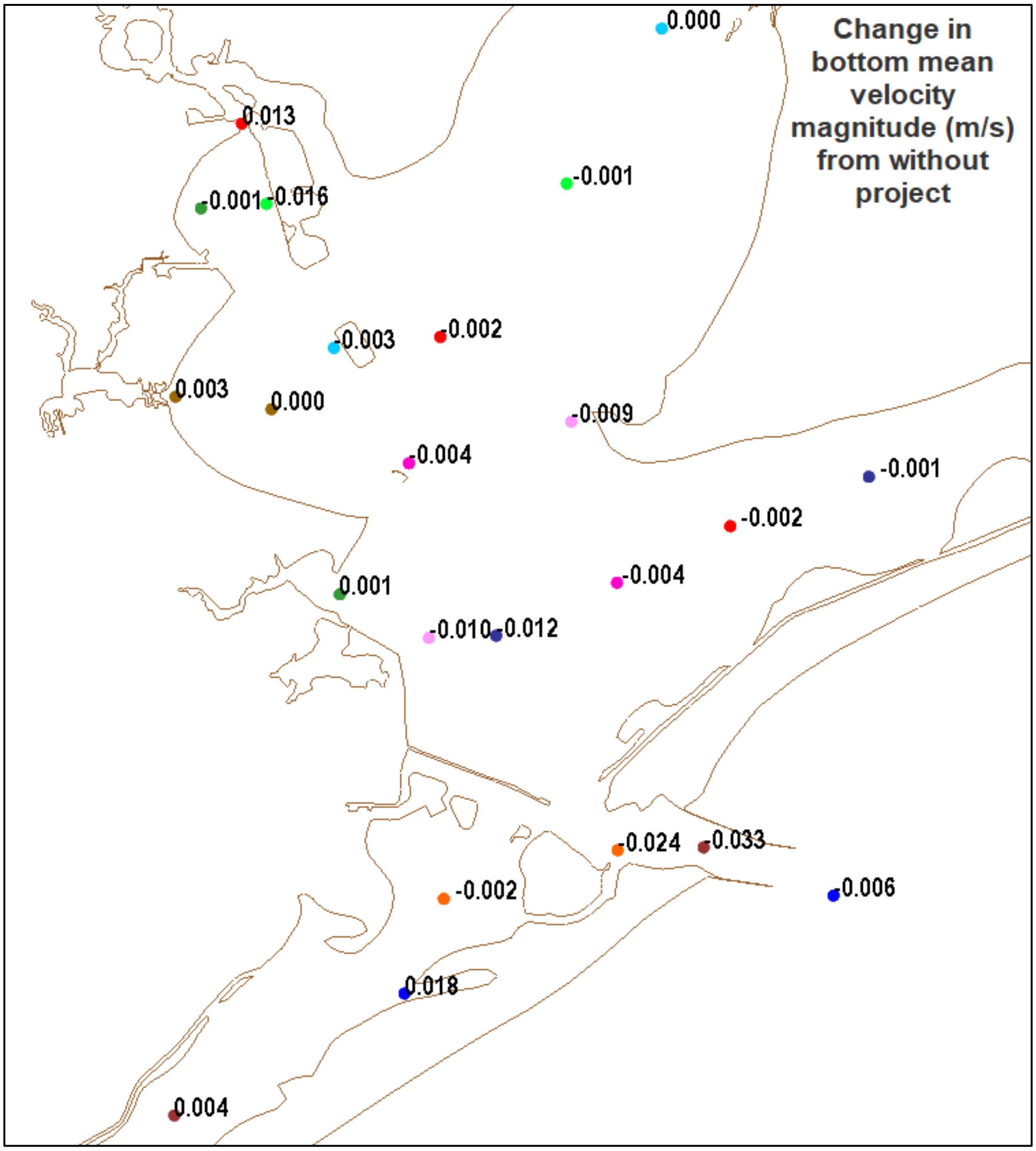


Table 4-5. Mean bottom velocity magnitude and absolute change from the without project alternative.

	PWOP Rerun Mean Bottom Velocity (m/s)	2019PWP Mean Bottom Velocity (m/s)	2019PWP Mean Bottom Velocity Change (m/s) from without project
HSC at Morgan's Point	0.153	0.165	0.013
HSC at Atkinson Island	0.143	0.127	-0.016
HSC at Mid Bay Marsh	0.170	0.167	-0.003
HSC at Red Fish Reef	0.207	0.203	-0.004
HSC at Lower Galveston Bay	0.334	0.322	-0.012
HSC at Bolivar Roads	0.376	0.352	-0.024
HSC at Entrance	0.415	0.382	-0.033
HSC at Gulf	0.179	0.173	-0.006
Upper Galveston Bay 1	0.030	0.029	-0.001
Upper Galveston Bay 2	0.045	0.045	0.000
Lower Galveston Bay	0.178	0.168	-0.010
Lower Trinity Bay	0.080	0.078	-0.002
Mid Trinity Bay	0.053	0.052	-0.001
Upper Trinity Bay	0.031	0.031	0.000
Western East Bay	0.125	0.121	-0.004
Eastern East Bay	0.044	0.044	-0.001
Eastern West Bay	0.085	0.083	-0.002
Mid West Bay	0.055	0.059	0.004
Offatts Bayou	0.050	0.068	0.018
Dickinson	0.045	0.046	0.001
Clear Creek	0.033	0.036	0.003
Smith Point	0.193	0.184	-0.009
Mid East Bay	0.066	0.064	-0.002

Figure 4-29. Change in mean surface velocity magnitude from PWOP condition.

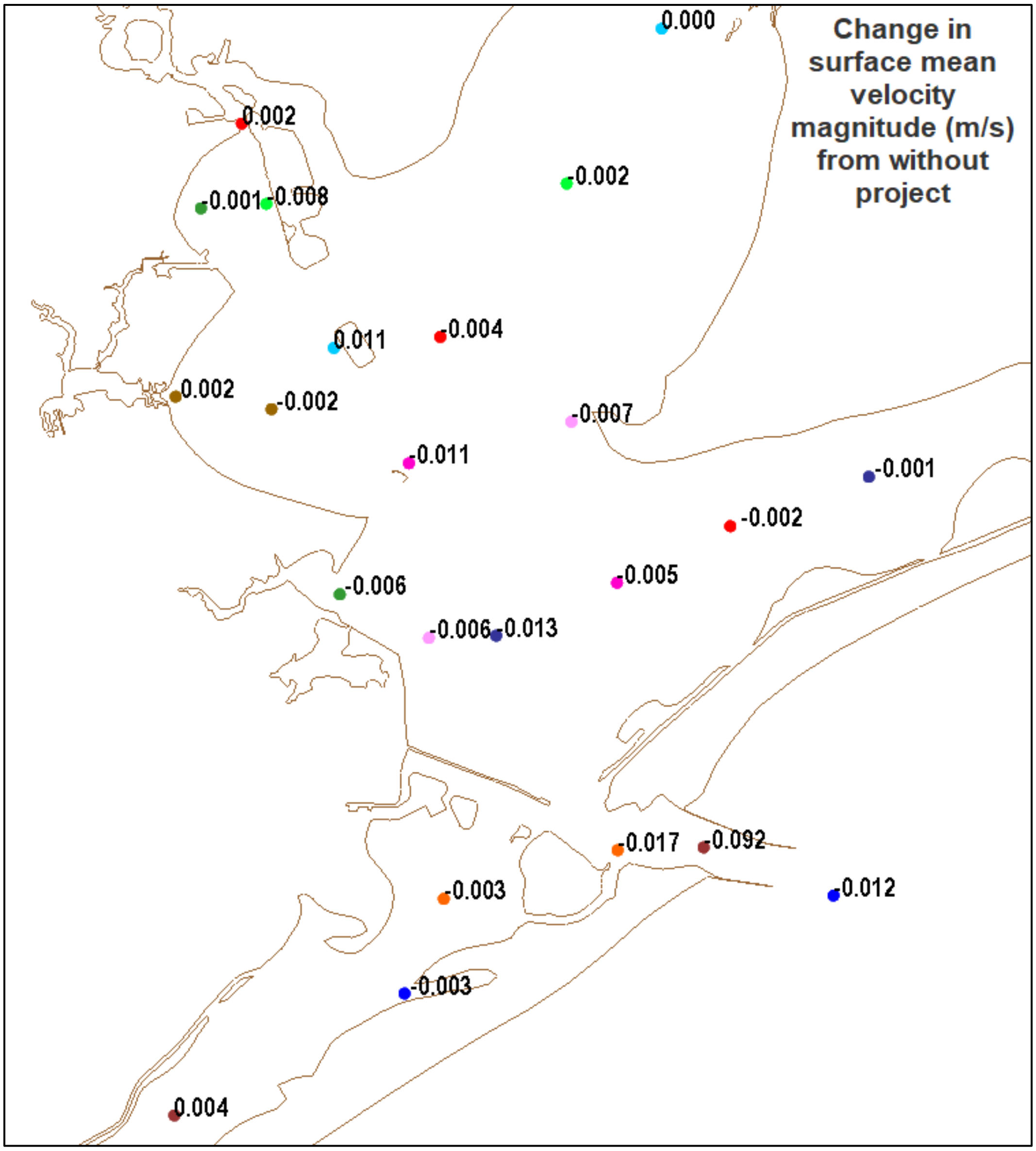


Table 4-6. Mean surface velocity magnitude and absolute change from the without project alternative.

	PWOP Rerun Mean Surface Velocity (m/s)	2019PWP Mean Surface Velocity (m/s)	2019PWP Mean Surface Velocity Change (m/s) from without project
HSC at Morgan's Point	0.189	0.191	0.002
HSC at Atkinson Island	0.131	0.124	-0.008
HSC at Mid Bay Marsh	0.178	0.189	0.011
HSC at Red Fish Reef	0.277	0.267	-0.011
HSC at Lower Galveston Bay	0.431	0.418	-0.013
HSC at Bolivar Roads	0.584	0.568	-0.017
HSC at Entrance	0.655	0.563	-0.092
HSC at Gulf	0.269	0.257	-0.012
Upper Galveston Bay 1	0.046	0.045	-0.001
Upper Galveston Bay 2	0.065	0.064	-0.002
Lower Galveston Bay	0.234	0.228	-0.006
Lower Trinity Bay	0.130	0.126	-0.004
Mid Trinity Bay	0.079	0.077	-0.002
Upper Trinity Bay	0.044	0.044	0.000
Western East Bay	0.172	0.167	-0.005
Eastern East Bay	0.060	0.059	-0.001
Eastern West Bay	0.119	0.116	-0.003
Mid West Bay	0.077	0.080	0.004
Offatts Bayou	0.110	0.108	-0.003
Dickinson	0.067	0.061	-0.006
Clear Creek	0.048	0.050	0.002
Smith Point	0.270	0.263	-0.007
Mid East Bay	0.092	0.090	-0.002

Figure 4-30. Bottom velocity magnitude percent less than for HSC at Morgan's Point.

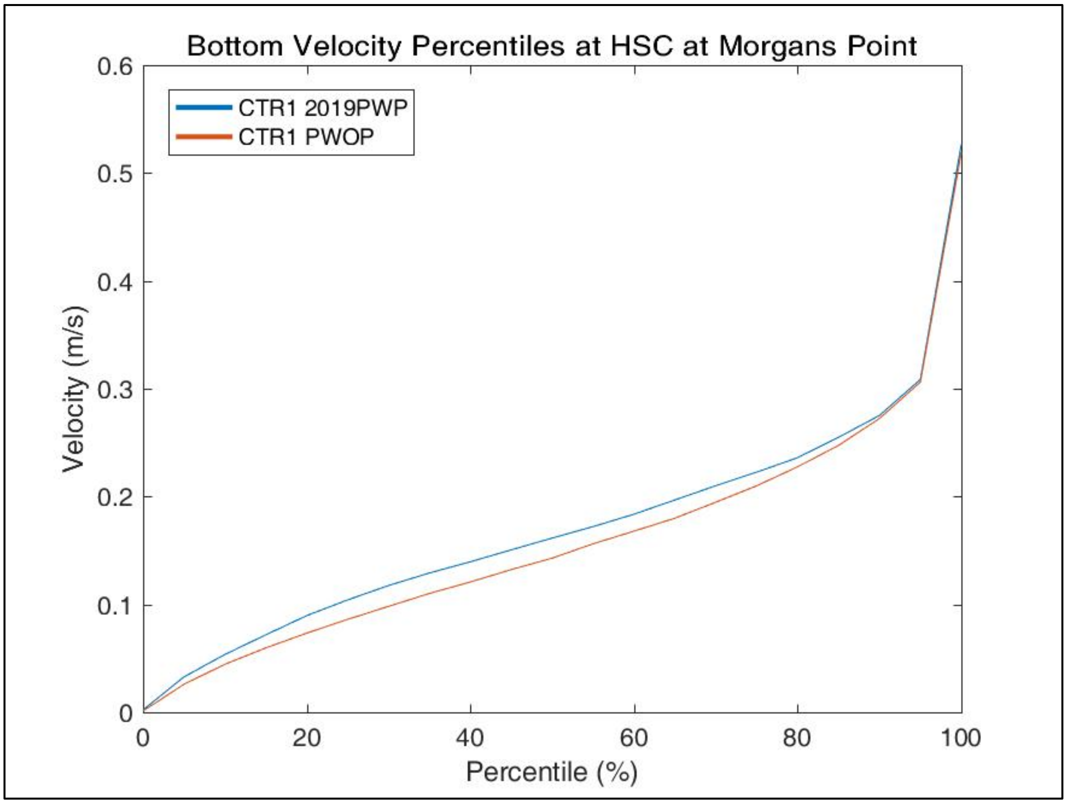


Figure 4-31. Bottom velocity magnitude maximum, mean, and minimum at HSC at Morgan's Point.

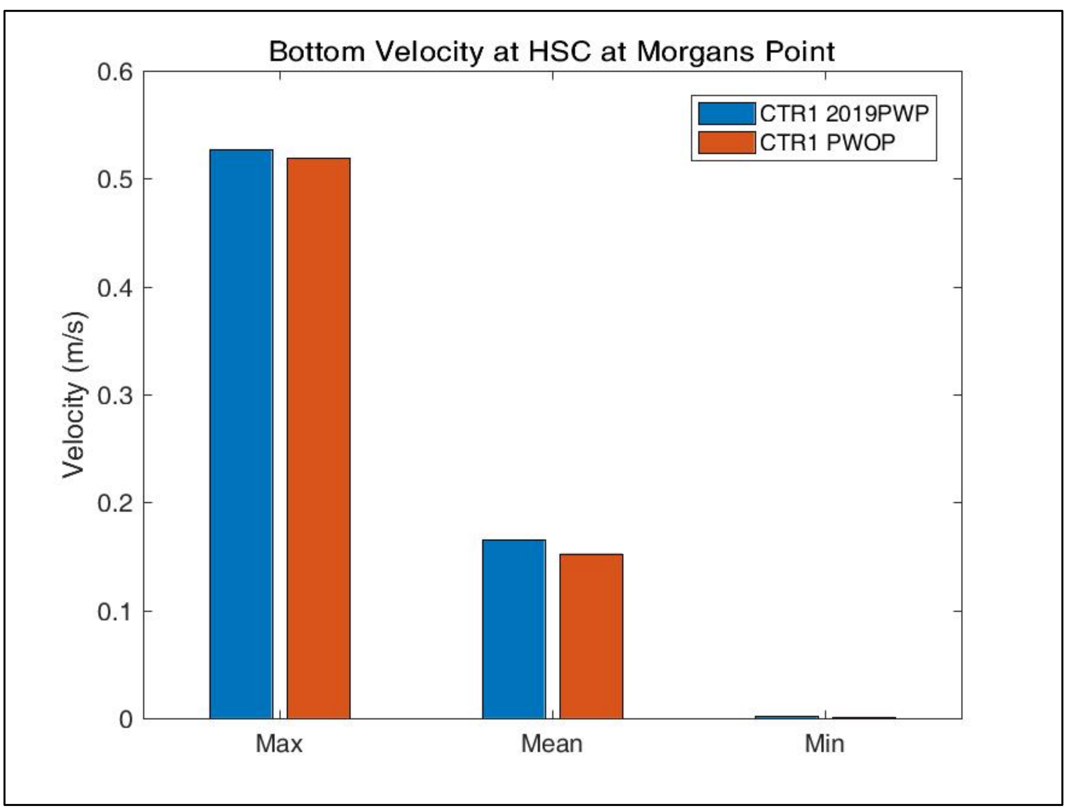


Figure 4-32. Surface velocity magnitude percent less than for HSC at Morgan's Point.

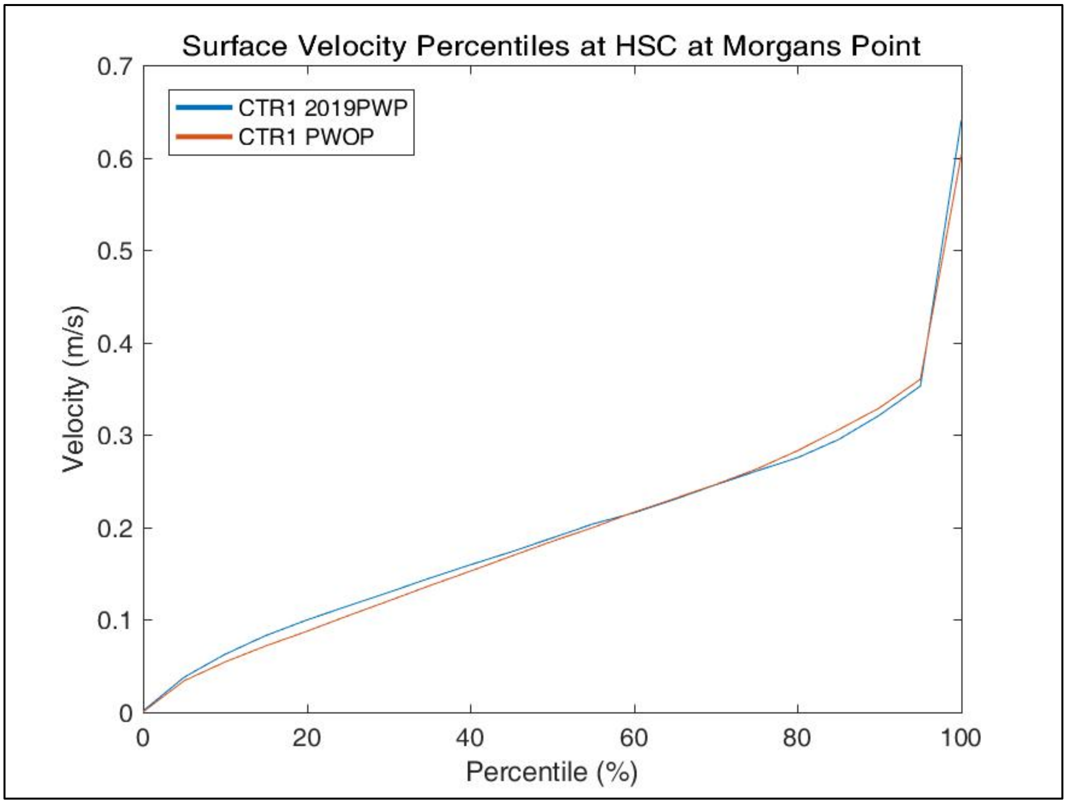


Figure 4-33. Surface velocity magnitude maximum, mean, and minimum at HSC at Morgan's Point.

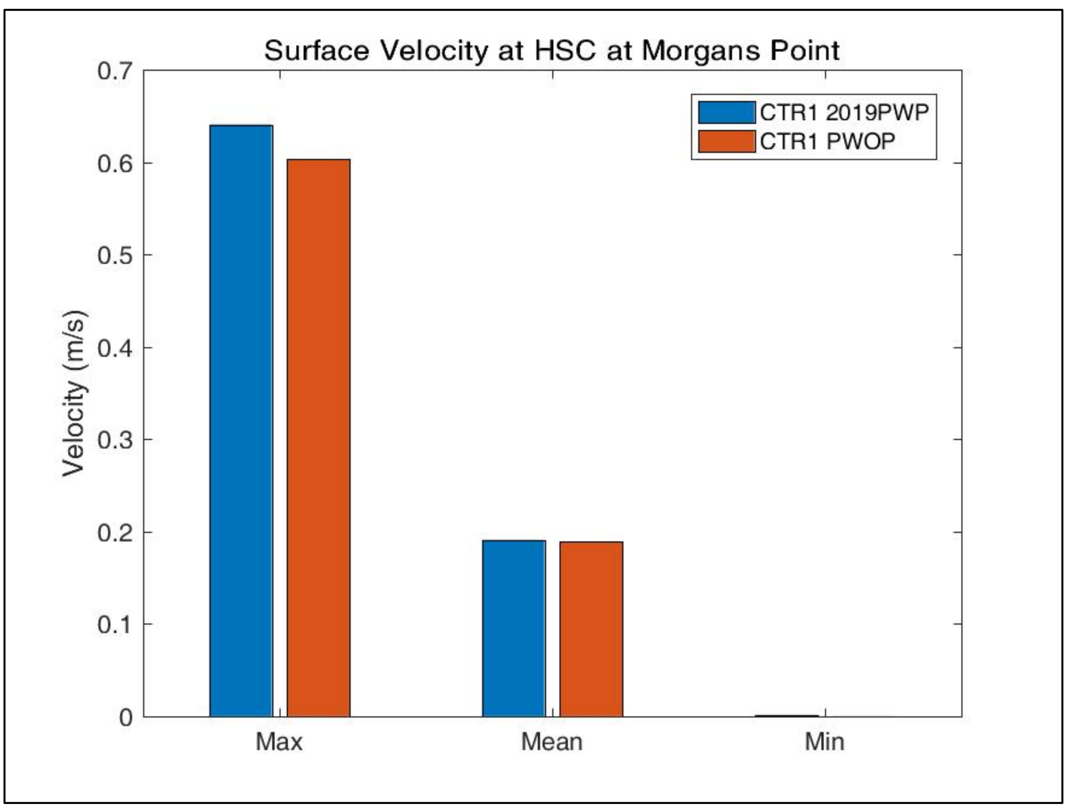


Figure 4-34. Bottom velocity magnitude percent less than for HSC at Lower Galveston Bay.

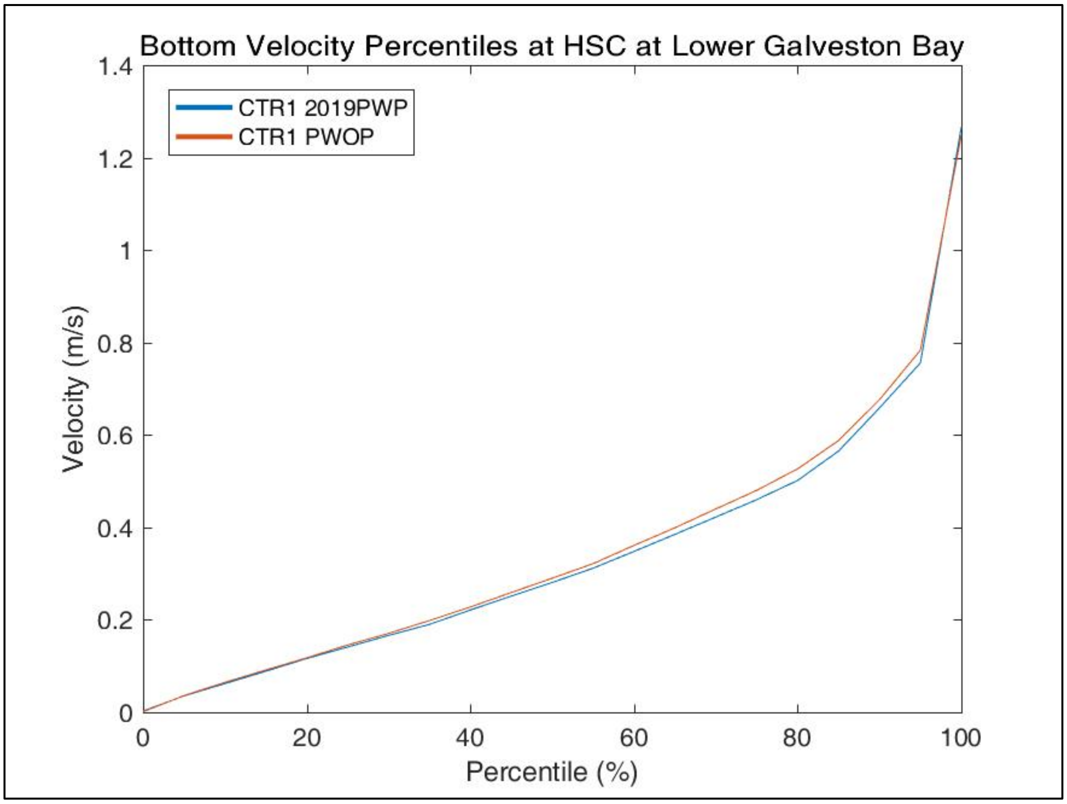


Figure 4-35. Bottom velocity magnitude maximum, mean, and minimum at HSC at Lower Galveston Bay.

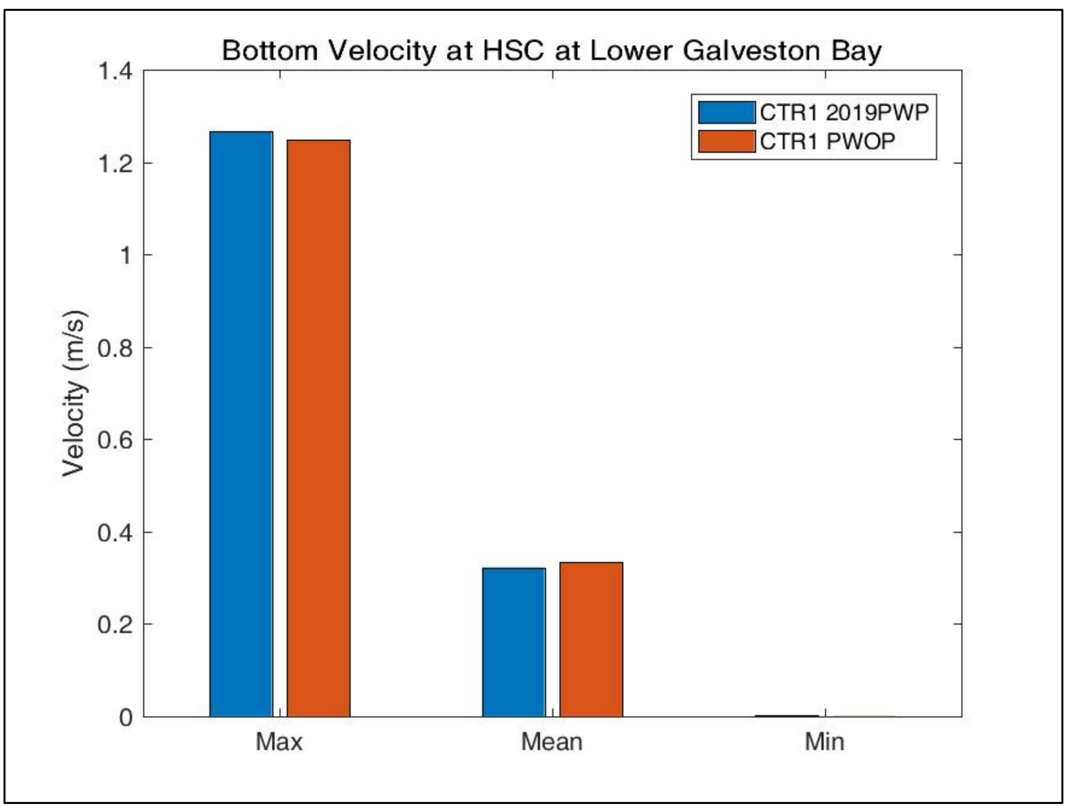


Figure 4-36. Surface velocity magnitude percent less than for HSC at Lower Galveston Bay.

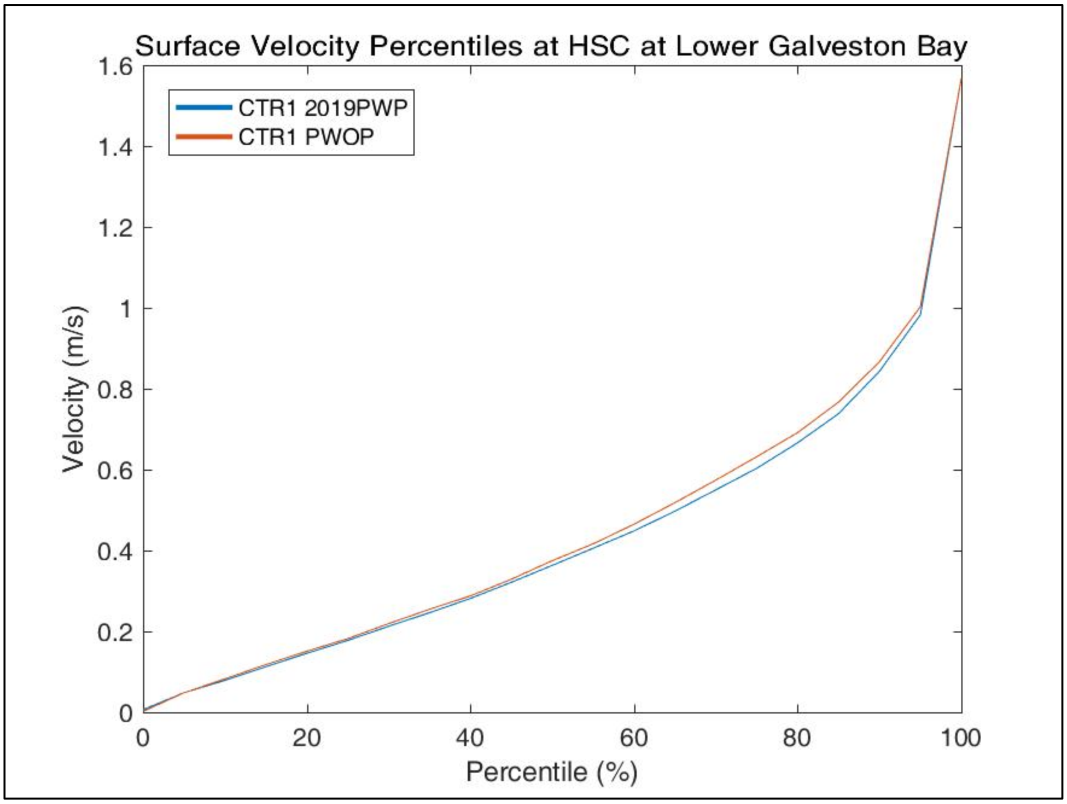


Figure 4-37. Surface velocity magnitude maximum, mean, and minimum at HSC at Lower Galveston Bay.

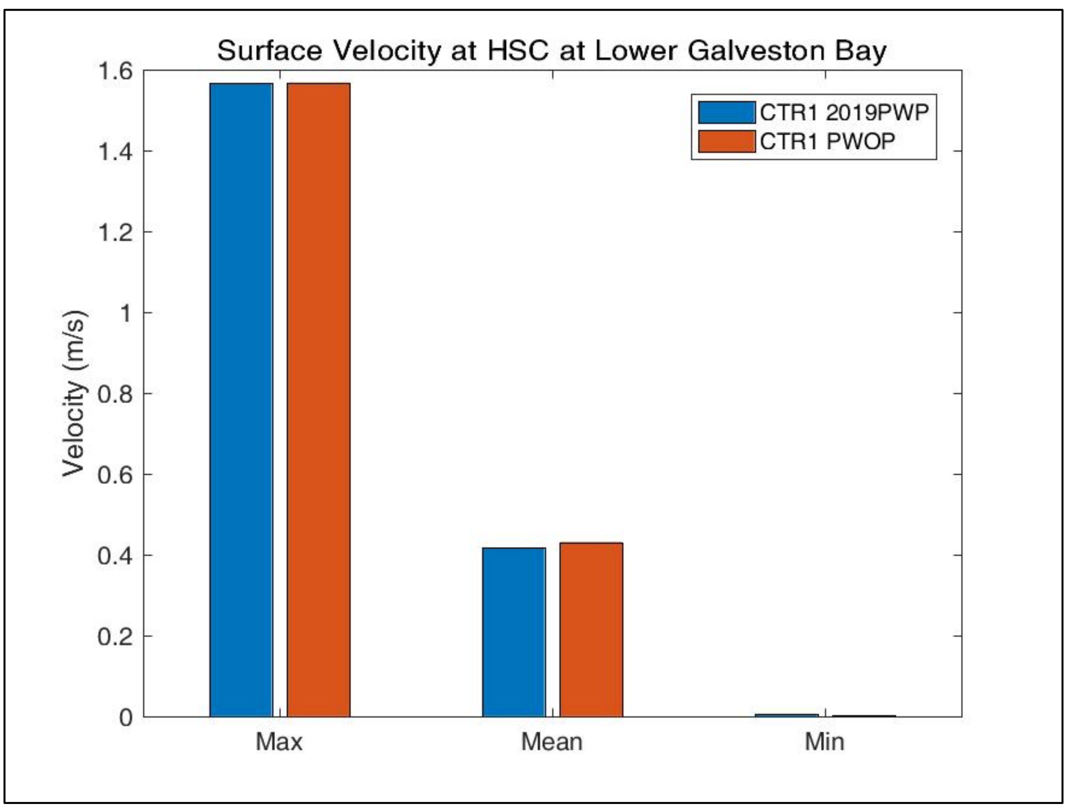


Figure 4-38. Bottom velocity magnitude percent less than for Upper Galveston Bay 2.

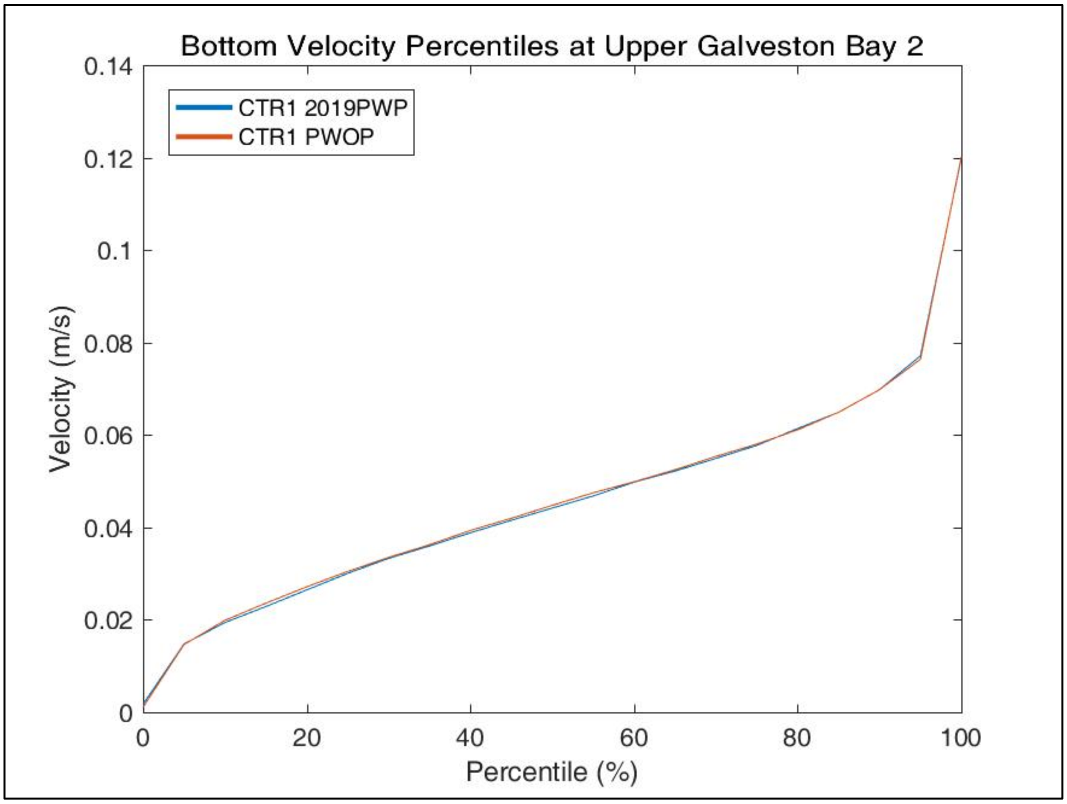


Figure 4-39. Bottom velocity magnitude maximum, mean, and minimum at Upper Galveston Bay 2.

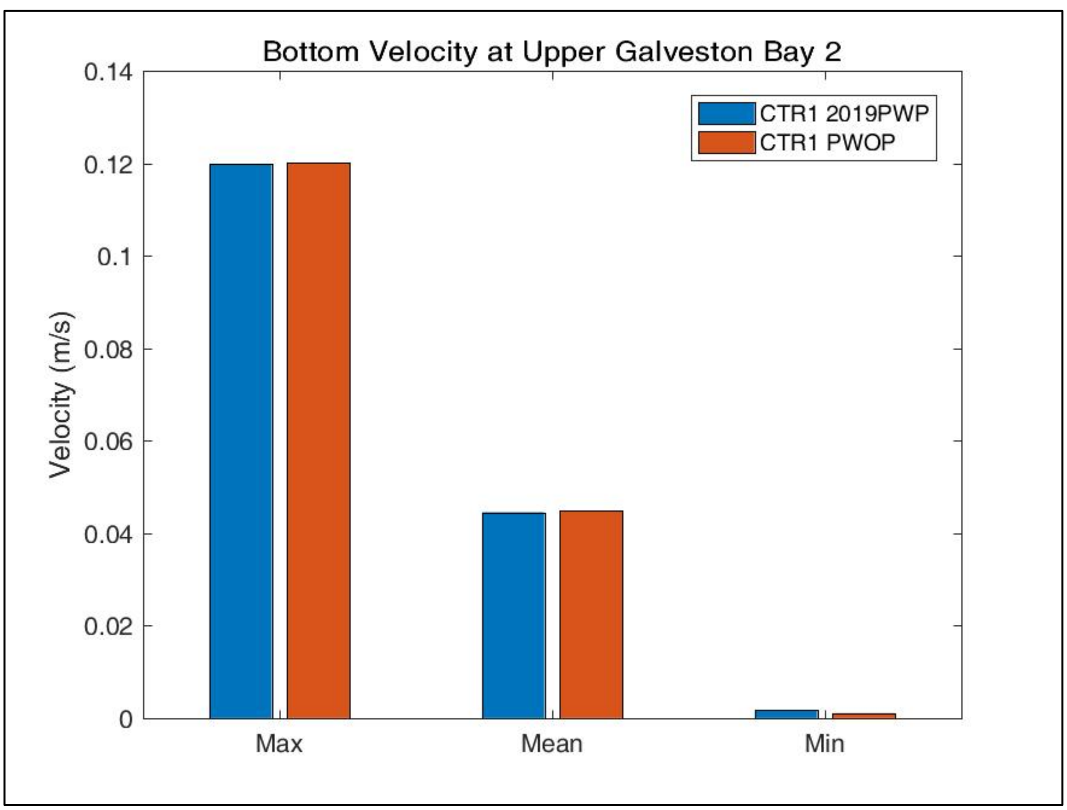


Figure 4-40. Surface velocity magnitude percent less than for Upper Galveston Bay 2.

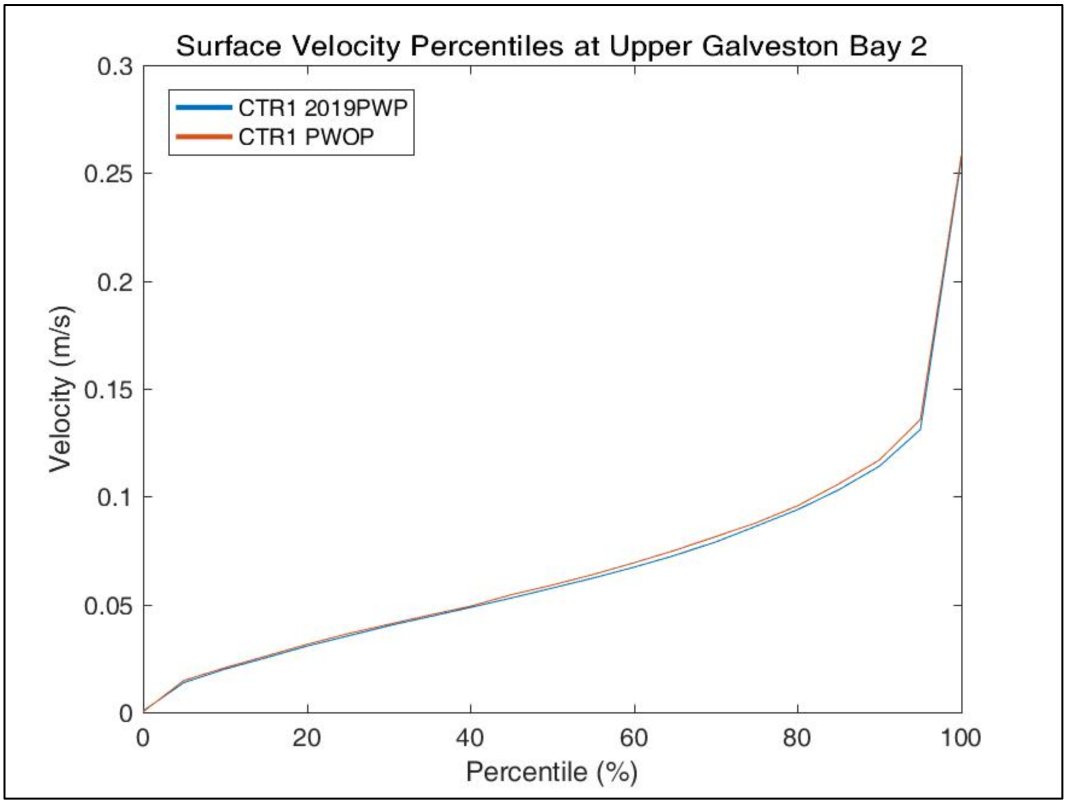


Figure 4-41. Surface velocity magnitude maximum, mean, and minimum at Upper Galveston Bay 2.

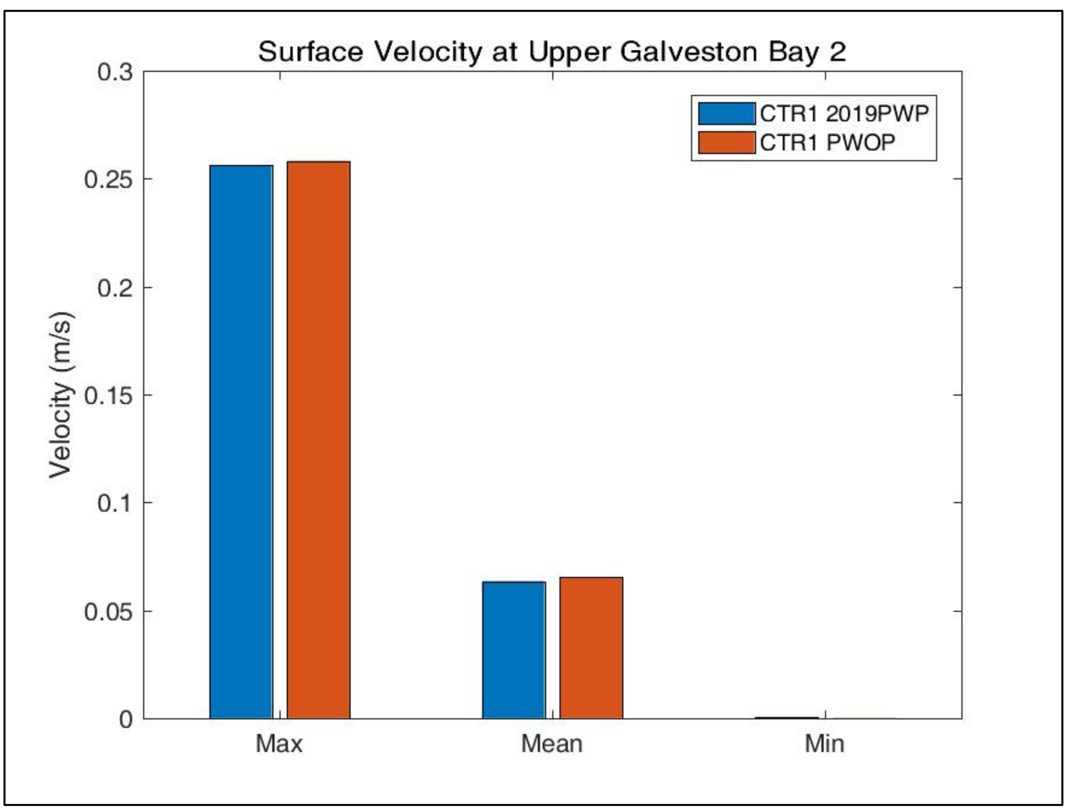


Figure 4-42. Bottom velocity magnitude percent less than for Upper Trinity Bay.

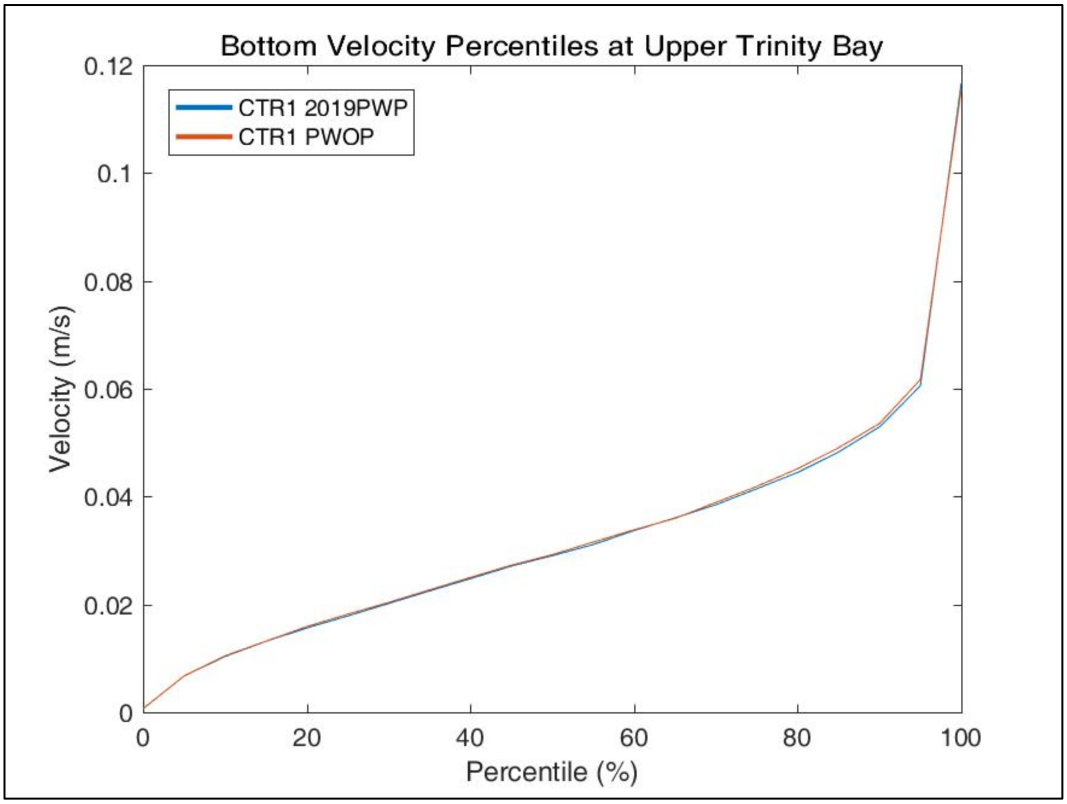


Figure 4-43. Bottom velocity magnitude maximum, mean, and minimum at Upper Trinity Bay.

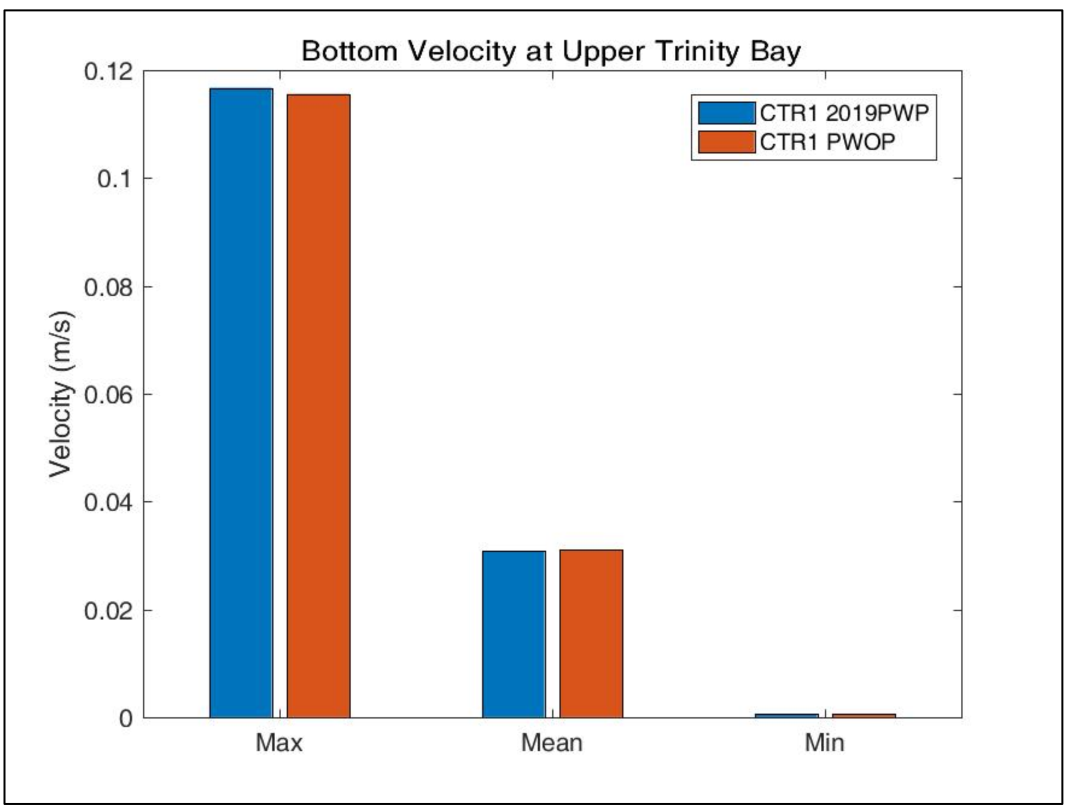


Figure 4-44. Surface velocity magnitude percent less than for Upper Trinity Bay.

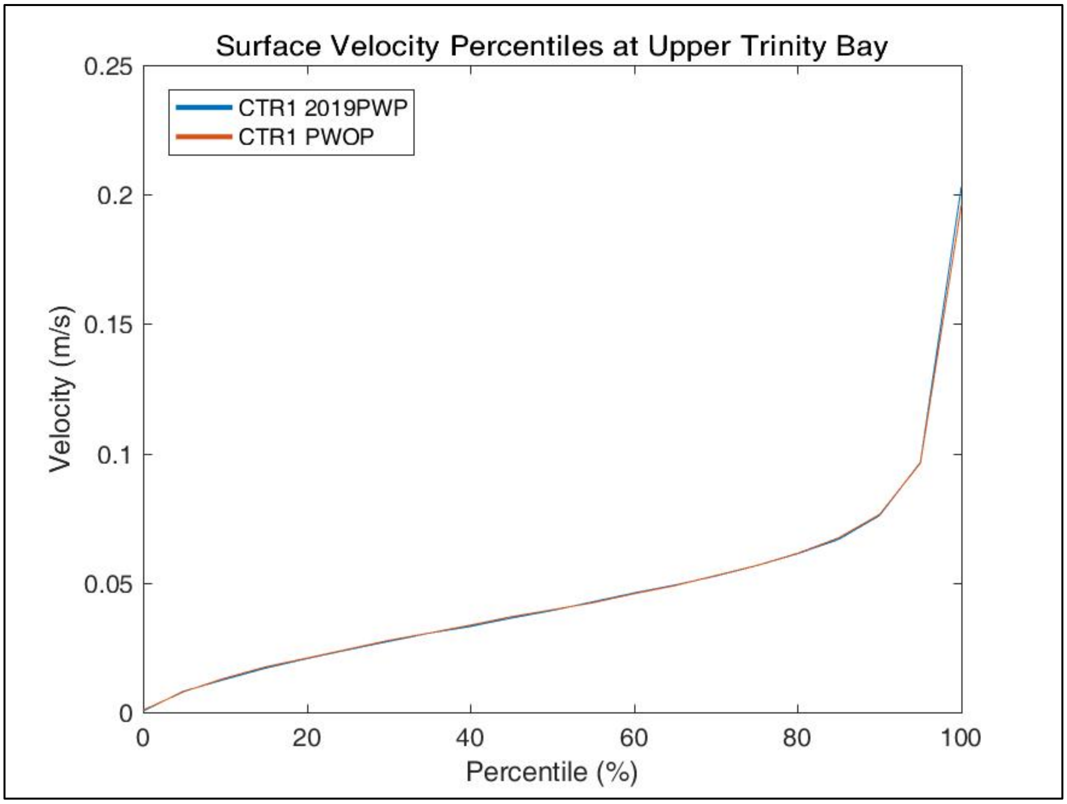


Figure 4-45. Surface velocity magnitude maximum, mean, and minimum at Upper Trinity Bay.

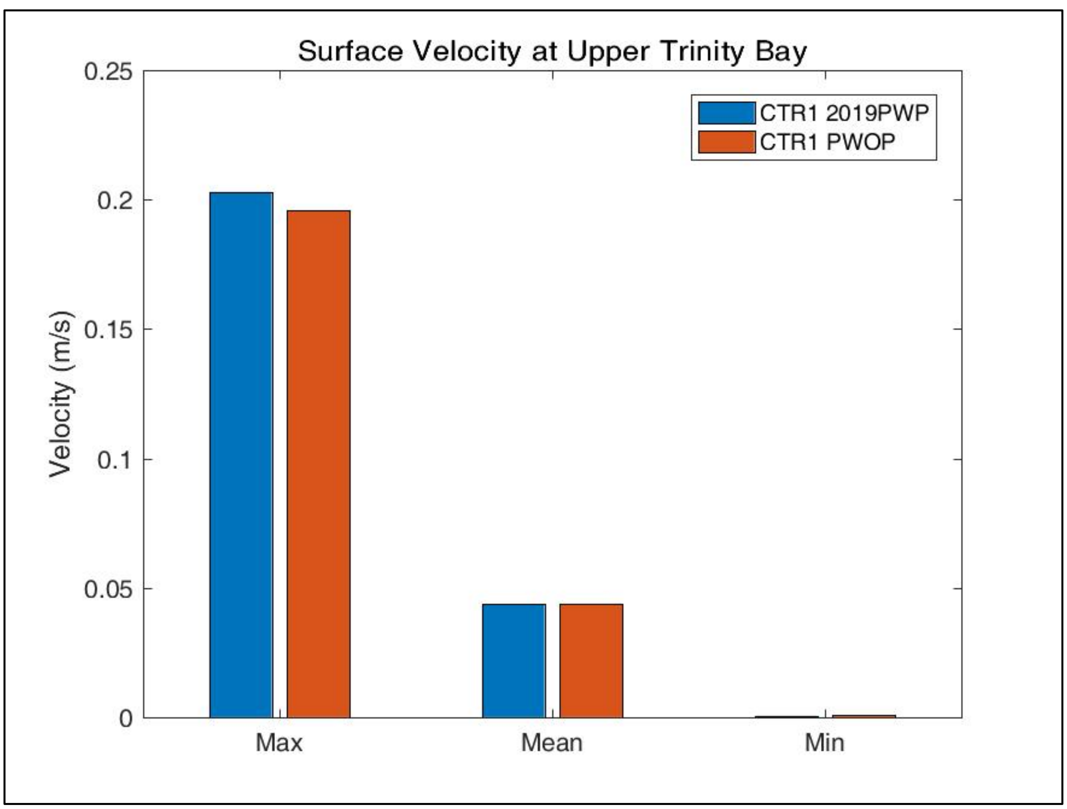


Figure 4-46. Bottom velocity magnitude percent less than for Eastern East Bay.

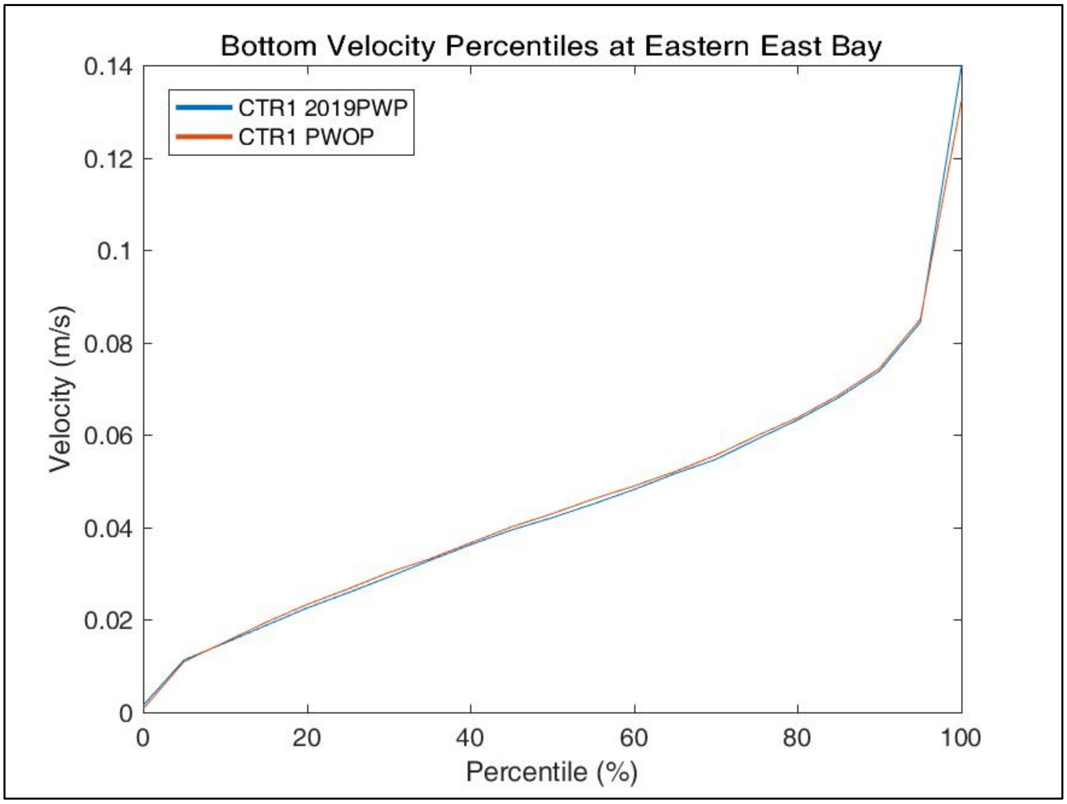


Figure 4-47. Bottom velocity magnitude maximum, mean, and minimum at Eastern East Bay.

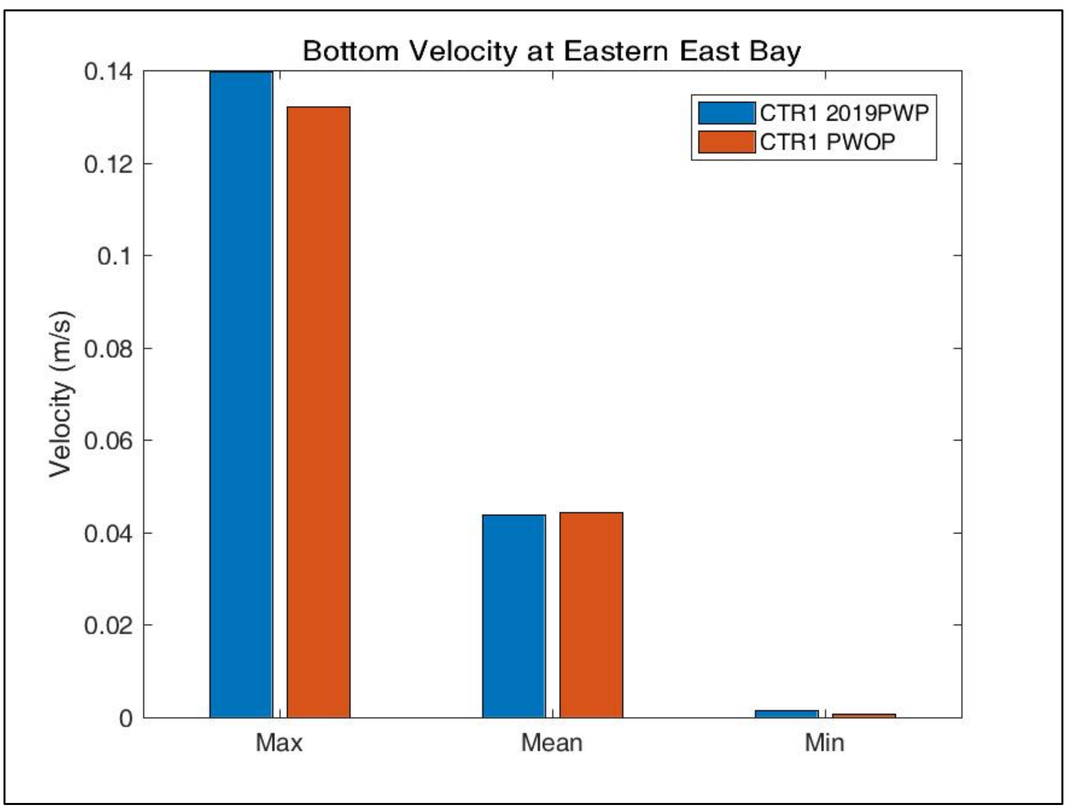


Figure 4-48. Surface velocity magnitude percent less than for Eastern East Bay.

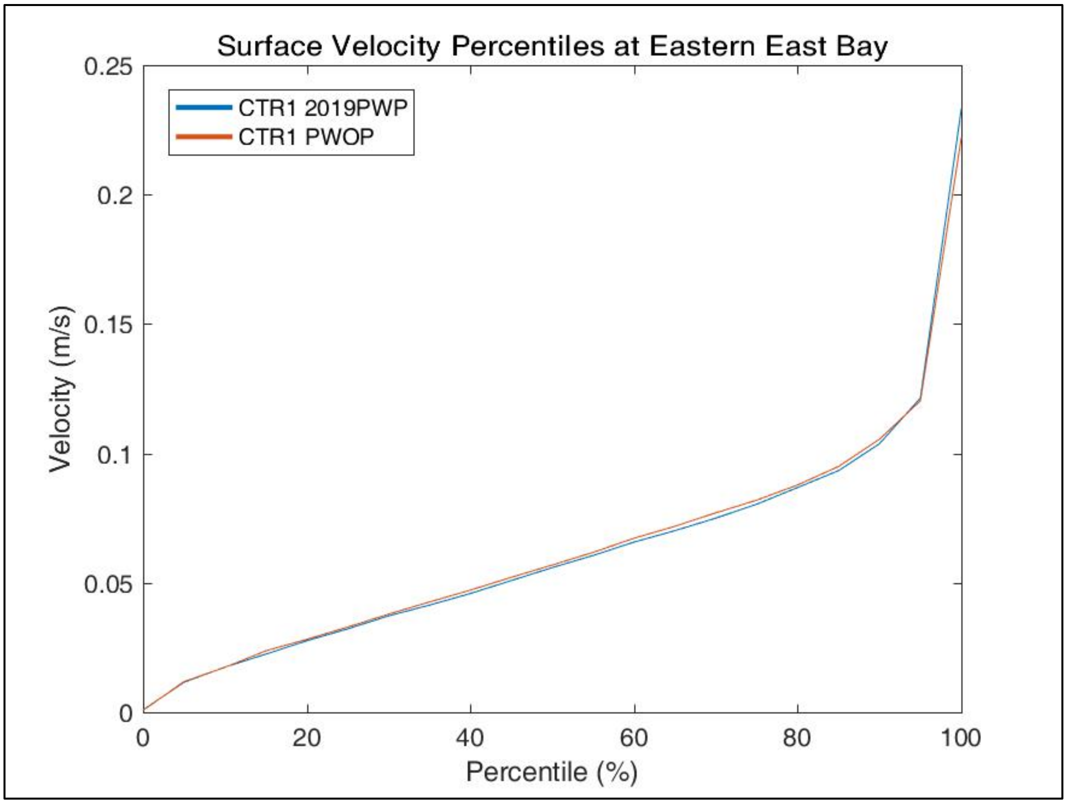


Figure 4-49. Surface velocity magnitude maximum, mean, and minimum at Eastern East Bay.

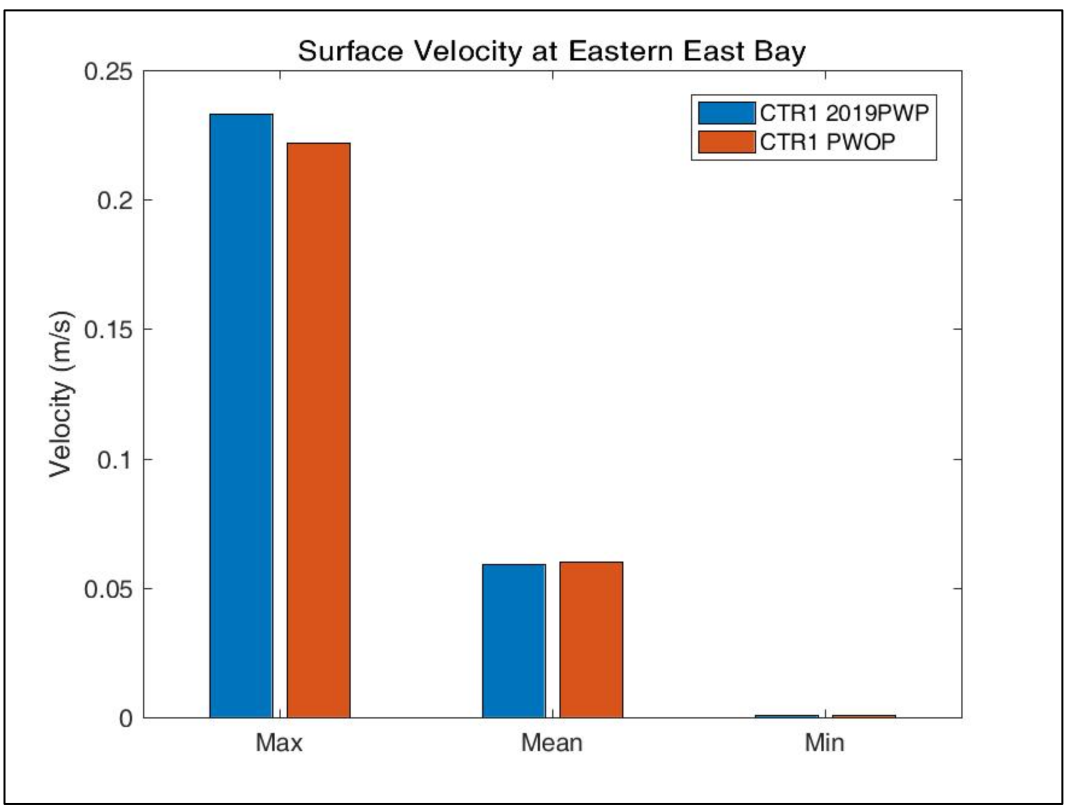


Figure 4-50. Bottom velocity magnitude percent less than for Mid West Bay.

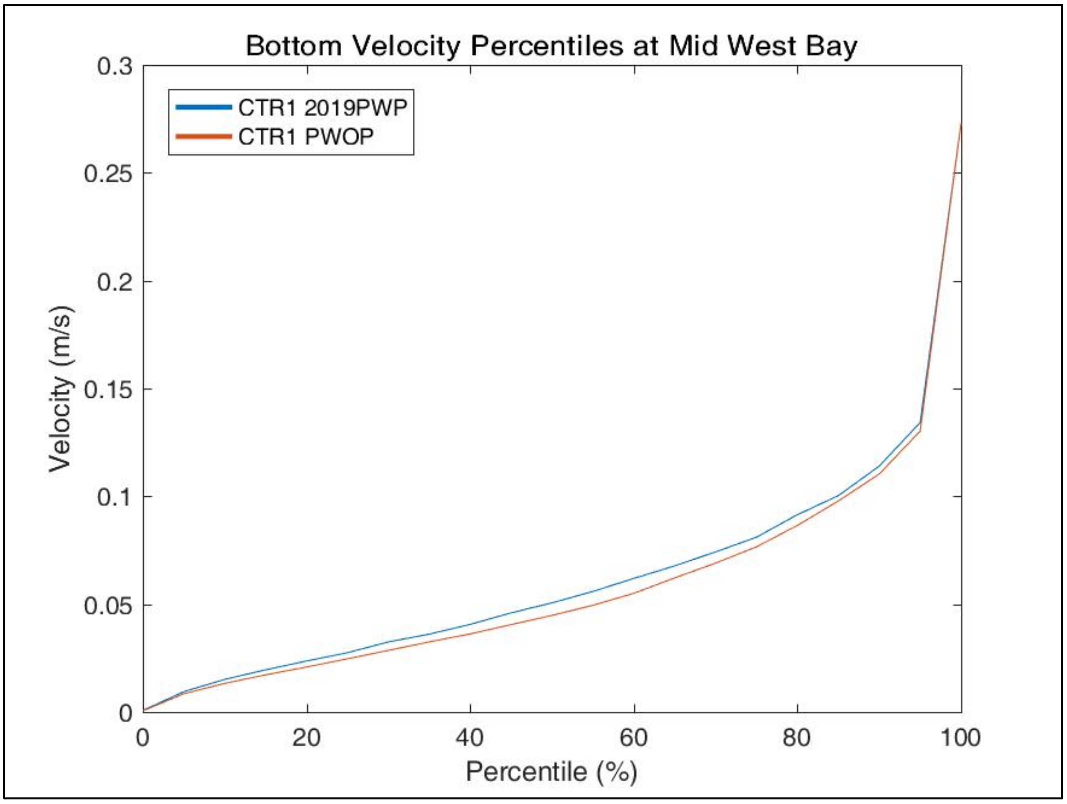


Figure 4-51. Bottom velocity magnitude maximum, mean, and minimum at Mid West Bay.

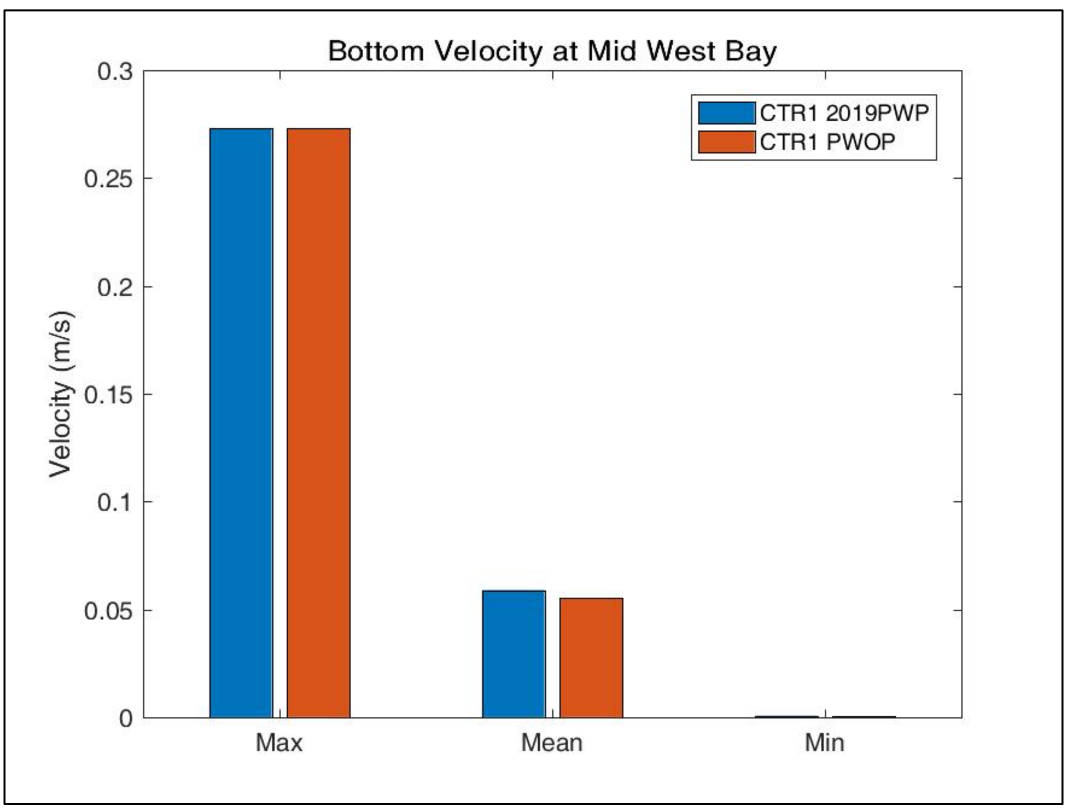


Figure 4-52. Surface velocity magnitude percent less than for Mid West Bay.

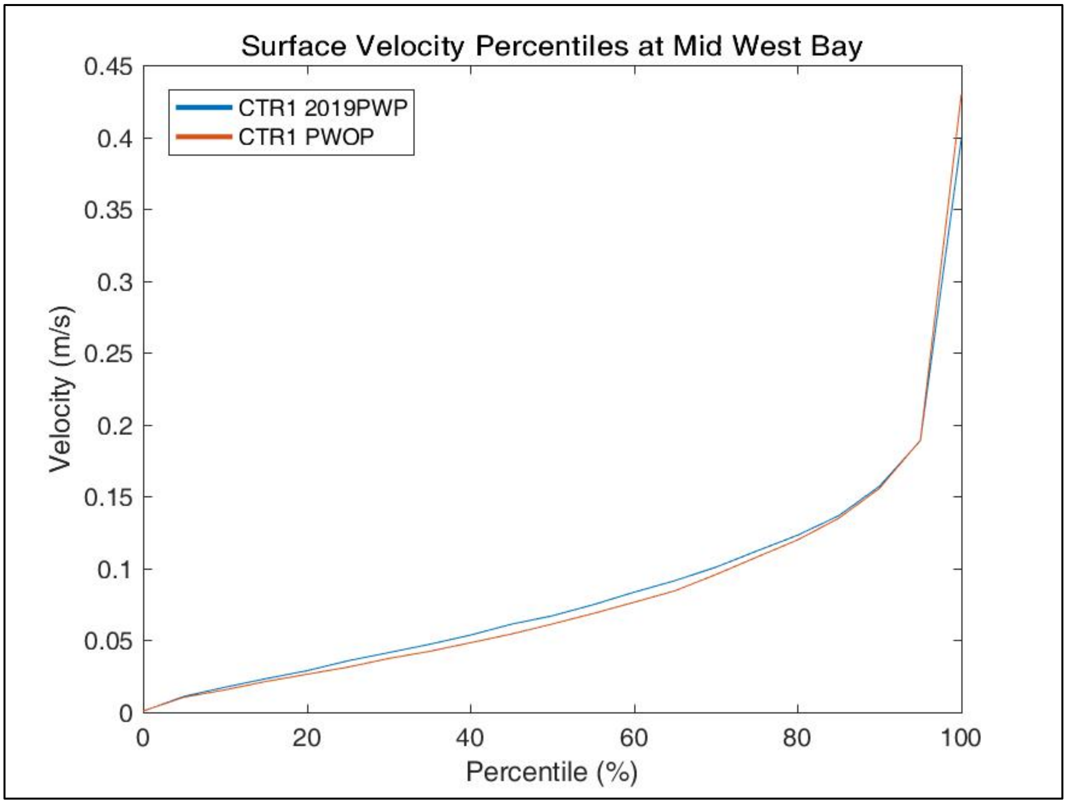
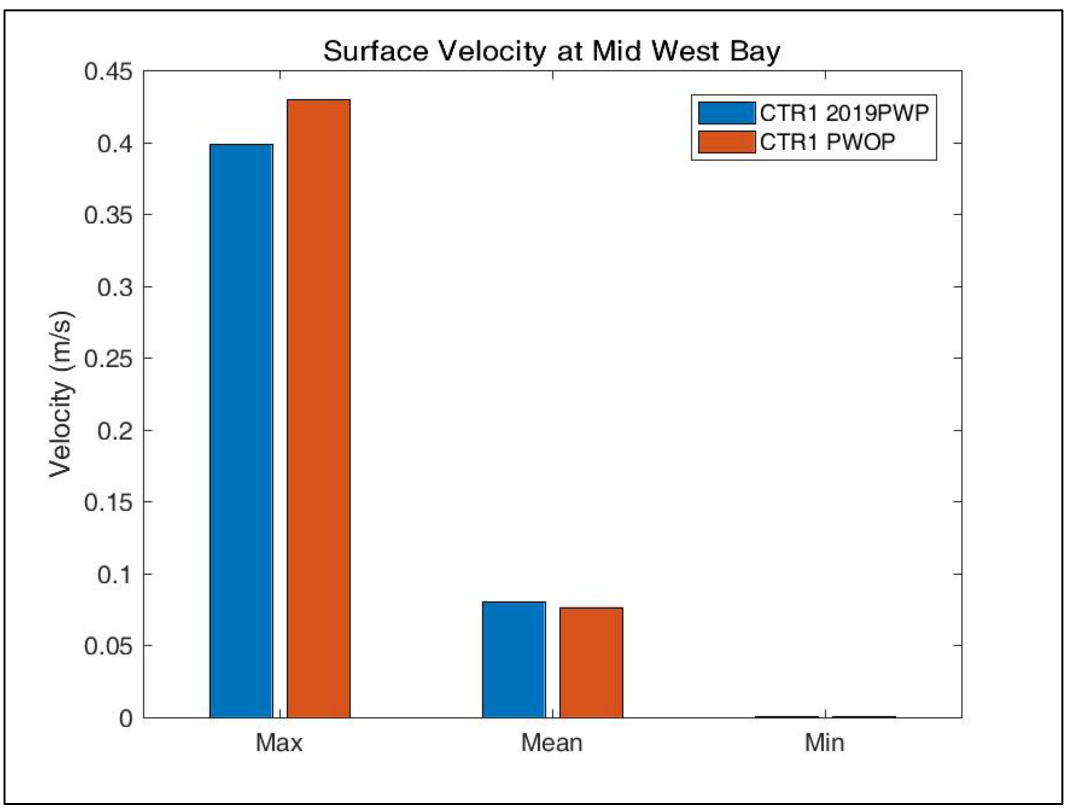


Figure 4-53. Surface velocity magnitude maximum, mean, and minimum at Mid West Bay.



Hydrodynamic Analysis at the Proposed Surge Barrier Location

The gated structures crossing the HSC and shallows at Bolivar Roads will impact local velocity and water levels in the area. The reduction in cross sectional area due to the structures forces a head difference across the structures and therefore a large velocity plume through the structures that could negatively affect navigation at certain times of the daily tidal signal.

Figure 4-54 shows the modified TSP as defined in the model along with a red observation arc through the navigation structure. This arc is not the same length as that in McAlpin et al. (2019 b); therefore, the computed head difference may not match the value provided in McAlpin et al. (2019 b). Figure 4-55 shows several days of tidal water surface elevation with the selected analysis tide (day 499 of the two-year simulation; 22 May of the analysis year) circled in red. This day experiences a large tide range during a spring tide period but the amplitude is not uncommon for this area. The water surface elevation across the structure at several points during this day are shown along with the surface velocity magnitude and vectors for each alternative in Figure 4-56 through Figure 4-59. The velocity magnitude is contoured from 0 to 3 m/s and the velocity vector length is fixed and intended to show direction only. The water surface elevation plot shows the present condition results.

For this analysis day, the largest surface velocity magnitudes as well as the largest head difference across the navigation structure occur at high tide and low tide as expected for the progressive wave behavior observed at Bolivar Roads (Savant and Berger 2015). The large tide range occurring daily during the spring tide creates jets of high magnitude velocity on the side of the structure to which the flow is directed – bay side for incoming flow and gulf side for outgoing flow. For this tidal signal, surface velocities through the navigation structure can reach 2 m/s (6.6 ft/s) in places. Eddies form on the backside of the structures, which may have impacts on navigation. During slack water the velocity magnitudes are much lower through the navigation structure but the velocity directions may be such that navigation is impaired. These vectors should be analyzed carefully when designing the final structure configuration such that navigation restrictions are fully understood.

The water surface elevation change across the navigation structure (or head difference) can also impact safe navigation and should be reviewed carefully. Table 4-7 provides the head difference along the observation arc for all alternatives at each of the analyzed tidal conditions. For this tidal signal, the head difference at high and low tide conditions ranges between 0.1 and 0.044 m. For this signal, the low tide condition produces a greater water surface elevation difference than the high tide condition.

Figure 4-54. Observation arc (red) for analyzing water surface elevation change through TSP navigation structure.

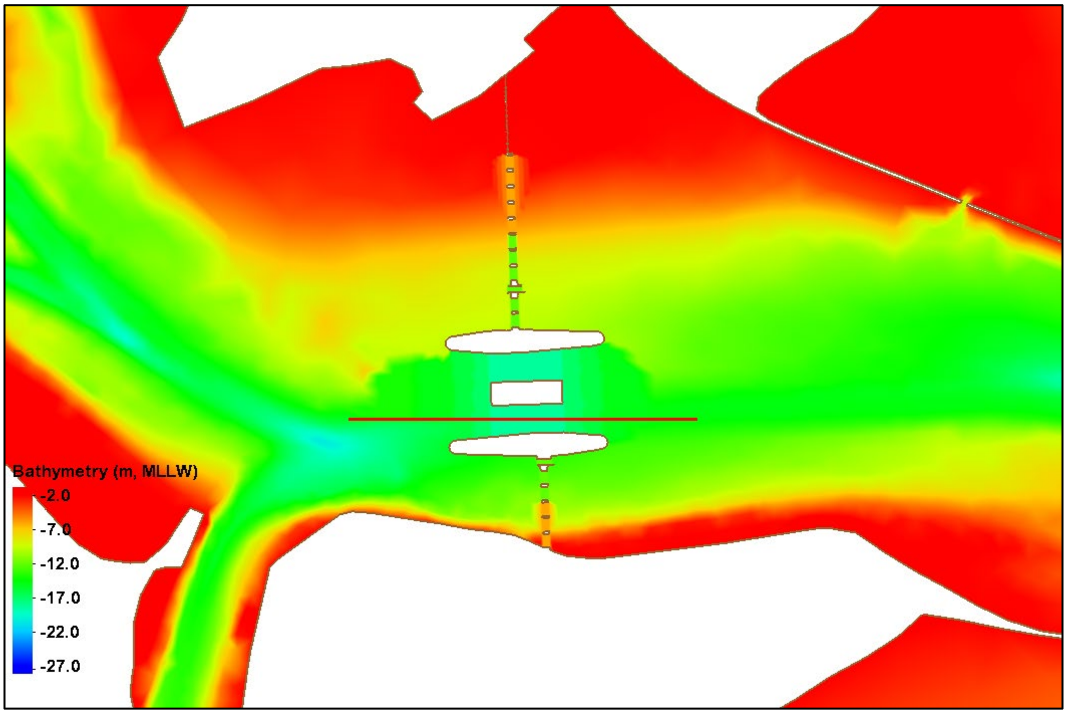


Figure 4-55. Present tide condition with analysis day circled in red.

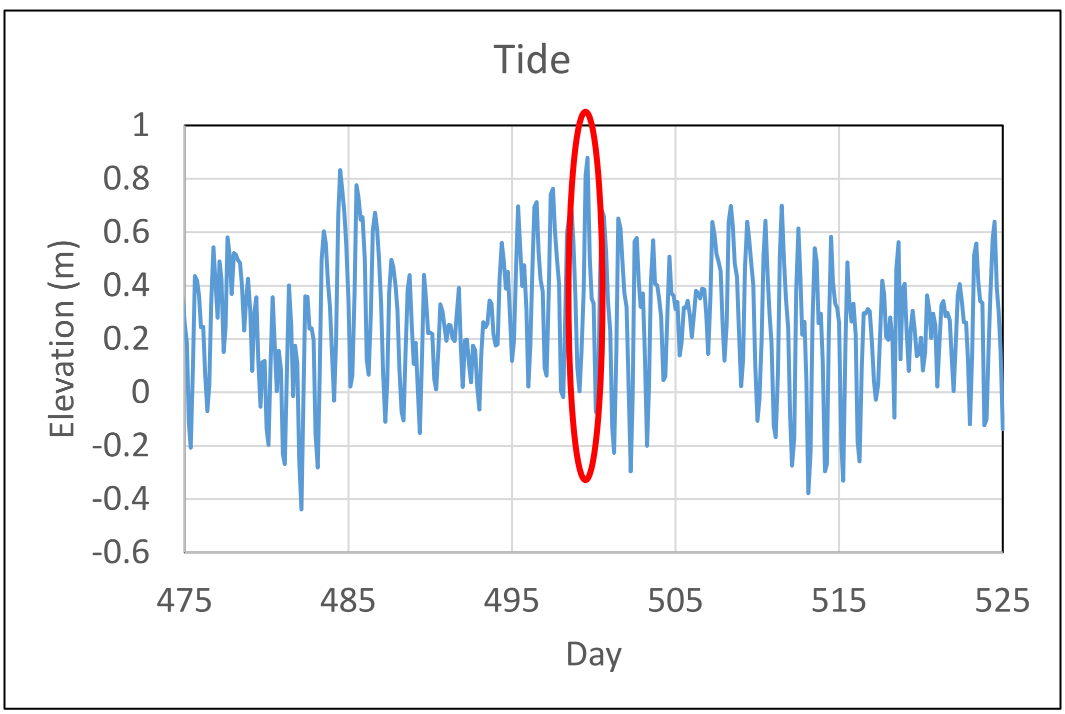


Figure 4-56. Velocity and water surface elevation at the TSP location at low tide.

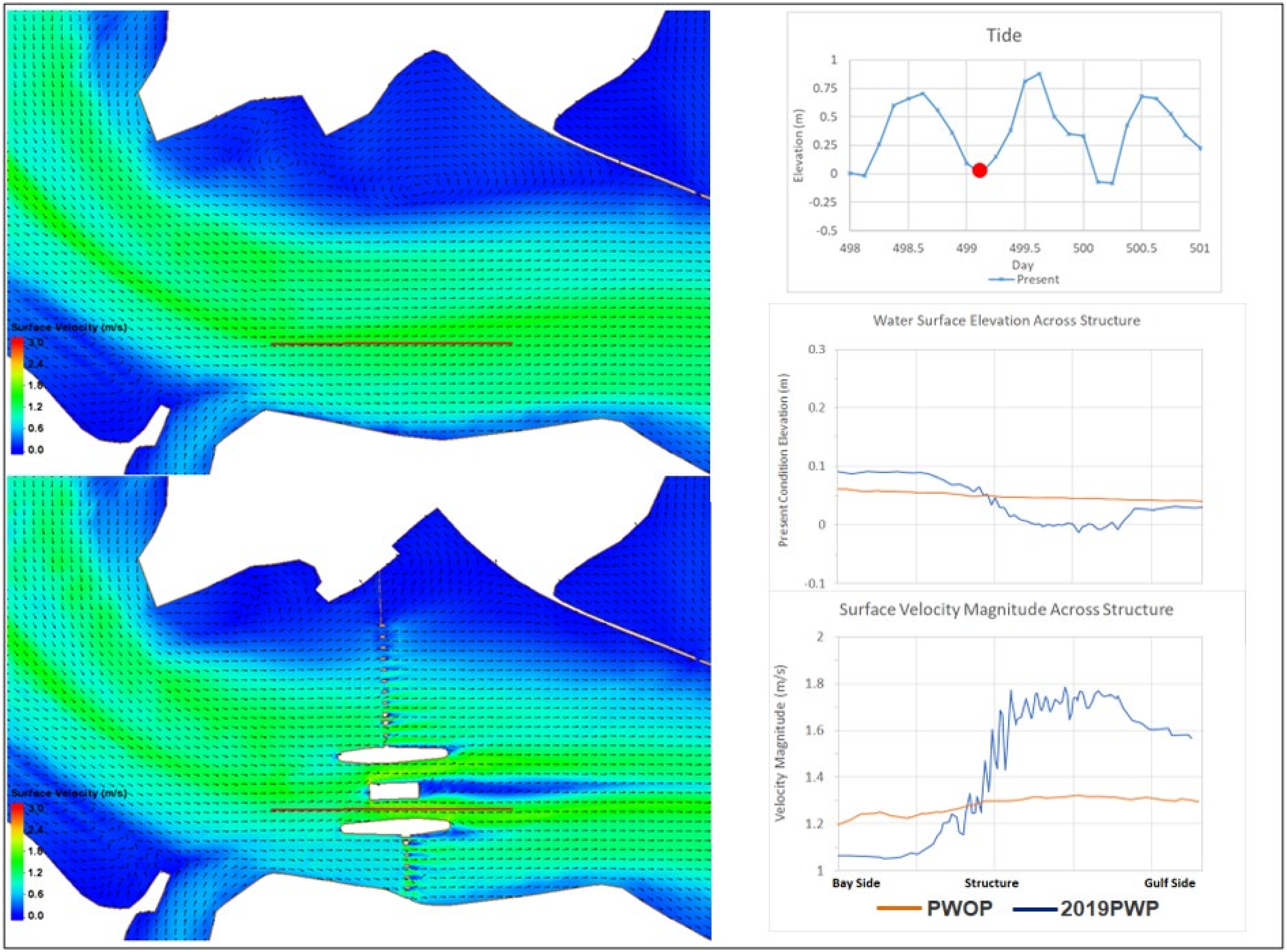


Figure 4-57. Velocity and water surface elevation at the TSP location at slack water during rising tide.

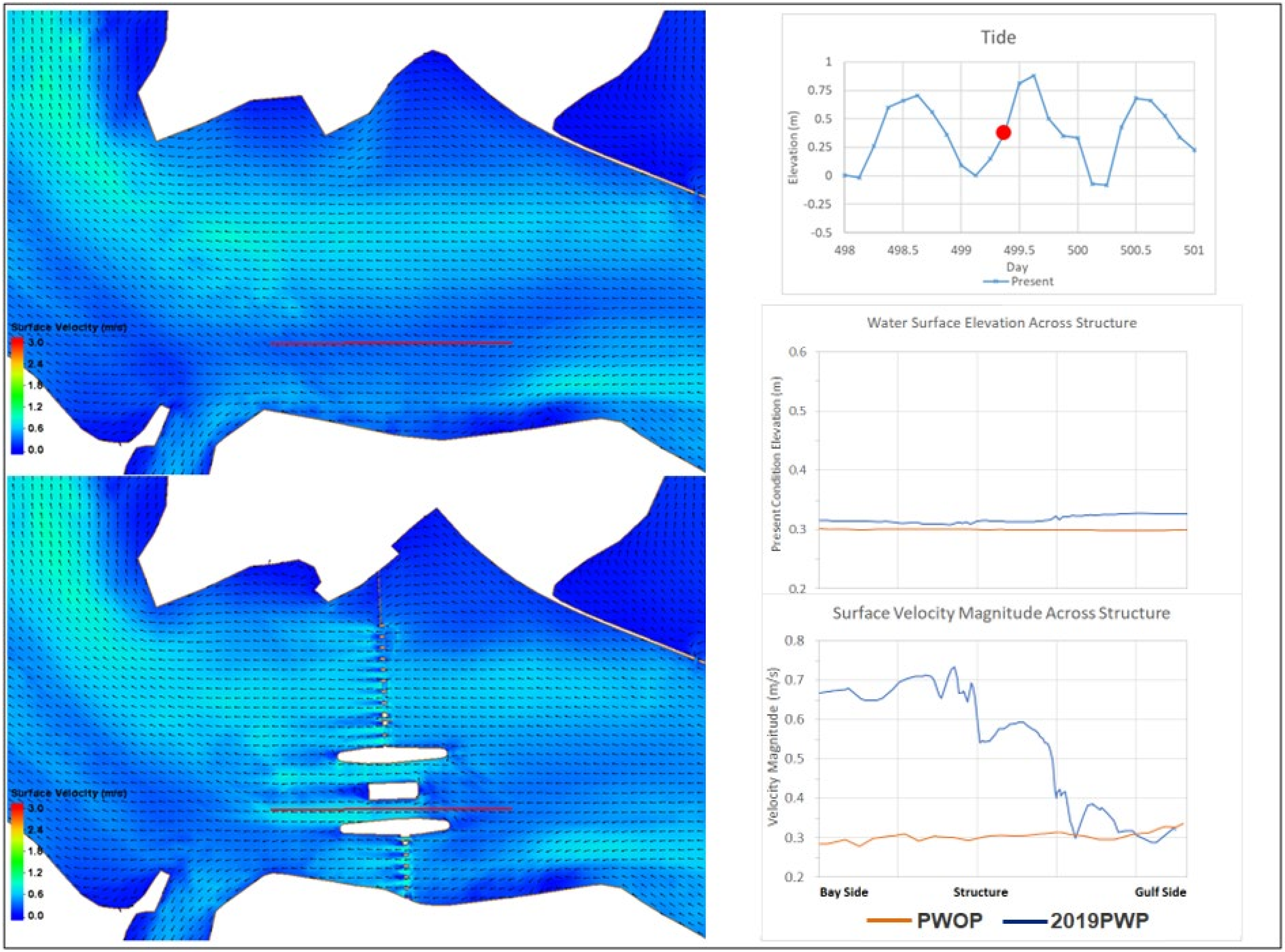


Figure 4-58. Velocity and water surface elevation at the TSP location at high tide.

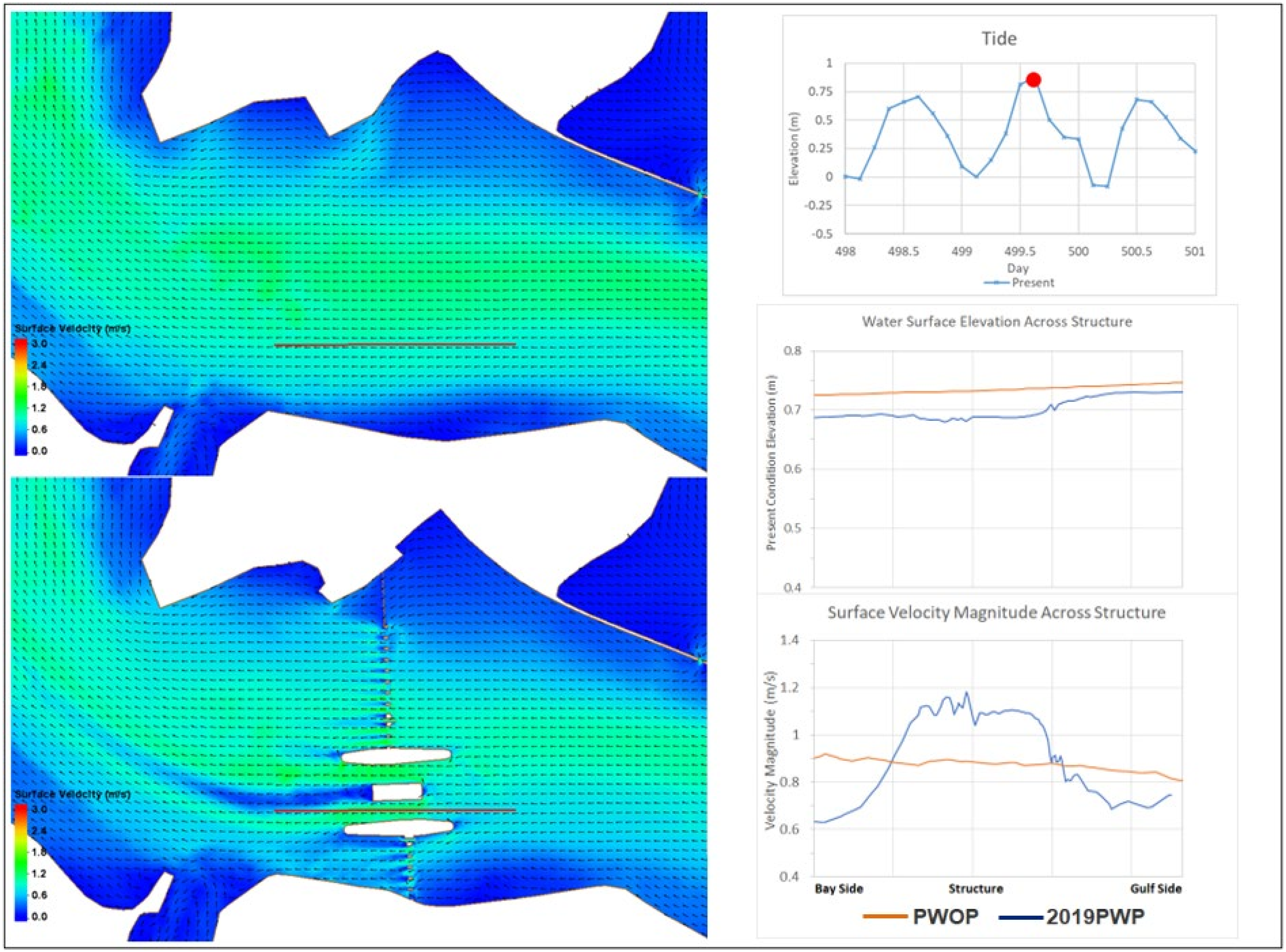


Figure 4-59. Velocity and water surface elevation at the TSP location at slack water during falling tide.

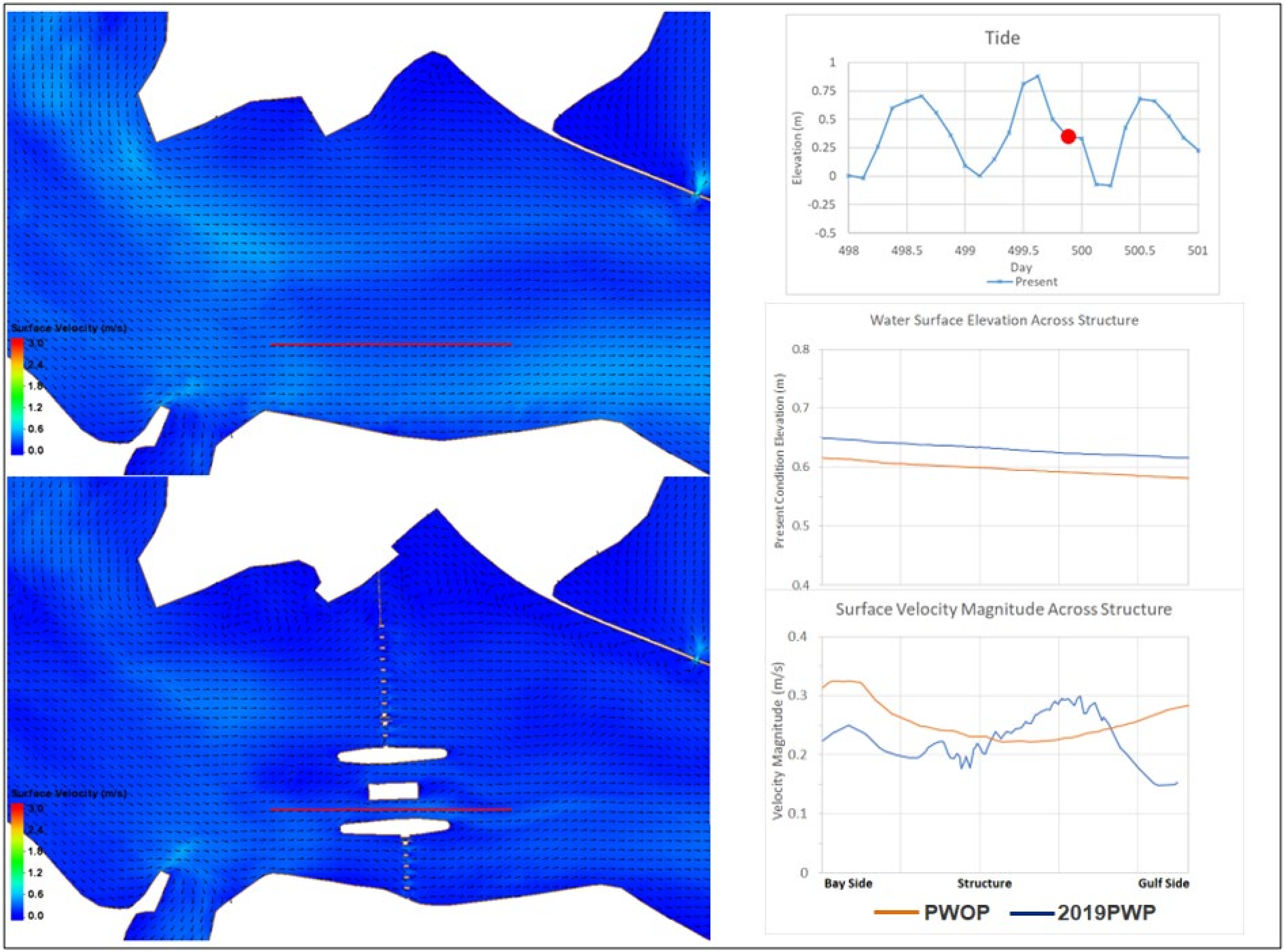


Table 4-7. Water surface elevation change (head difference) across the navigation structure.

Tide Condition	Head Difference (m)	
	2019PWP	PWOP
Low Tide	0.104	0.021
Rising Tide Slack	0.011	0.002
High Tide	0.044	0.021
High Tide Slack	0.033	0.034

5 Characteristic Larval Transport Results

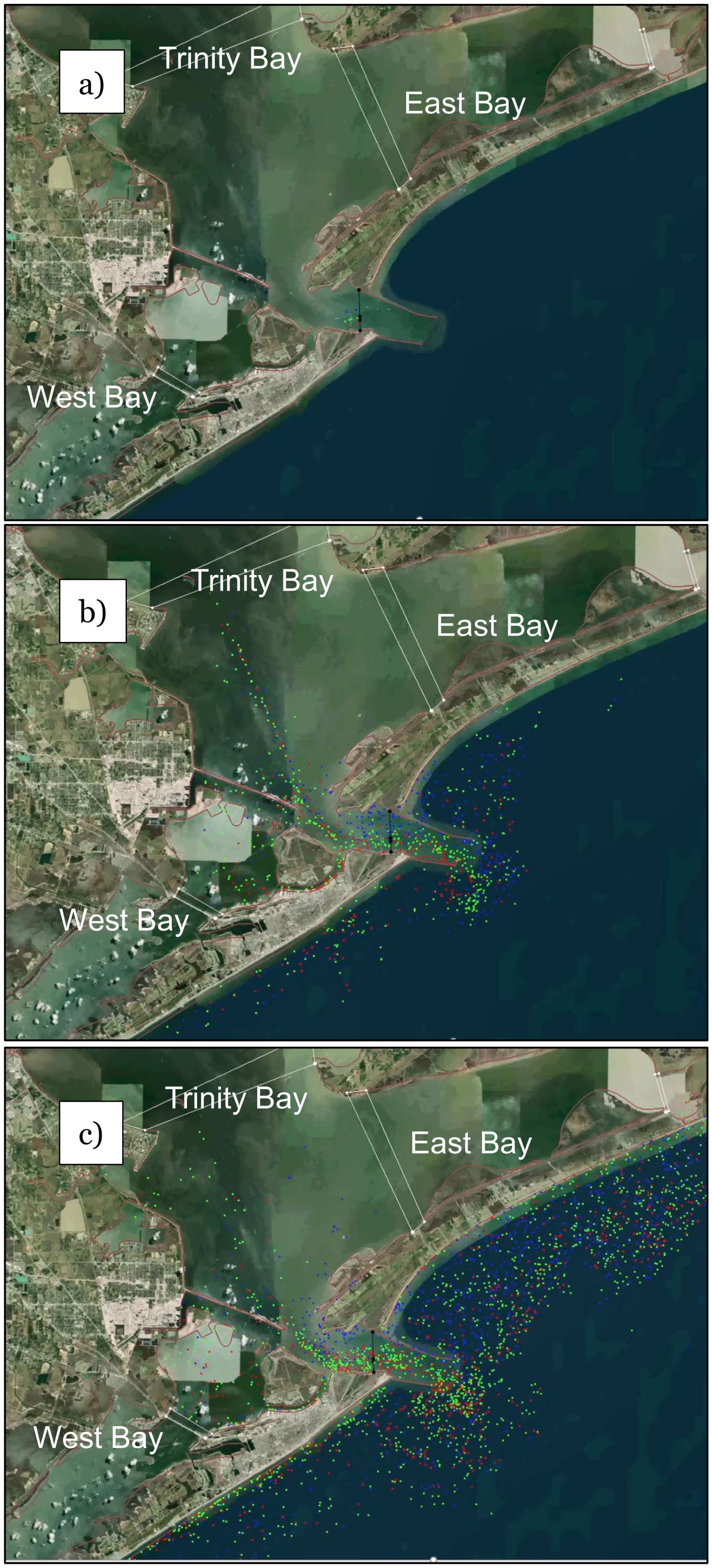
The Particle Tracking Model simulated five weeks of characteristic larval transport for the with and without project conditions. Results are presented as particle positions, time series of recruitment, recruitment rate, and finally, an analysis of recruitment numbers based on various parameters.

Particle Positions

Particle locations are presented as snapshots of the larval marine species transport at different points in time. These results show qualitative information regarding preferred transport direction and certain dynamic elements of the system.

Particles are initiated across the channel (Figure 5-1a). As mentioned in the methods section, the number of particles initiated in each section differs. In the figures this is visualized through color coding. Twenty-five percent of the particles are initiated on the south-west side (red), fifty percent of the particles are initiated across the navigation channel (green), and the remaining twenty-five percent on the north-east side (blue). Because this flow is tidal, particles move in and out of the inlet. After a week (Figure 5-1b), a portion of the particles have been transported into the bay towards the recruitment areas. One dominant transport pathway is within the navigation channel into Trinity Bay. There is also a constant flow of particles towards the West Bay. There are significantly fewer particles moving towards the East Bay recruitment area. Figure 5-1c, shows a snapshot of the particle positions after 3 weeks. Many of the particles are transported along the coastline outside of Galveston Bay.

Figure 5-1. Particle positions at a) day 1, b) day 7, and c) day 21.

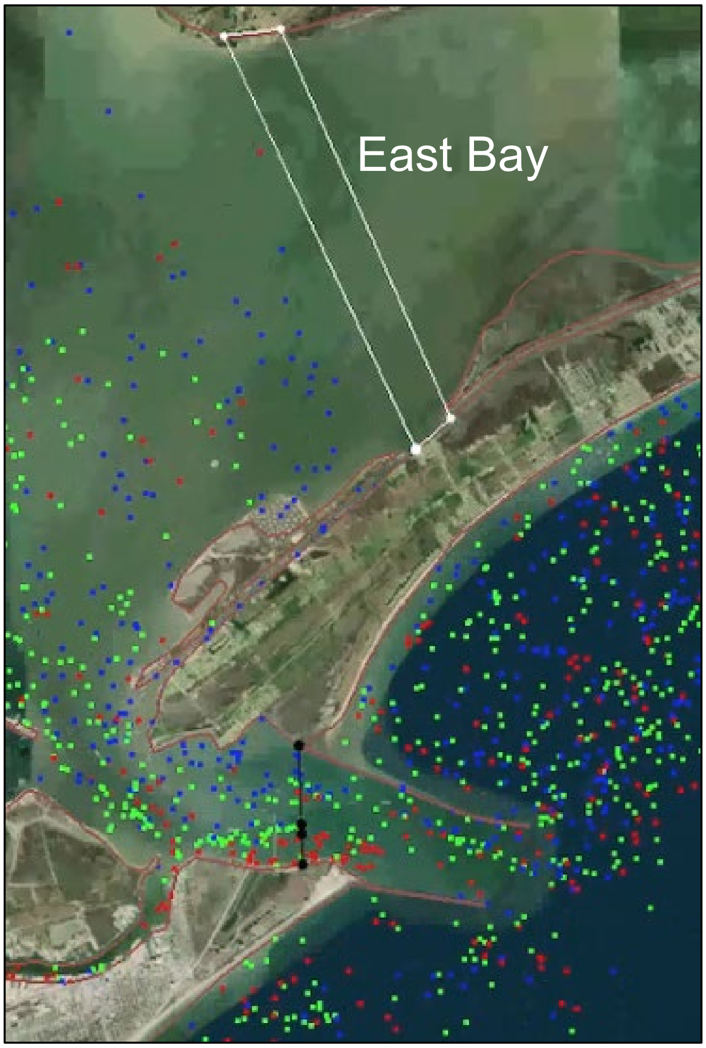


Although thousands of particles are initiated, only a fraction of them reach the recruitment area. The tidal nature of the system means that although the particles are initiated close to the gate position within the inlet, as the tide moves out, it forces the particles into the surrounding gulf. At some points in the simulation, most of the particles (Figure 5-2) have been swept out of the inlet and are traveling along the shorelines.

Figure 5-2. Particle position focused on transport along the shoreline .

Another noticeable characteristic of this system is the limited transport into the East Bay region. Although there are steady streams of particles that flow into Trinity and West Bay recruitment areas, East Bay recruitment is sporadic within the modeled time period. It is also evident that the majority of particles entering East Bay (Figure 5-3) are those that are initiated on the northwest side of the navigation channel (shown in blue in the figure).

Figure 5-3. Particle positions focused on transport into the East Bay.



Rollover Pass is currently a closed system. However, for the time frame of the hydrodynamics modeled, it has been left open. A recruitment trap was placed at Rollover Pass to determine if there was a significant percentage of particles that might enter into East Bay through this pass. Results show (Figure 5-4) that there are small amounts of particles that are transported through Rollover Pass, but not enough to significantly impact overall statistics.

Figure 5-4. Particles entering Galveston Bay area through Rollover Pass.

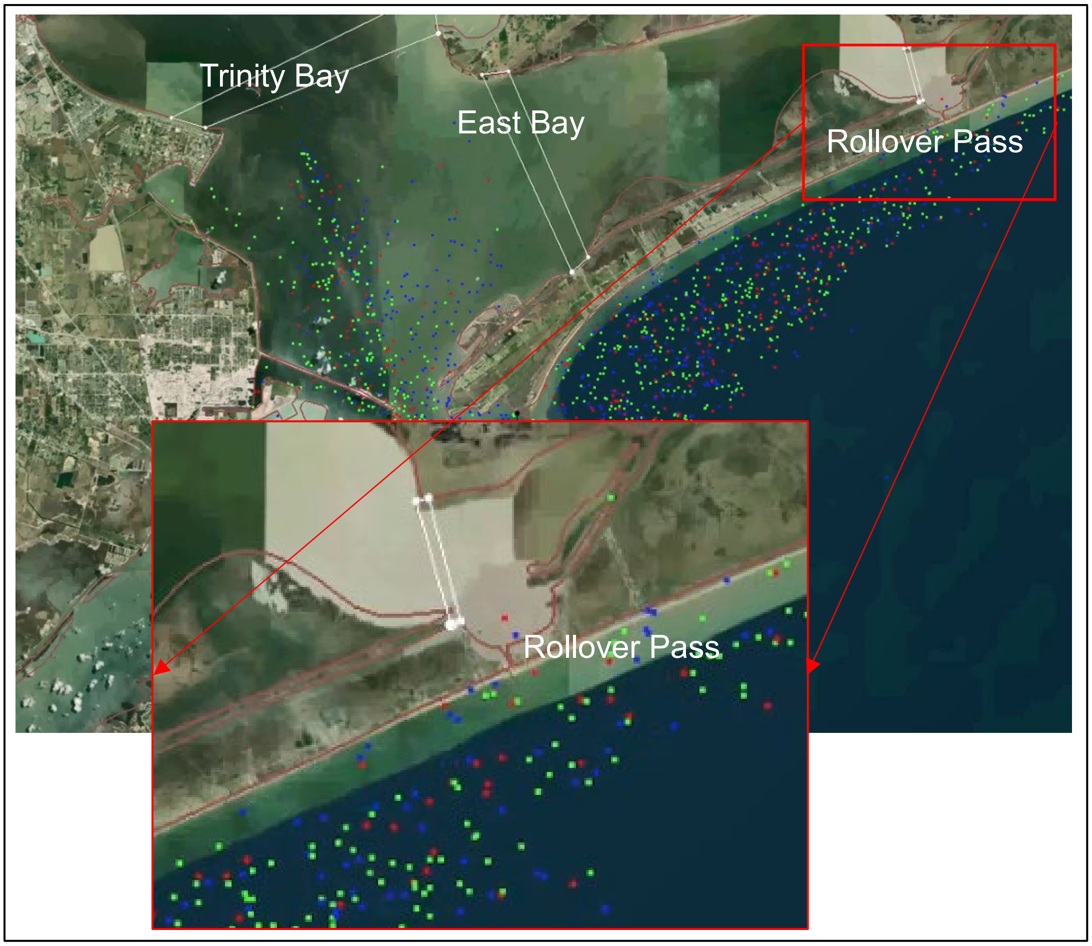


Figure 5-5 shows a comparison at two weeks of the a) base condition and b) with project condition. Qualitatively the two cases appear to be very similar. The overall transport trends are the same: 1) pathway of particles moving within navigation channel to Trinity Bay, 2) transport of particles along the shoreline, 3) transport towards West Bay, and 4) few particles moving towards East Bay. It is evident from this snap shot that a statistical analysis is necessary to understand any quantitative differences.

Figure 5-5. Comparison of a) base condition and b) with project conditions.

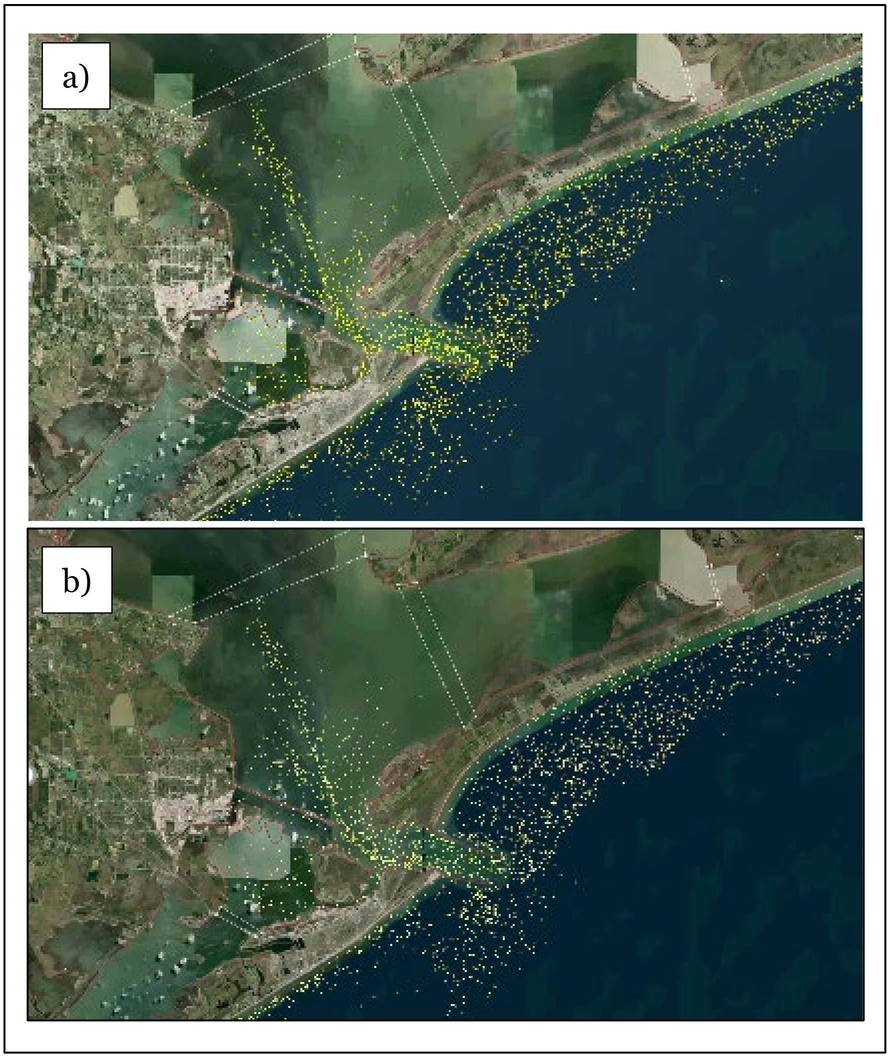
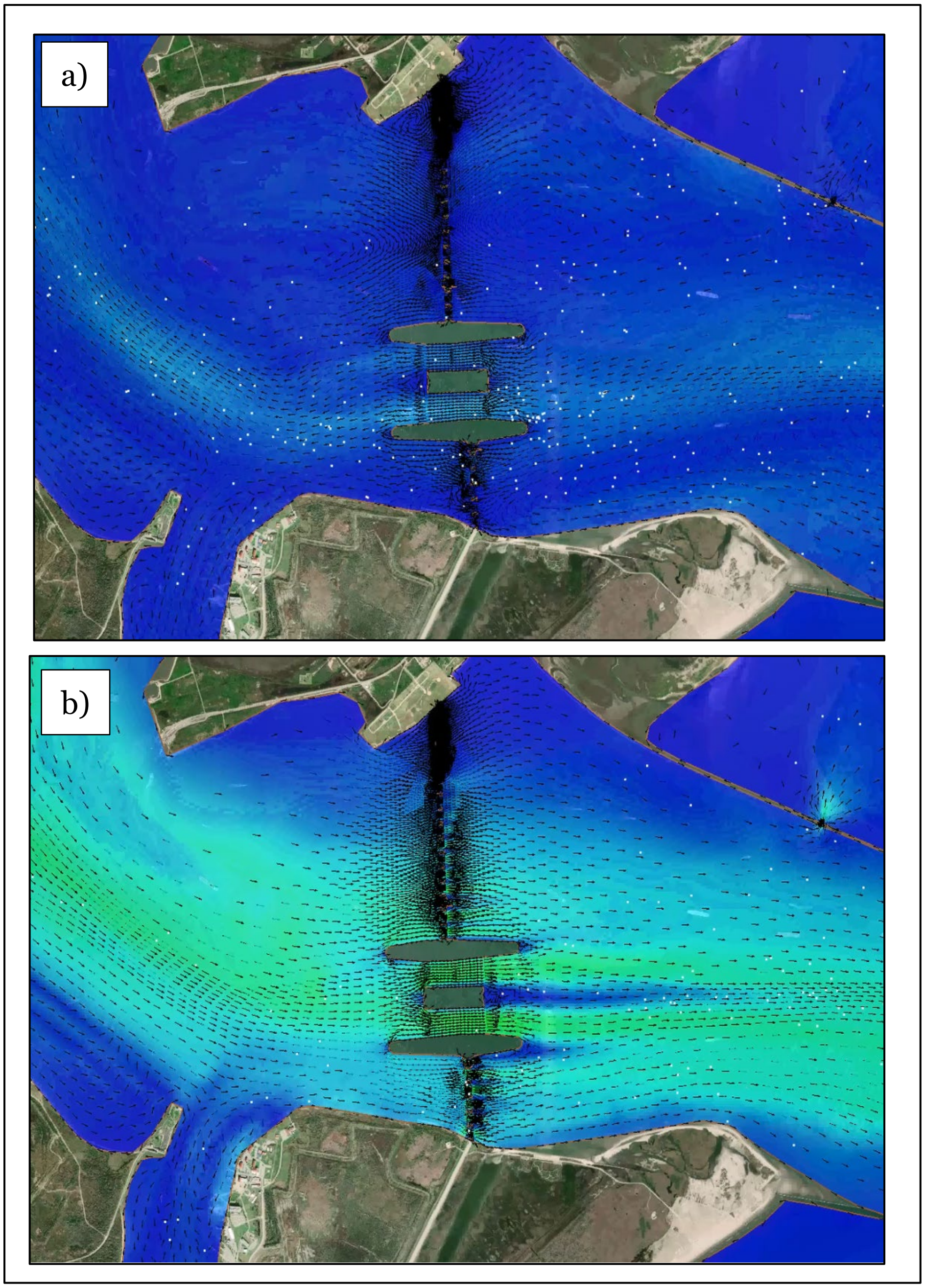


Figure 5-6 shows particle results in the vicinity of the gate structure at a) a low flow period and b) a high flow period. Directly behind the gate a recirculation region develops during simulation. It is not maintained throughout the entire simulation but evolves and devolves with time. This recirculation region appears to shelter a small fraction of particles, preventing them from being transported out into the Gulf during the outgoing tide.

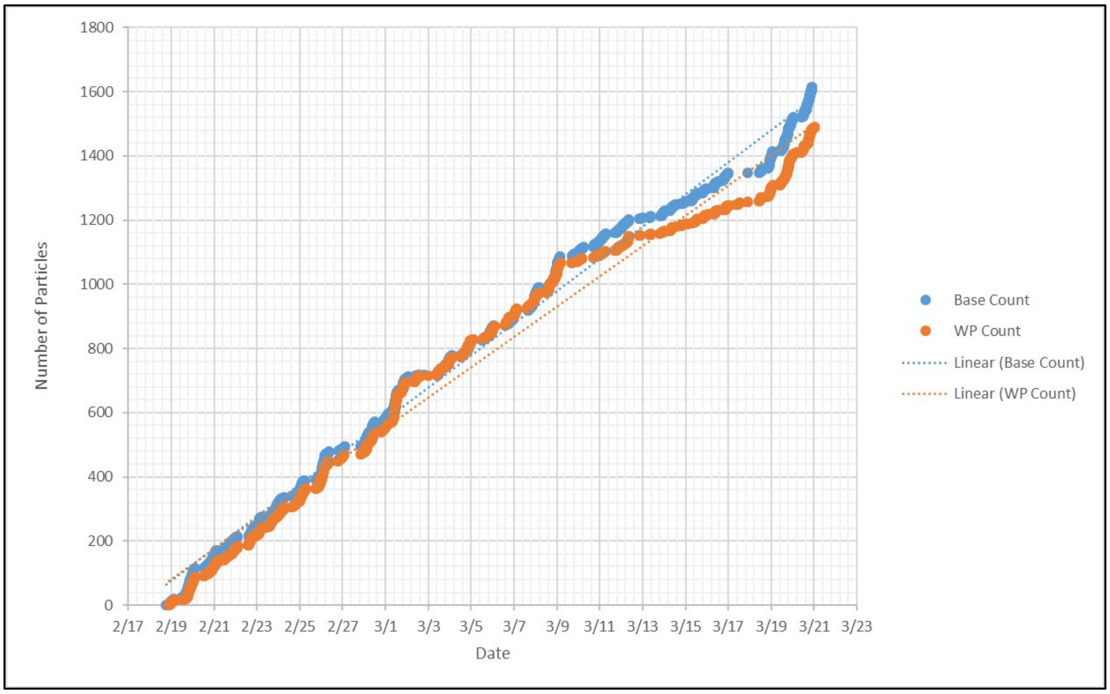
Figure 5-6. Particle transport near the gate a) low flow period and b) high flow period.



Time Series of Recruitment

Time series of recruitment provides an assessment of the rate of recruitment as well as the impact of external forcings on the recruitment rate. Figure 5-7 shows the recruitment rate of the particles for the without project or base condition (blue), and the with-project condition (orange). As a particle reaches the recruitment area, it is counted. The total number of particles recruited at a specific time is visualized in the time series of recruitment. The peaks and plateaus of the recruitment plot are representative of times during which many particles are transported into the recruitment area and then subsequent times (for example, as the tide flows out) when no particles are recruited.

Figure 5-7. Time series of recruitment of particles for without project or base condition (blue) and with project (WP) condition (orange).

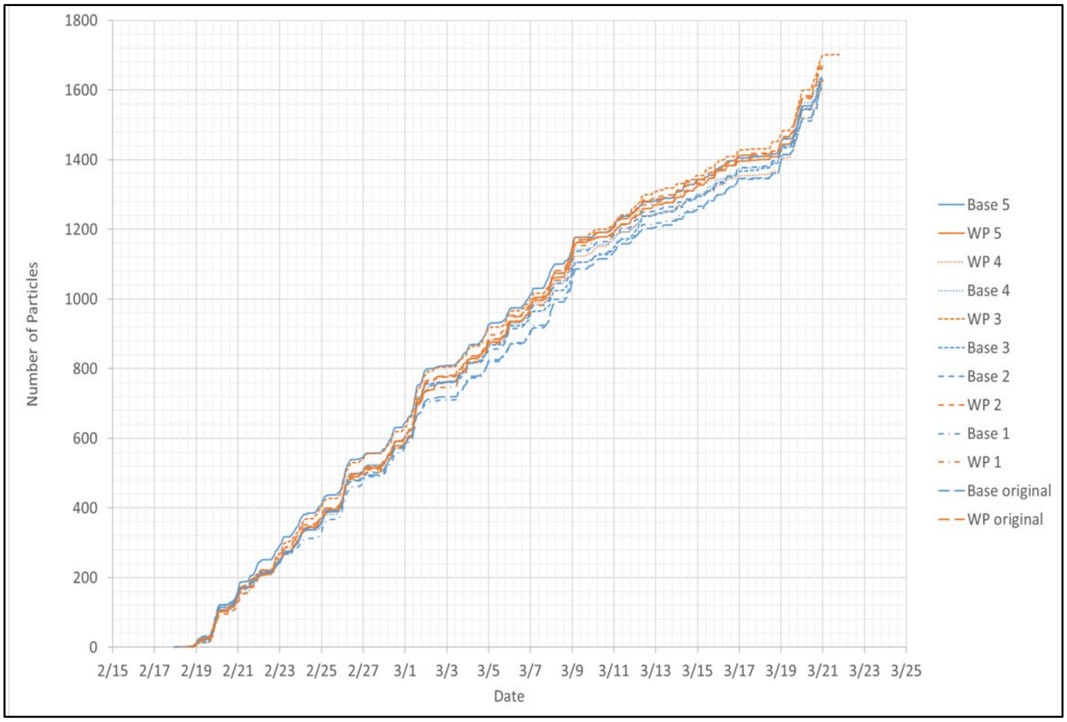


For the most part, we see that the two lines are visually the same, until the end of the simulation where there is a separation and then the lines move back towards each other. To understand if the period of difference between the time series is significant, a series of sensitivity simulations is performed.

Sensitivity Simulations

Because particle recruitment is dependent on the Lagrangian transport algorithm which have several random parameters, the same initial conditions can produce slightly different results. The primary source of the randomness is from the random walk diffusion subroutine contained within the model (King and Lackey 2015), but there is also randomness that occurs as particles interact with boundaries. A series of simulations is performed to determine the impact of the randomness on recruitment and to see if differences between the base case and with project case are within the sensitivity of the results. Figure 5-8 shows the outcome of the 12 simulations (six base condition, and six with project condition).

Figure 5-8. Outcome of PTM sensitivity simulations for without project or base condition (blue) and with project (WP) (orange).



To quantify the differences between the simulations, the slope of the time series was determined (slope = number of recruited particles/simulation length). This slope can be defined as a rate of particle recruitment (Table 5-1). The rate results show that the average rate of recruitment between the simulations for the base case is 53.4 particles per day and for the with-project case is 54.4 particles per day. There is a range of results of approximately 3.5 particles per day for both cases and a standard deviation of approximately 1.3. The differences between the average rates fall within the sensitivity of the model runs, thus the model results are considered as comparable.

Table 5-1. Rate of particle recruitment sensitivity table.

	Without Project or Base	With Project (WP)
Original	53.1	54.8
Sensitivity Simulation 1	51.6	55.1
Sensitivity Simulation 2	53.1	54.7
Sensitivity Simulation 3	54.9	56.3
Sensitivity Simulation 4	53.1	52.5
Sensitivity Simulation 5	54.6	52.9
Average	53.4	54.4
Minimum	51.6	52.5
Max	54.9	56.3
Range	3.3	3.8
Standard deviation	1.2	1.4

The change in the tidal prism at Bolivar Roads is a reduction of 3.22% as shown in Table 4-2. Although there is a restriction on the volume of water exchanging through the structures, the particle recruitment is essentially unchanged. The reduced cross-sectional area imposed by the structures generates increased velocity at times of high and low tide, making it easier for particles to get pushed into the bay and recruited. It appears that the increased velocity at the structures is making up for the reduced tidal prism exchange, giving a near zero net change on the particle transport.

Recruitment Analysis

Recruitment statistics are shown in this section with comparisons of behavior, recruitment area, and alternative. Behavior type can potentially be attributed to a specific marine species, which may give insight into the impact of the alternatives to those species. Figure 5-9 shows a chart which compares the number of particles recruited for the base (without project) and with project conditions, separated into each behavior type. As expected from the time series of recruitment, the overall recruitment is very similar between the two hydrodynamic conditions. It can be noted, however, that the recruitment level is impacted by behavior. The tidal vertical particles have the largest recruitment levels. The diel vertical and bottom movers have the lowest recruitment levels. Bottom movers experience the lowest velocities, so that may be expected. The trend which shows higher levels of recruitment for particles which have tidal vertical characteristic behavior suggests that for this system, that style of transport is the most efficient.

Figure 5-9. Comparison of recruitment (combined from all recuritment locations) based on behavior for without project or base condition (blue), with project (WP) (orange).

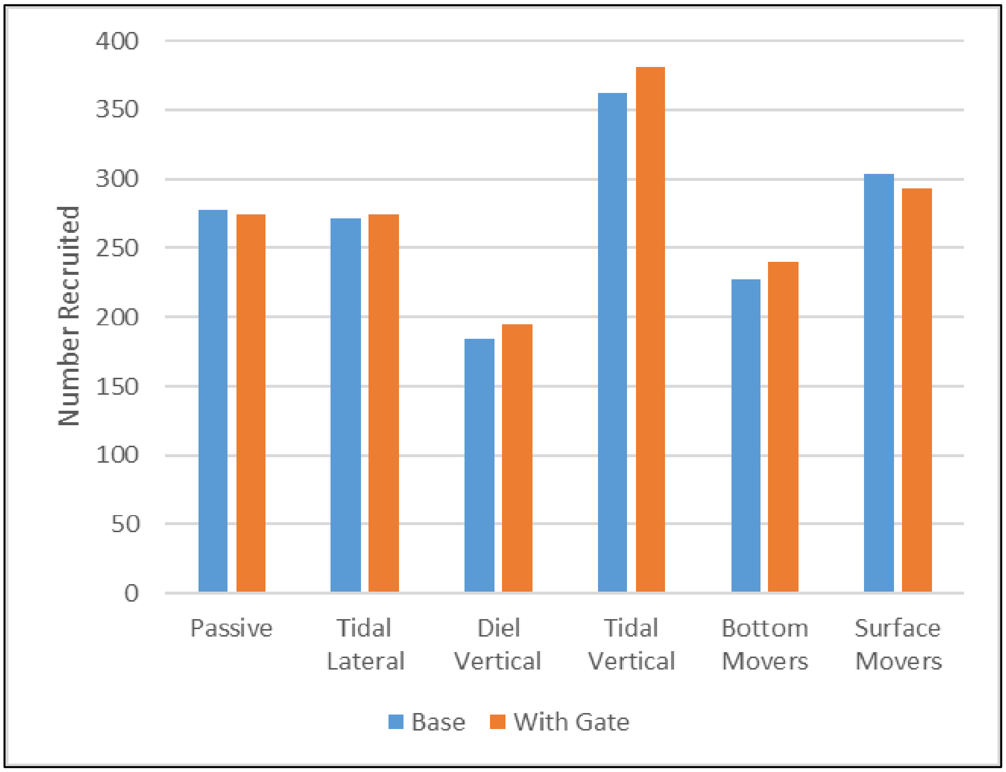


Figure 5-10 shows a comparison of the recruitment rate based on the four recruitment locations. As expected from the particle position results, the main pathways to recruitment are at the Trinity and West Bay areas. The East Bay location shows approximately 10-15% of the particles recruited at that location. Rollover Pass has the least amount of recruitment which is also in alignment with the particle position results.

Figure 5-10. Comparison of recruitment based on recruitment location for without project or base condition (blue), with project (WP) (orange).

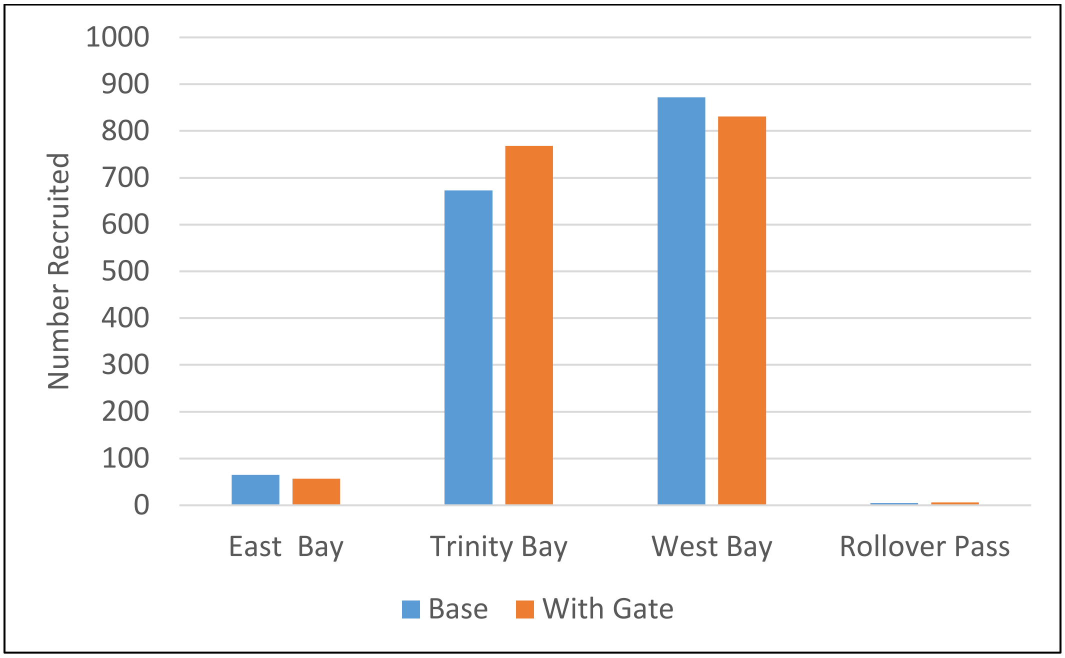


Figure 5-11 and Figure 5-12 show the breakdown of recruitment based on behavior and recruitment locations for the base condition and with project condition respectively. As expected, there is a trend that the largest number of particles to be recruited for either the base or the with project condition are ultimately recruited at Trinity Bay and West Bay. Interestingly it appears that there is a slight preference in the base case particles that are recruited at East Bay. The majority of particles that are recruited at East Bay in the base case seem to be tidal vertical. However, because the number of particles recruited at East Bay is so small, that may be an artifact of the simulation. To understand that trend better, a sensitivity study of tidal vertical particle transport into East Bay would need to be performed. That is potentially a question that can be addressed in future work.

Figure 5-11. Comparison of recruitment with behaviors and location for without project or base condition.

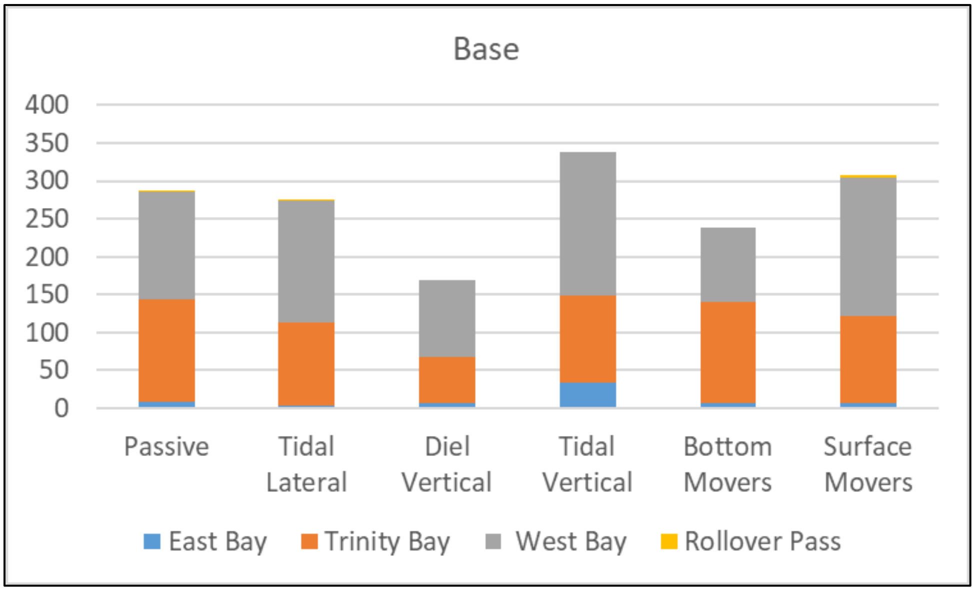
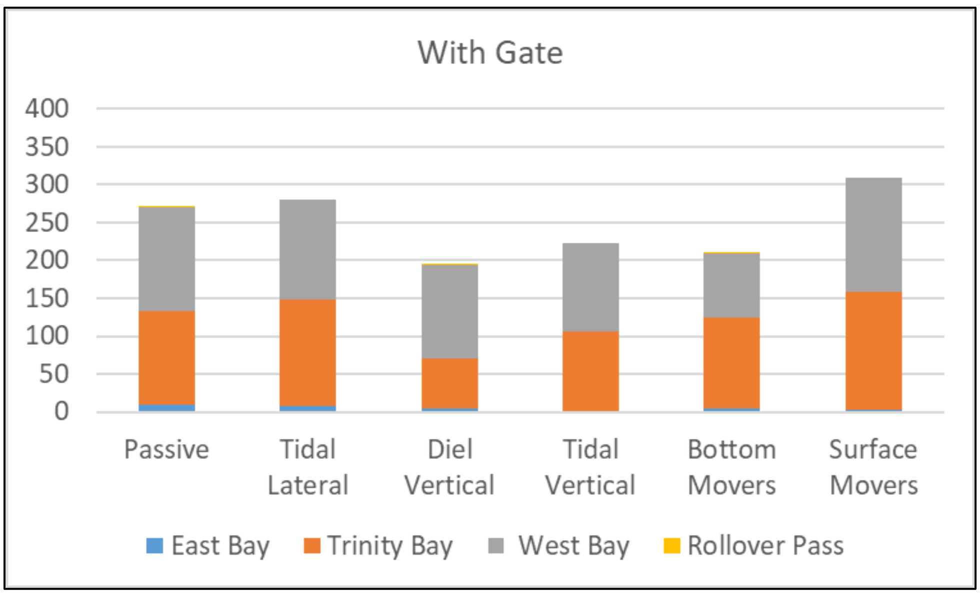


Figure 5-12. Comparison of recruitment with behaviors and location for with project condition.



6 Summary

This report provides an assessment of the recruitment of particles which maintain characteristic larval marine species transport within Galveston Bay. Model simulations compare current conditions with proposed structure conditions. The document provides details of the 3D AdH numerical model results for the Coastal Texas, Region 1 estuarine modeling of the modified Tentatively Selected Plan. The AdH results were used as model input for the Particle Tracking Model (PTM) and provided an assessment of the tidal prism, salinity, water surface elevation, and velocity changes due to the proposed structures.

Hydrodynamic Modeling

The two alternatives – present without project and present with project – are simulated over a two-year period with the first year for salinity initialization and the second year for analysis of hydrodynamic and salinity results. Overall, the present with project alternative had little effect on bay salinity and velocity patterns, but it does generate significant local changes in velocity patterns near the gated structure. The TSP also impacts the tidal prism – the exchange of water in and out of the bay system on each tide – as well as the tidal amplitudes within the bays.

The salinity was analyzed at 23 locations along the HSC and in the surrounding bays. On average, the salinity did not vary by more than 2 ppt between with and without project conditions at any location. At some locations the maximum or minimum salinity values varied by more, but these are extreme values and likely only occur a couple of times throughout the simulation year. The percent less than plots of salinity show the range of salinity values for all locations over the simulation period and, again, show little variation between with and without project results.

The average tidal prism and average tidal amplitudes at the 23 locations did vary between with and without project over the simulation year. The tidal prism change with the project alternative in place is a 3.22% reduction for the present conditions. The tidal amplitudes also reduced at all bay side locations – between 2.4 and 5.7 %. The tidal amplitude increased at locations on the Gulf side of the gated structure.

The velocity magnitudes vary little between with and without project for locations away from the gated structure TSP. The mean surface and bottom velocity magnitudes generally drop when the project is in place but this change is less than 0.1 m/s at all 23 analysis points and for most locations is 0.05 m/s or less.

The hydrodynamic values at the location of the gated structure show increased velocity magnitudes, eddy formations, and water surface elevation changes across the structures. These patterns should be reviewed in coordination with navigation requirements such that the final TSP design provides for safe navigation throughout the typical tidal conditions for the area. It is understood that more detailed and advanced physical and computational modeling will be conducted during the PED phase to resolve the 3D circulation and forcing around the gated structure as well as optimize the final structure design.

Larval Transport

Characteristic larval marine species transport was modeled using the Particle Tracking Model (PTM). A five-week period was simulated using AdH hydro as input and particles which had specific characteristic behaviors: passive, tidal vertical, diel vertical, bottom dwellers, top dwellers, and tidal lateral. Comparison of the impact of the added structure on larval marine species transport within the area was presented in the form of particle position maps, time series of recruitment, and graphs of the number of recruited particles based on specific characteristics such as behaviors and where recruitment occurred.

Results show very little difference between the amount of larval recruitment for the with and without project conditions. A sensitivity analysis was performed which shows the recruitment differences between the with and without project conditions are within the sensitivity of the model. The similarities between the with and without project recruitment results are supported by the tidal prism results. The gate structure was added with the specific plan that the overall volume of flow into the system would remain relatively constant. This was accomplished by deepening the channel.

For both the with and without project conditions, the larval transport model results show some differences in recruitment based on characteristic behavior. Bottom dwellers and diel vertical particles seem to have the smallest rates of recruitment. Tidal vertical particles have the highest rate of recruitment. It was also shown that for both the with and without project conditions, the largest recruitment occurs at the West Bay and Trinity Bay locations and that there is very little recruitment into the East Bay.

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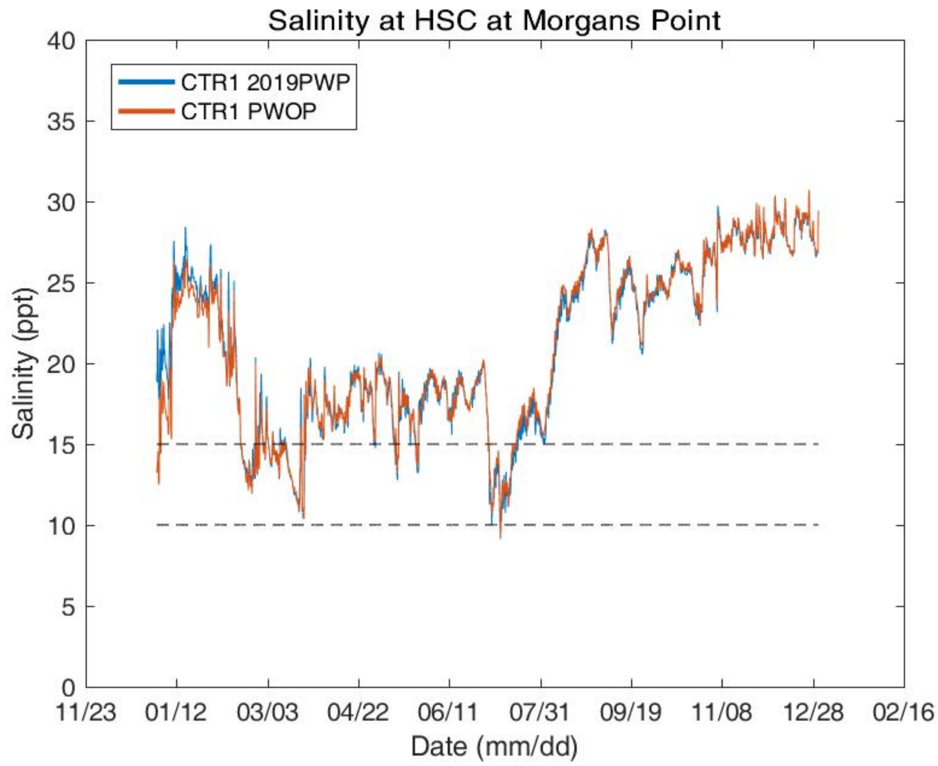
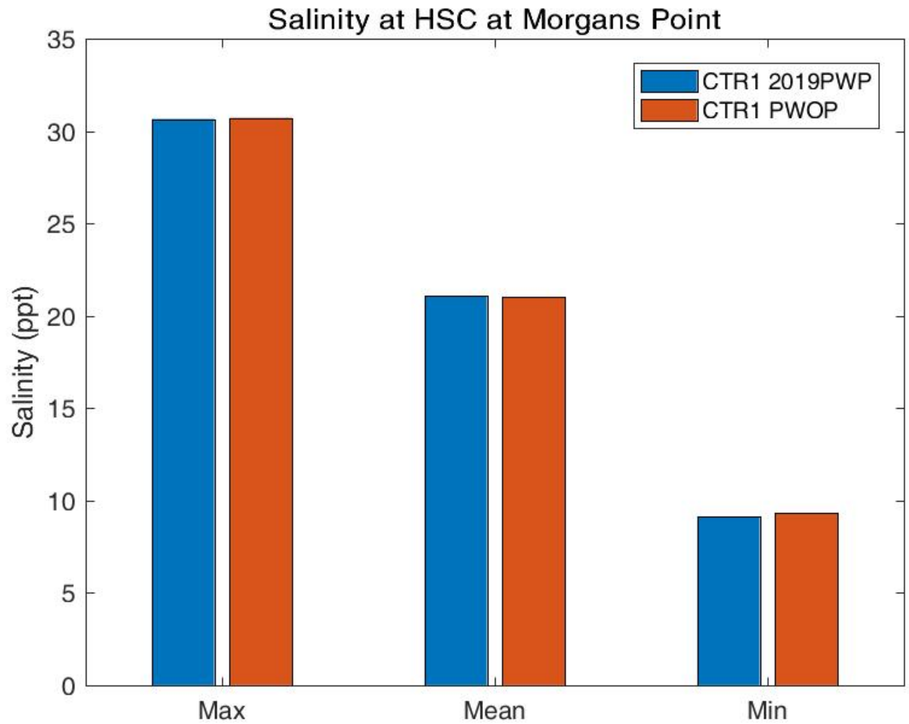
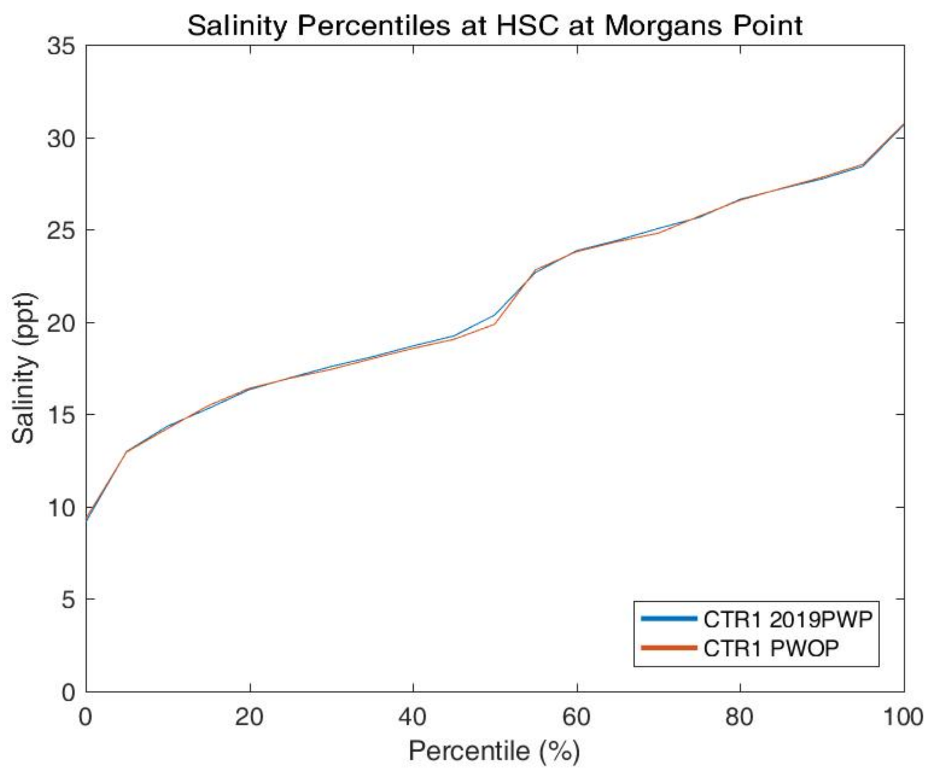
Appendix A: Salinity Point Analysis




Salinity at HSC at Morgans Point
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
35
30
25
20
15
10
5
0
Max
Mean
Min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CTR1 PWOP
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25
20
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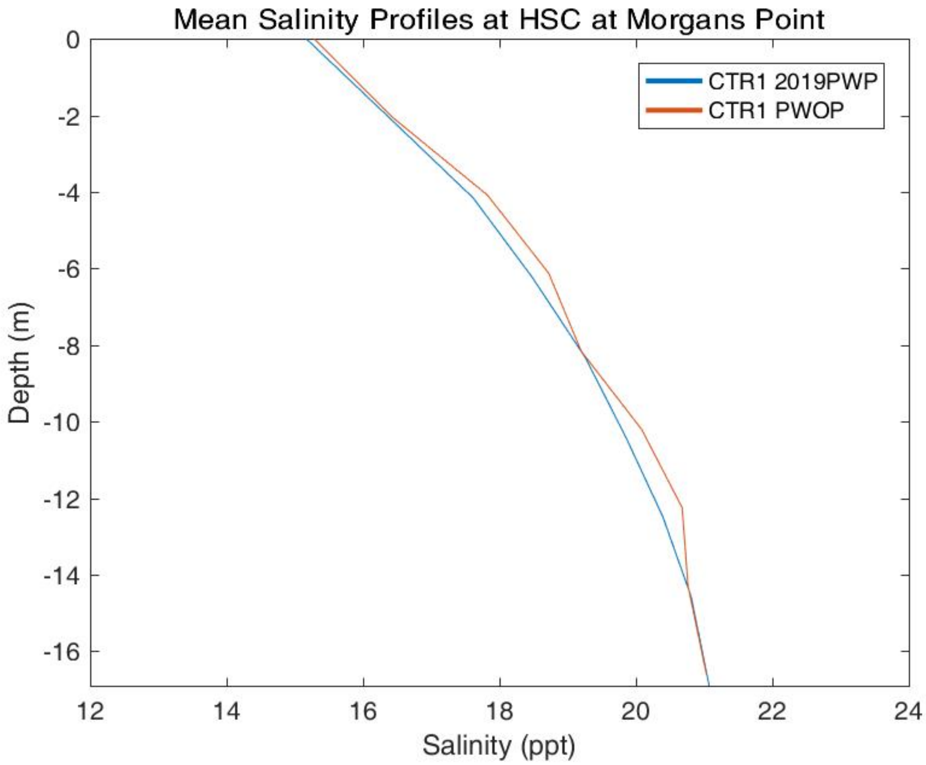
20
40
60
80
100
Percentile (%)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CTR1 PWOP
Depth (m)
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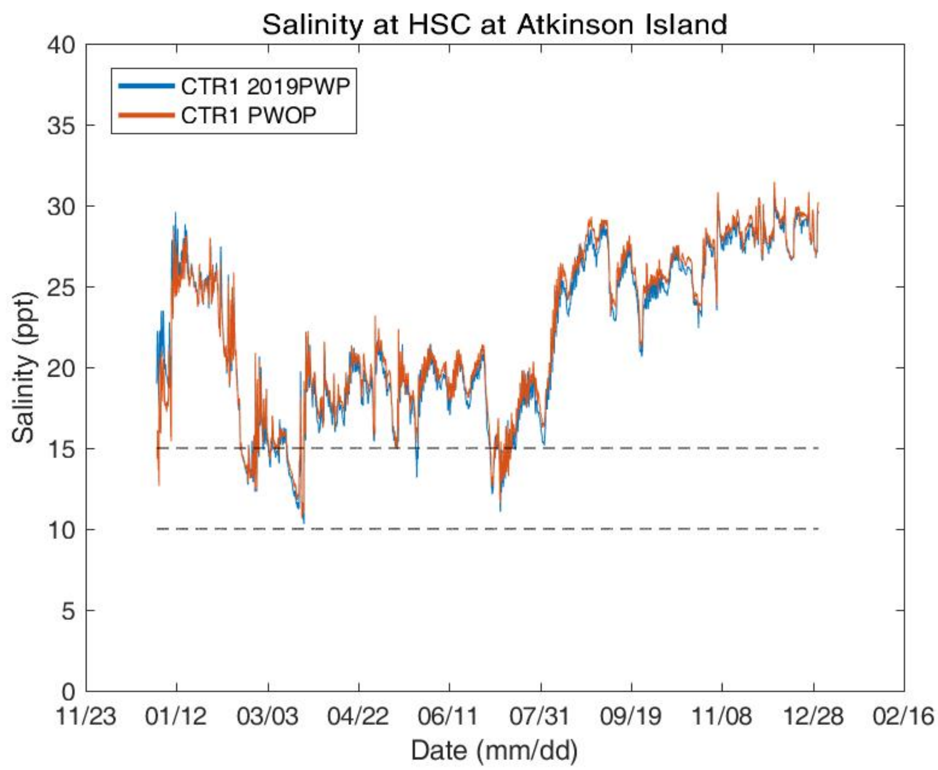
-8
-10
-12
-14
-16
12
14
16
18
20
22
24
Salinity (ppt)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CTR1 PWOP
Salinity (ppt)
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10
15
20
25
30
35
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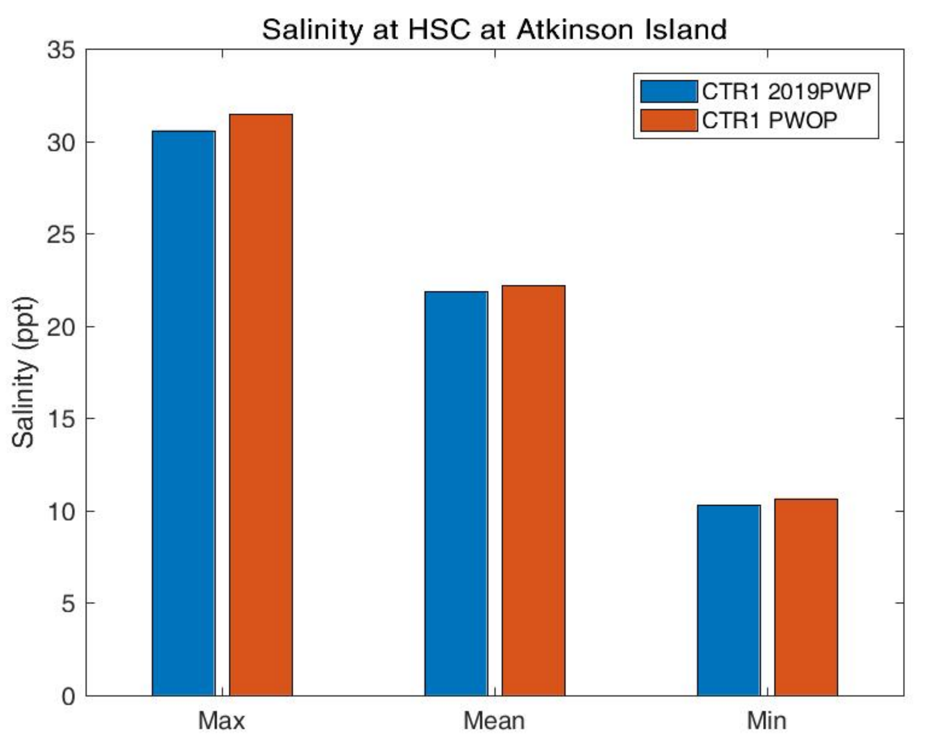
12/28
02/16
Date (mm/dd)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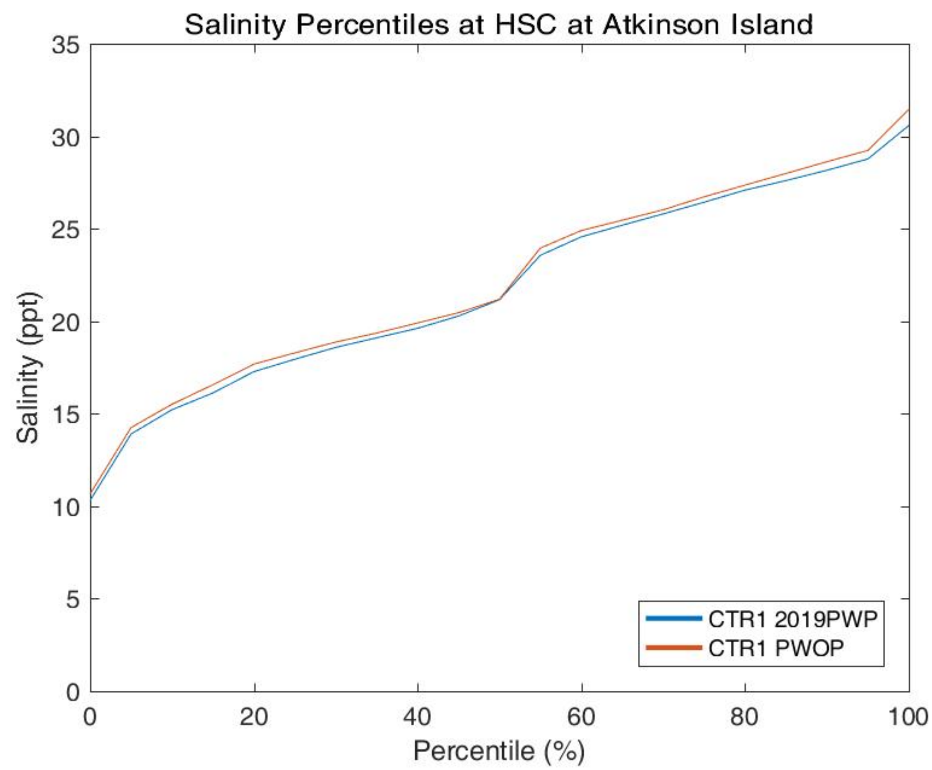
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min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Salinity (ppt)
Percentile (%)
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CTR1 PWOP
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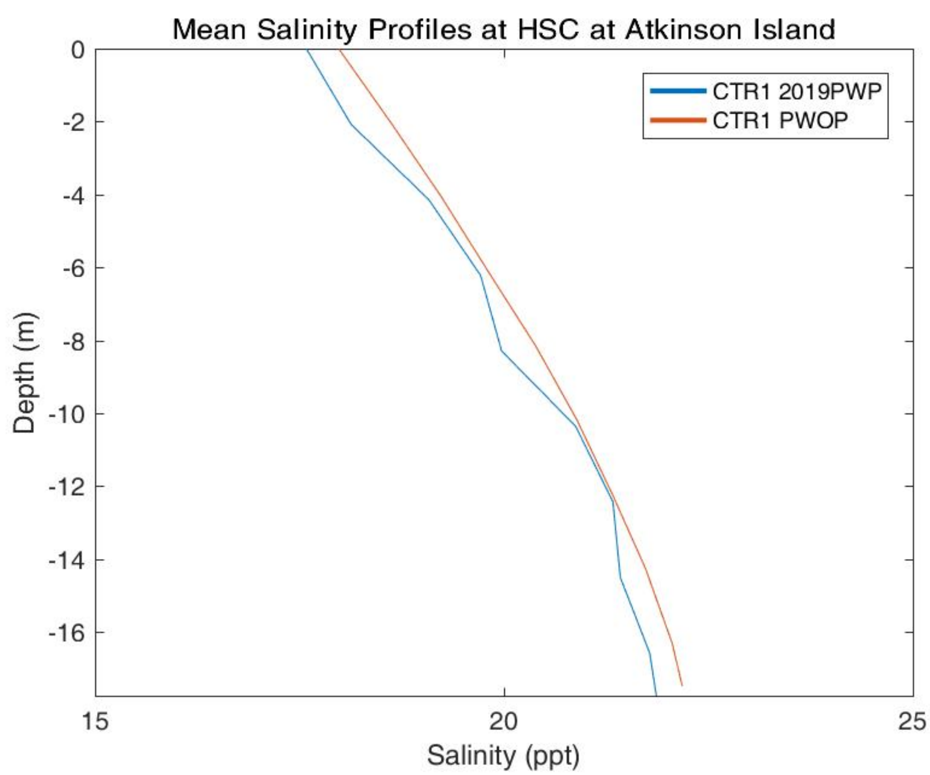
60
80
100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Depth (m)
Salinity (ppt)
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CTR1 PWOP
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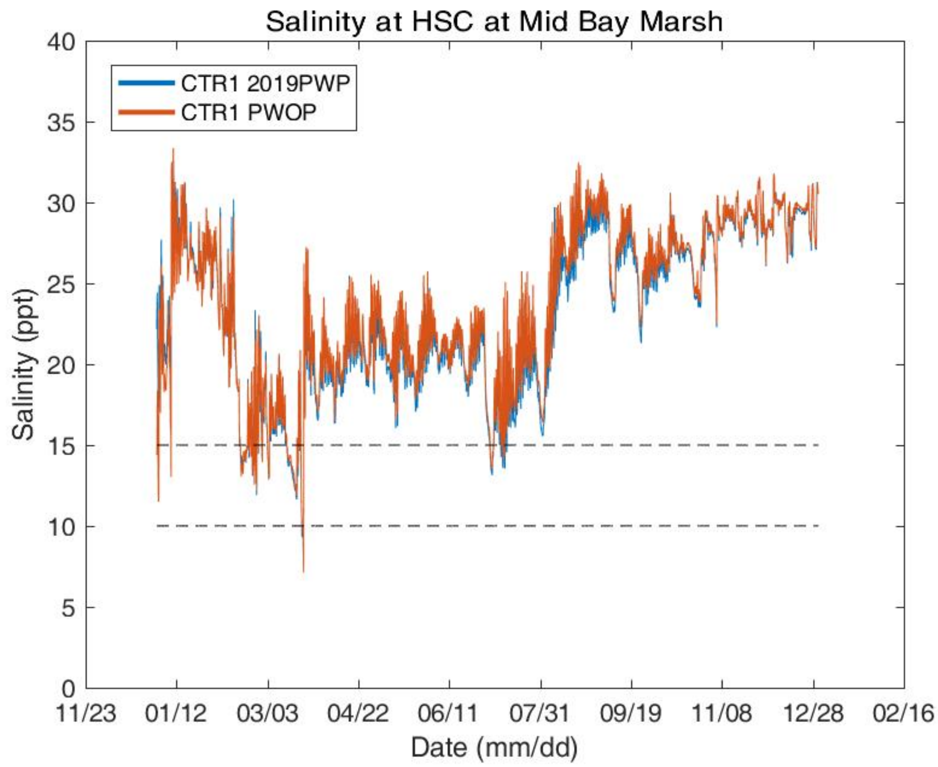
20
25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CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
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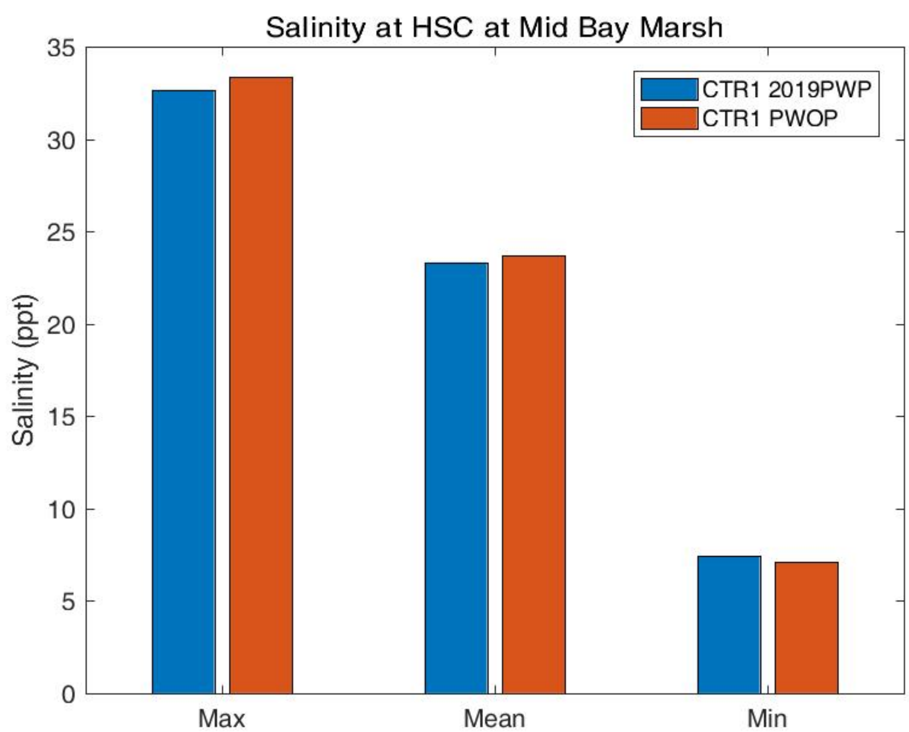
11/08
12/28
02/16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CTR1 PWOP
Salinity (ppt)
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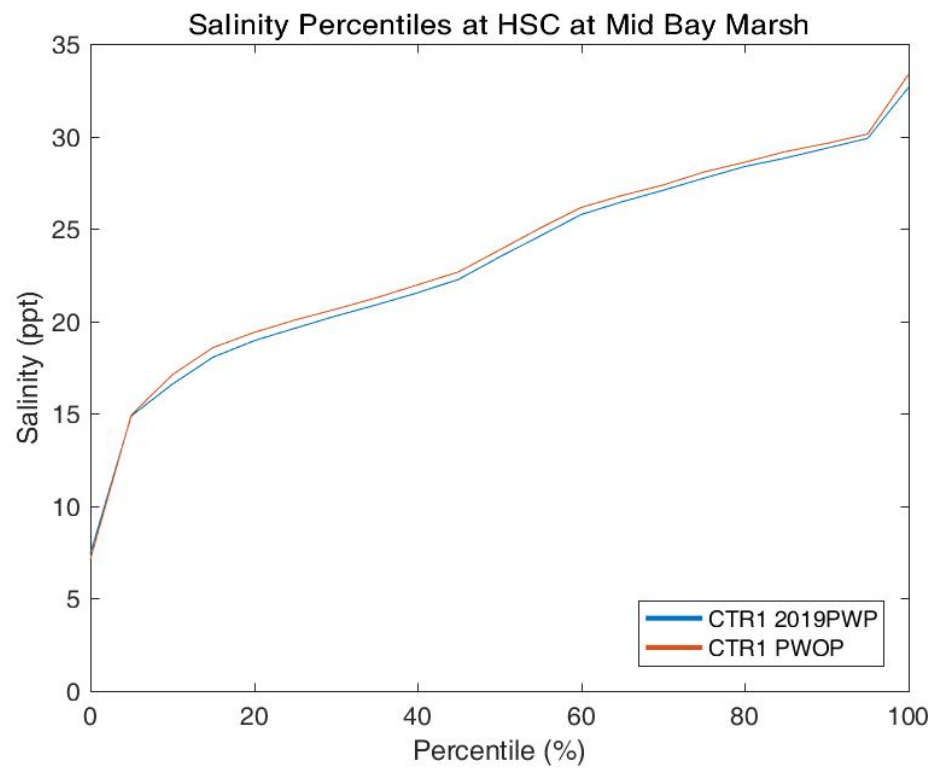
Max
Mean
Min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Salinity (ppt)
Percentile (%)
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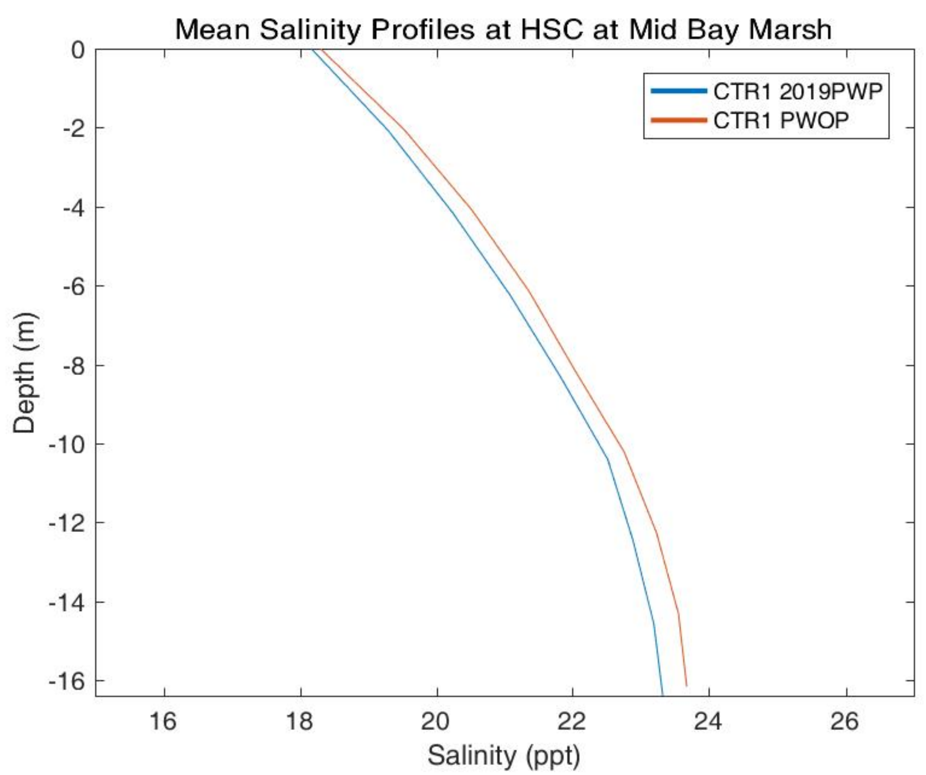
100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Depth (m)
Salinity (ppt)
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CTR1 PWOP
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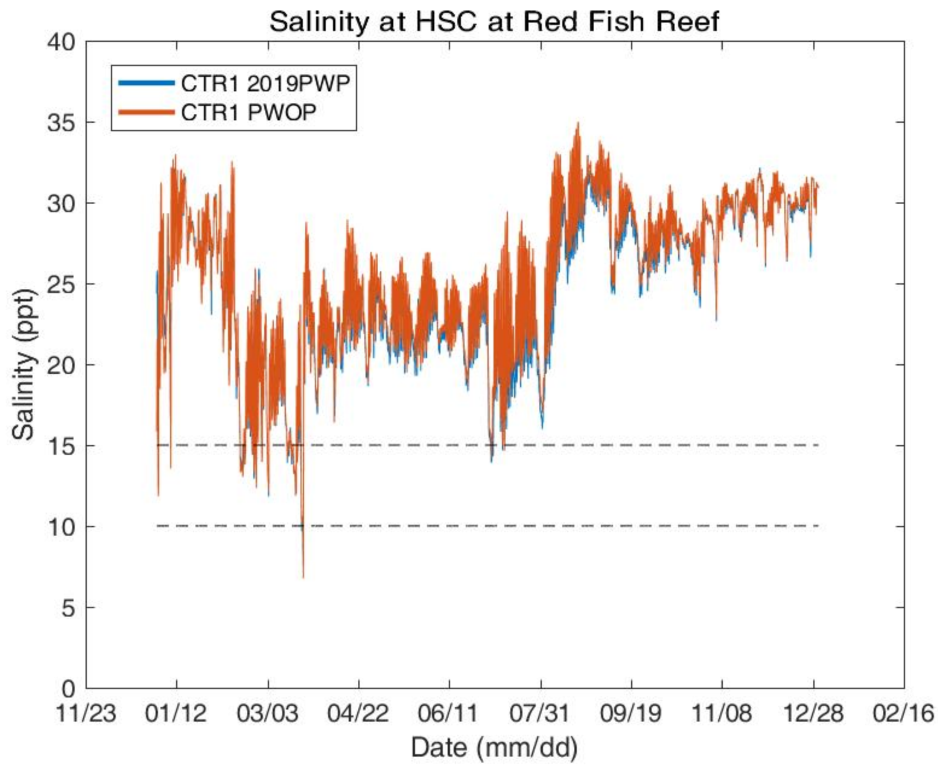
Salinity at HSC at Red Fish Reef
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CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
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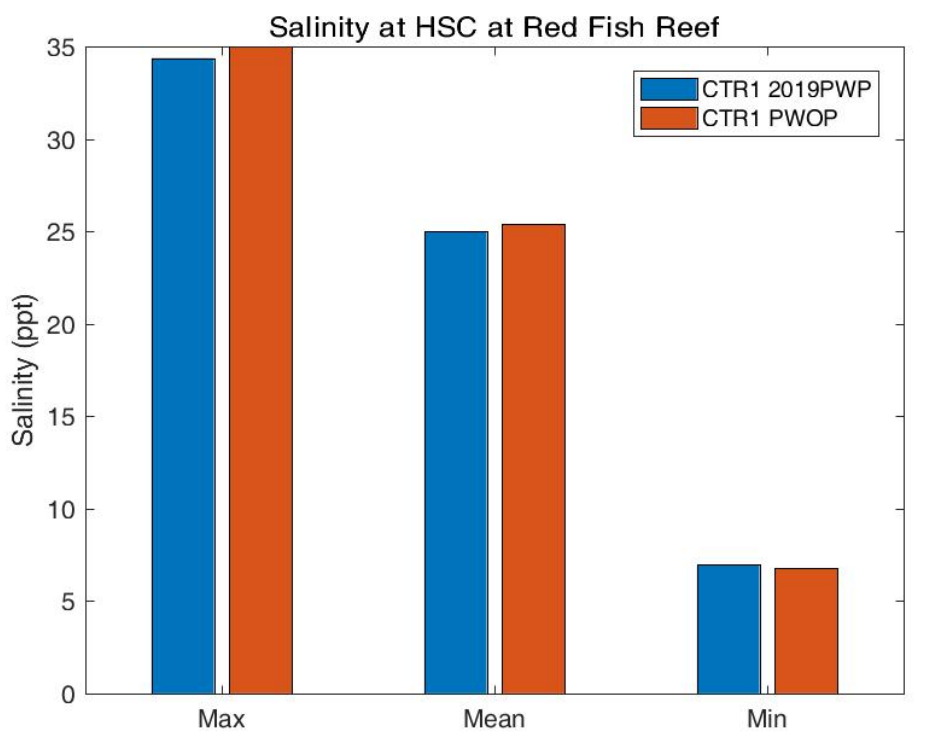
11/08
12/28
02/16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CTR1 PWOP
Salinity (ppt)
0
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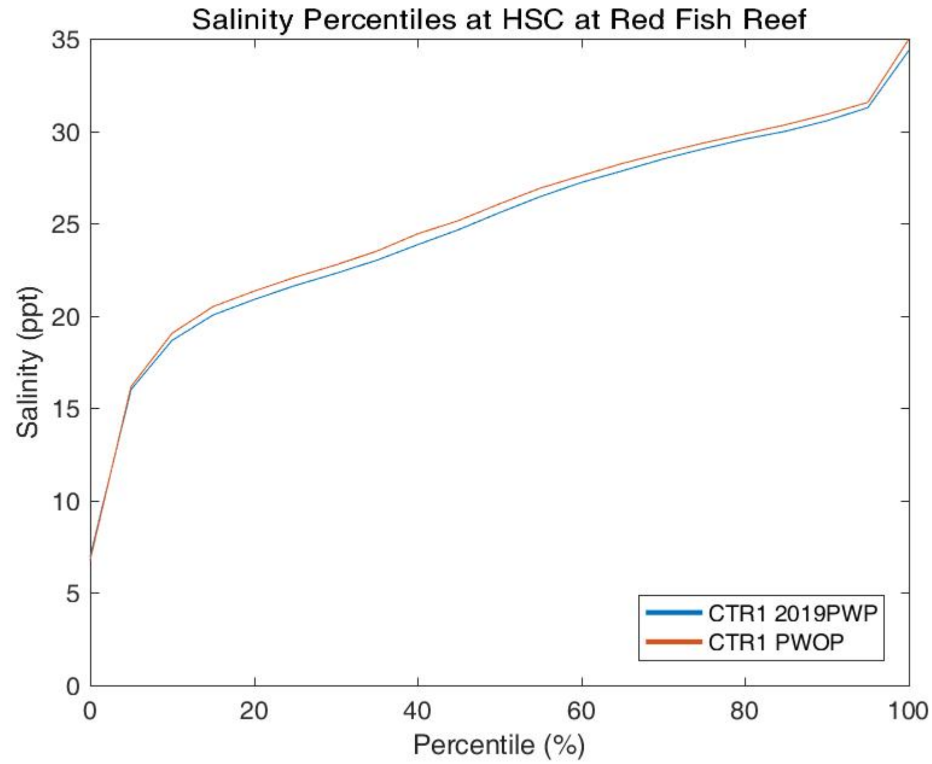
Max
Mean
Min


Salinity Percentiles at HSC at Red Fish Reef
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
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30
25
20
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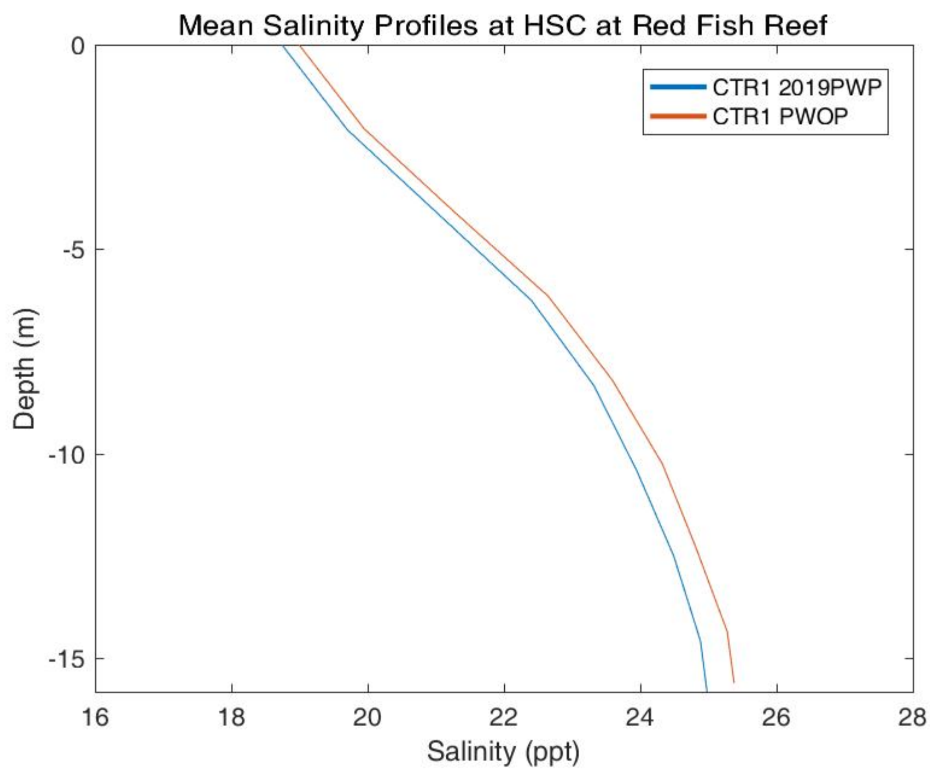
60
80
100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Depth (m)
Salinity (ppt)
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CTR1 PWOP
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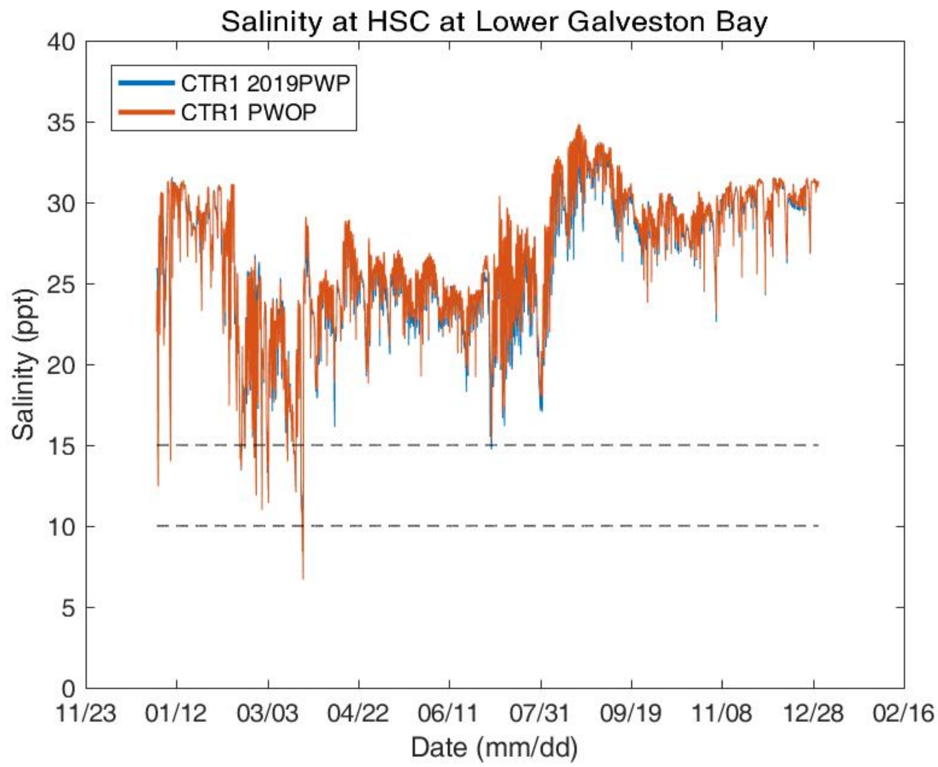
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CTR1 PWOP
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10
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20
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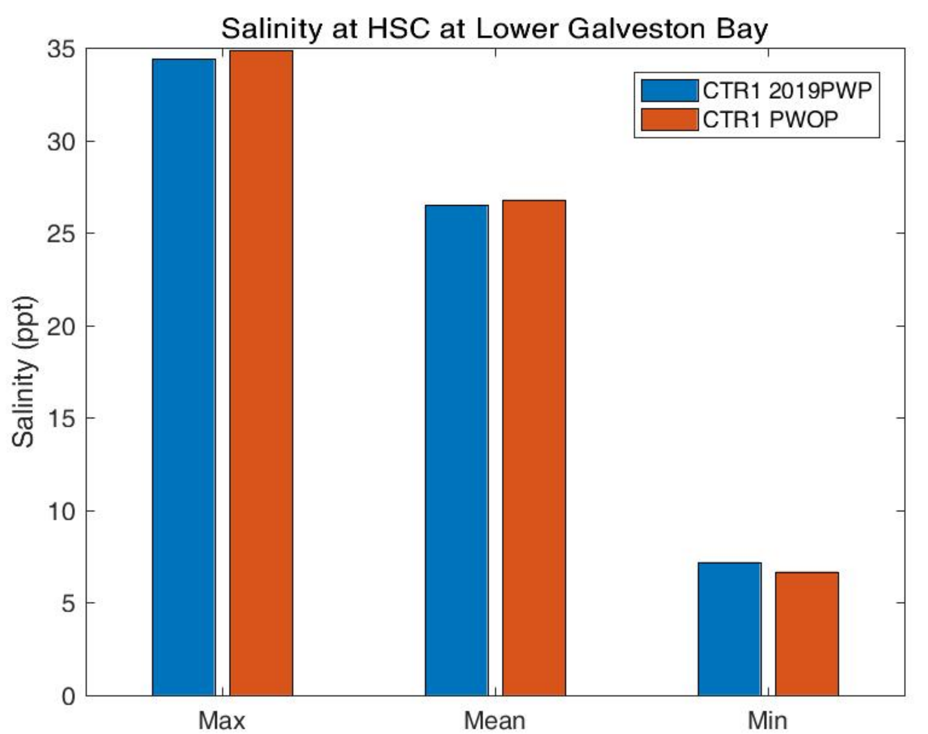
02/16
Date (mm/dd)


Salinity at HSC at Lower Galveston Bay
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CTR1 PWOP
Salinity (ppt)
0
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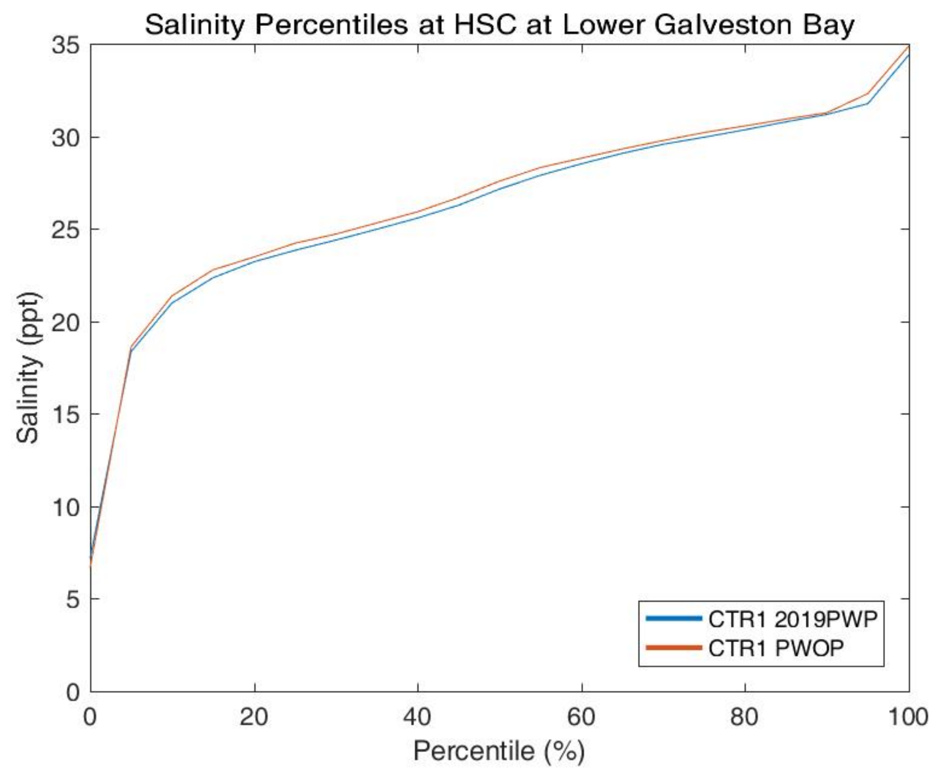
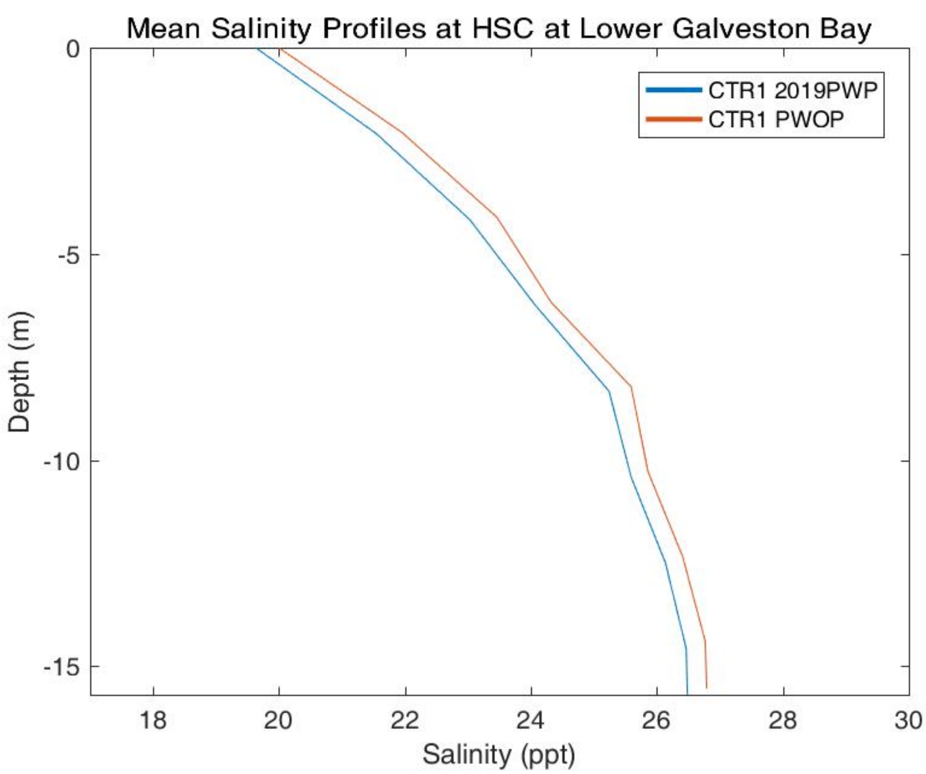
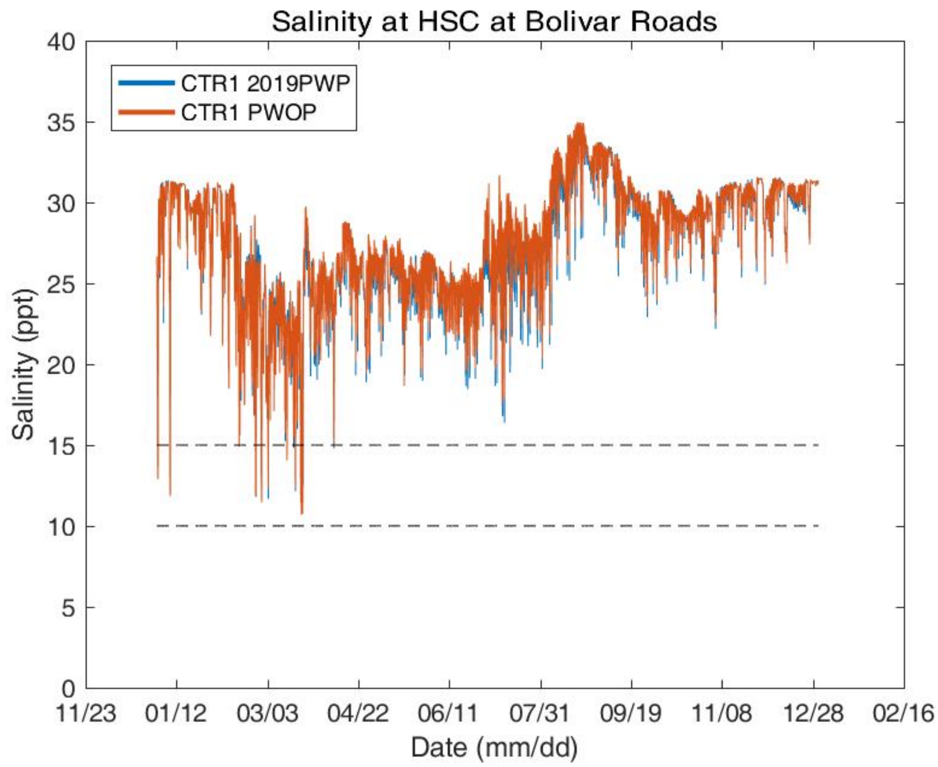
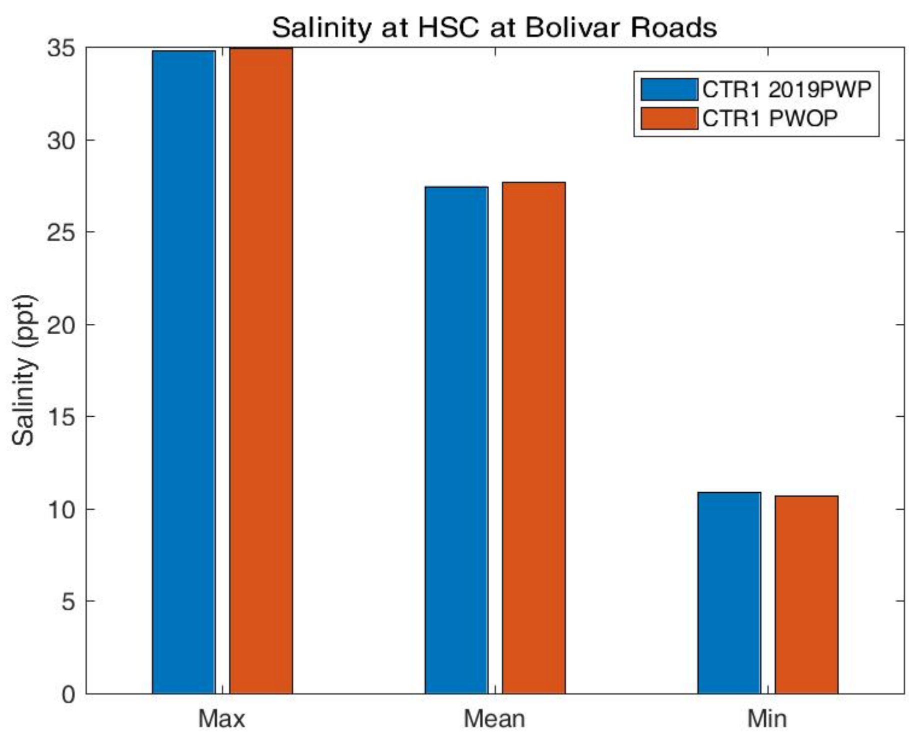
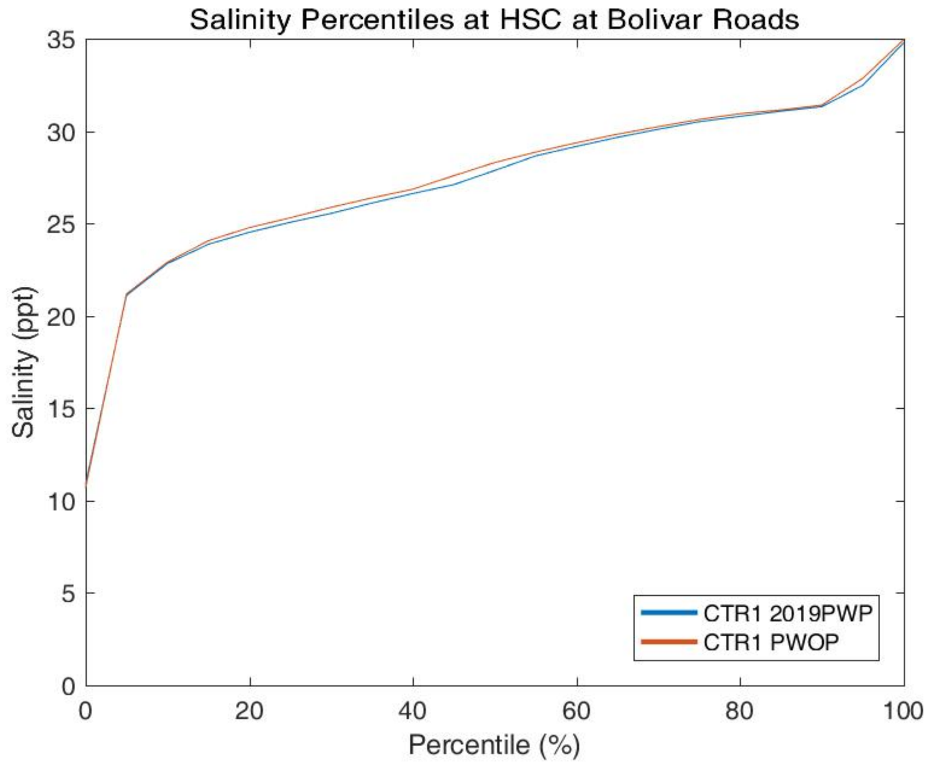
Min

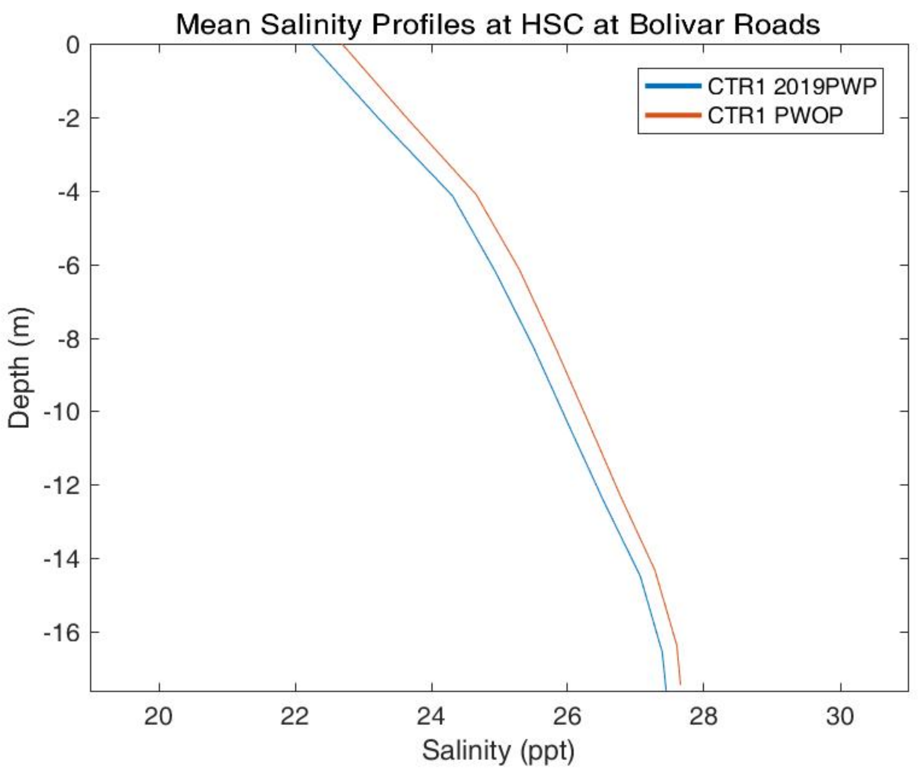

Salinity Percentiles at HSC at Lower Galveston Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

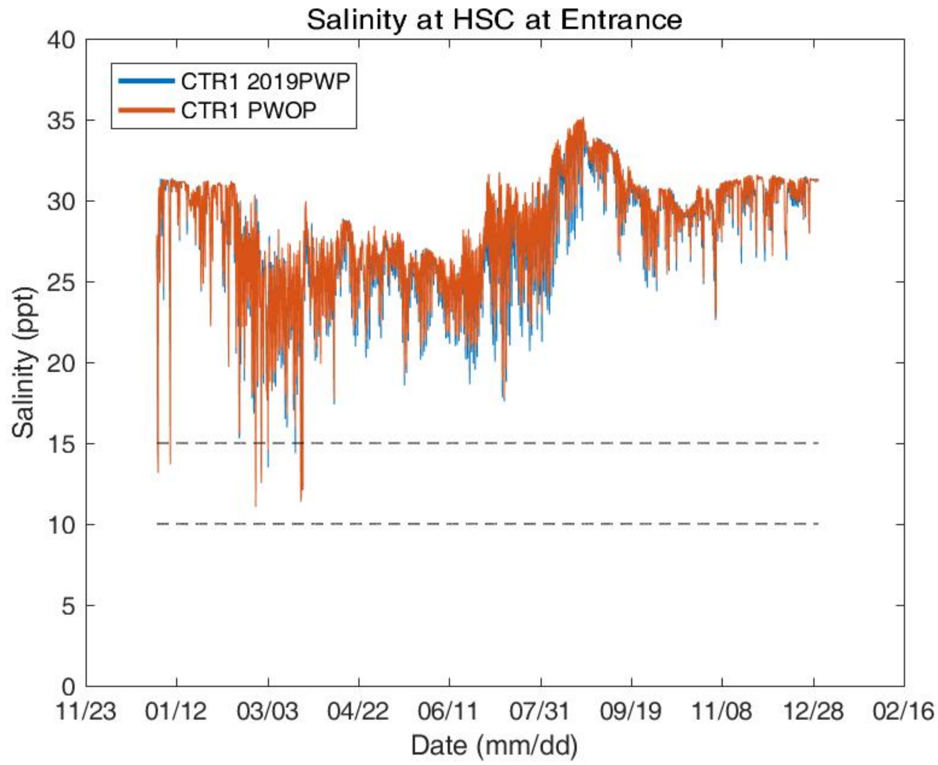

Mean Salinity Profiles at HSC at Lower Galveston Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-5
-10
-15
18
20
22
24
26
28
30

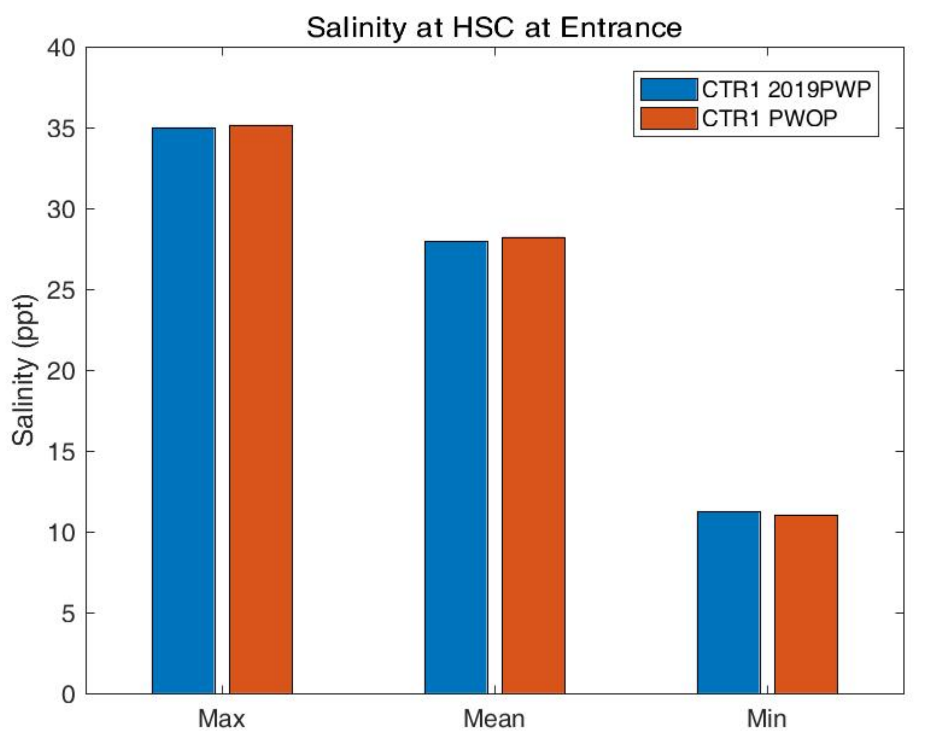

Salinity at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
40
35
30
25
20
15
10
5
0
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

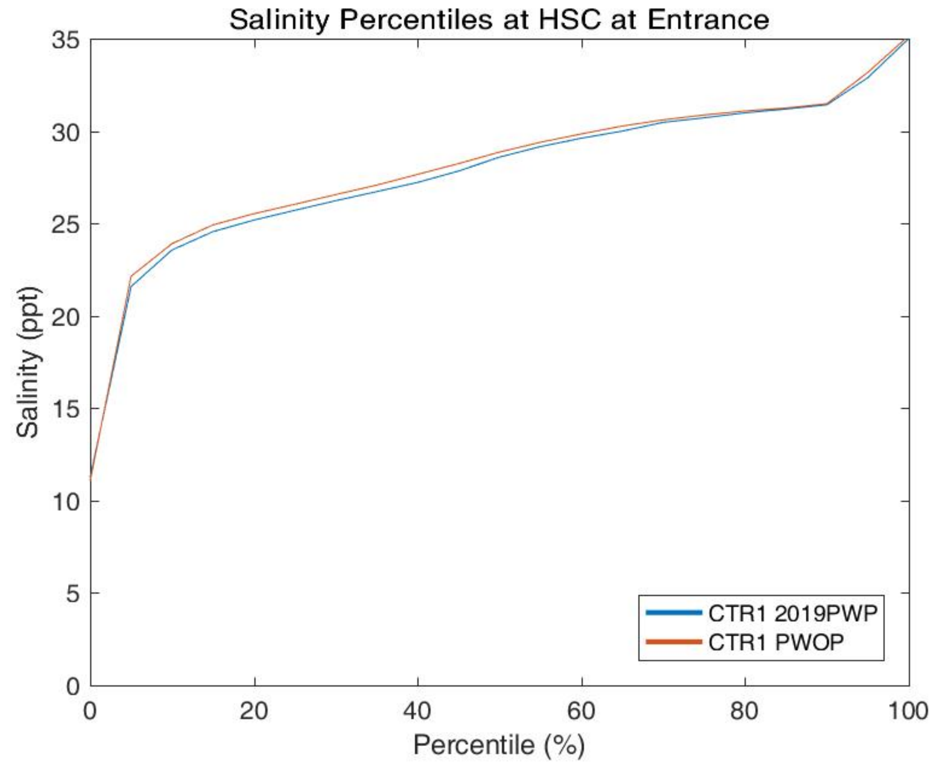

Salinity at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
35
30
25
20
15
10
5
0
Max
Mean
Min

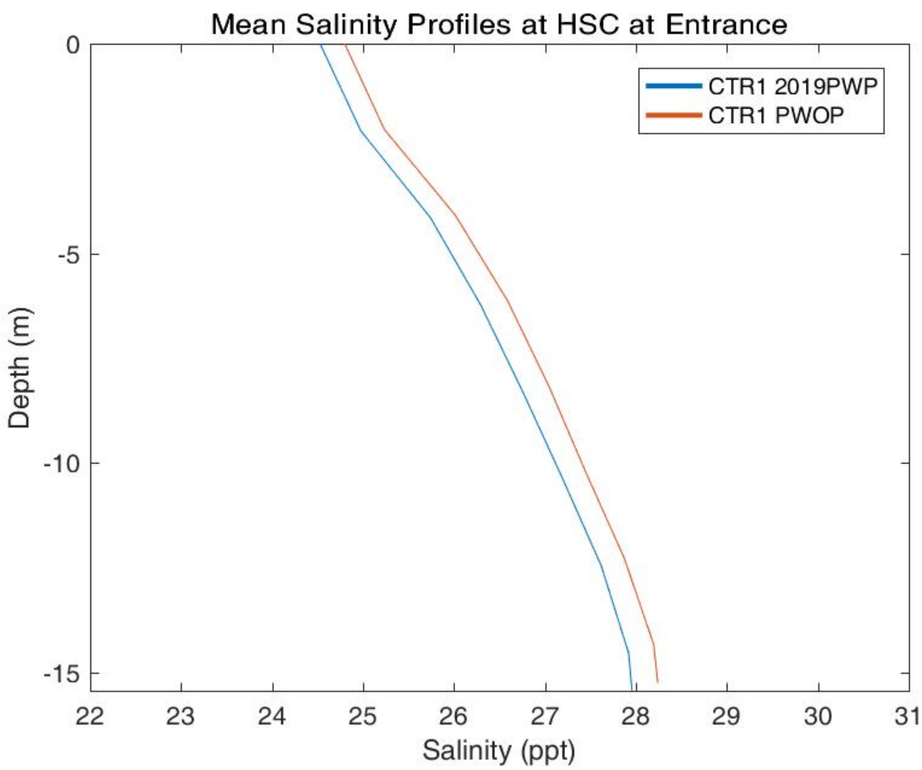

Salinity Percentiles at HSC at Bolivar Roads
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

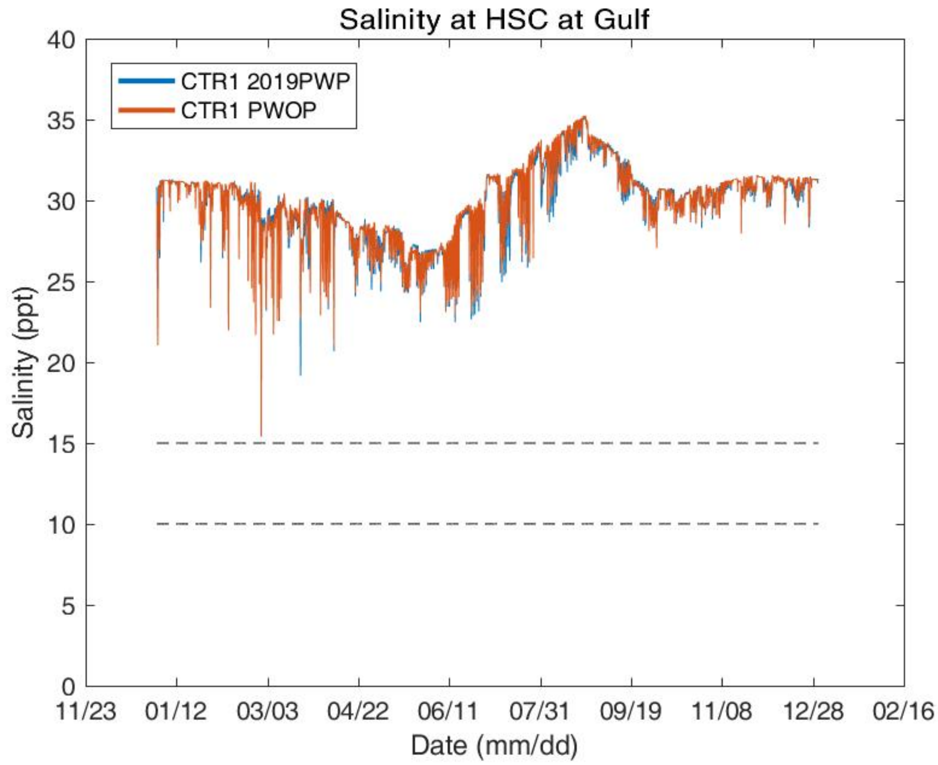

Mean Salinity Profiles at HSC at Bolivar Roads
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-2
-4
-6
-8
-10
-12
-14
-16
20
22
24
26
28
30

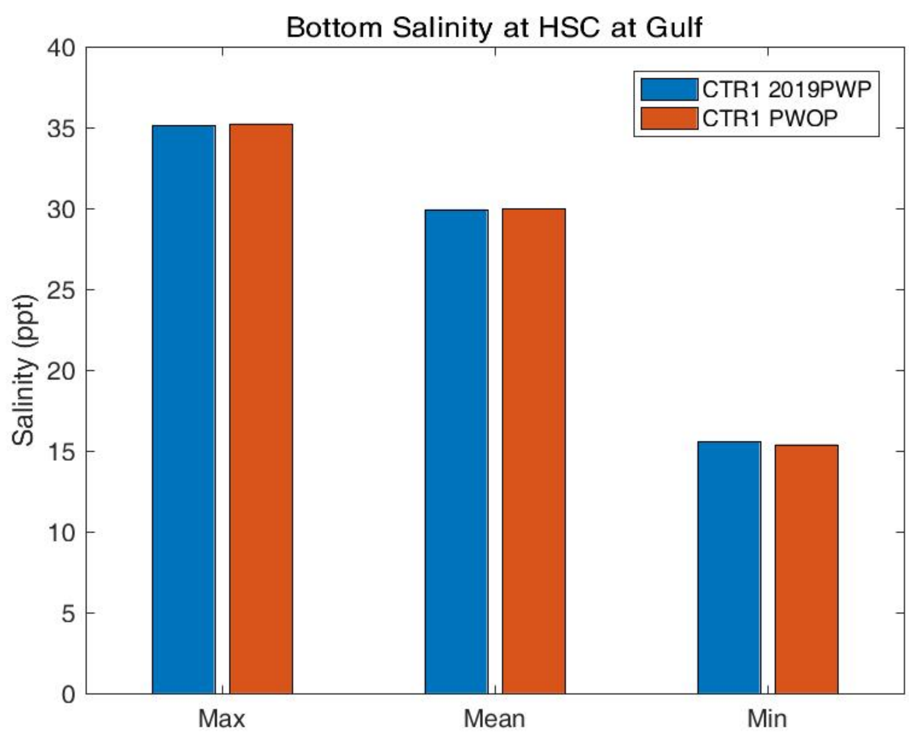

Salinity at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
40
35
30
25
20
15
10
5
0
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

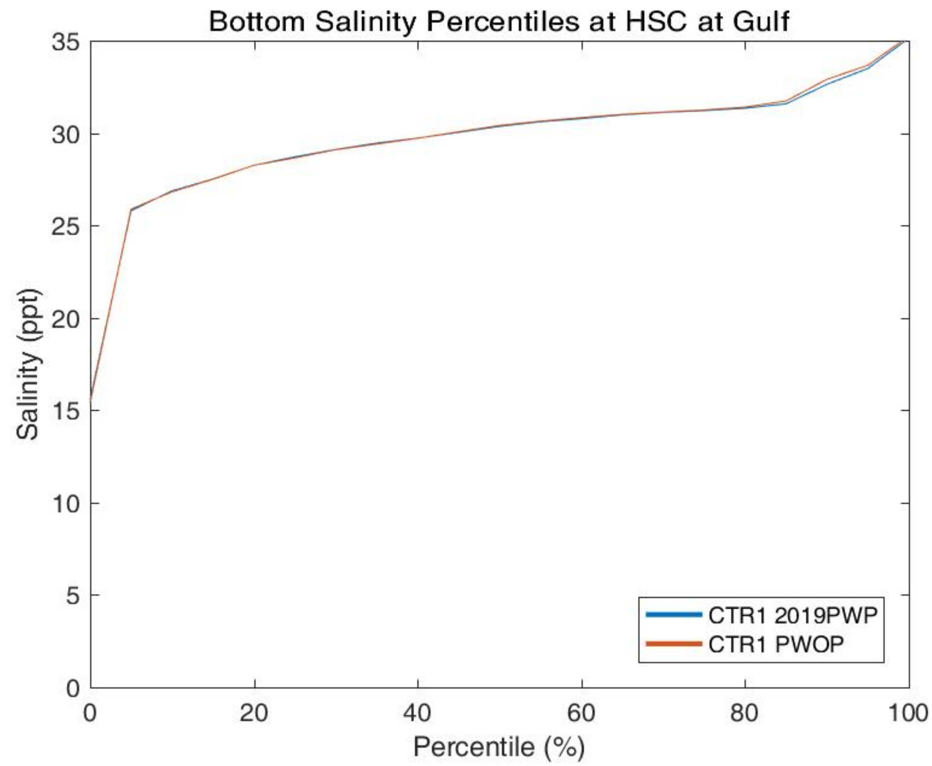

Salinity at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
40
35
30
25
20
15
10
5
0
Max
Mean
Min

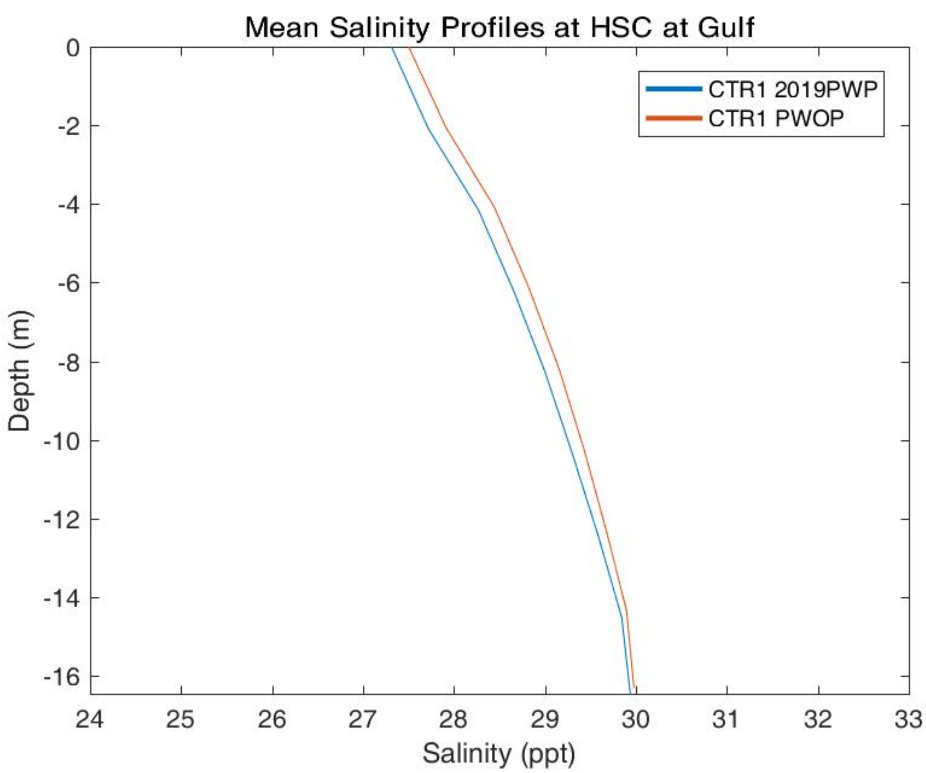

Salinity Percentiles at HSC at Entrance
Salinity (ppt)
Percentile (%)
35
30
25
20
15
10
5
0
0
20
40
60
80
100
CTR1 2019PWP
CTR1 PWOP

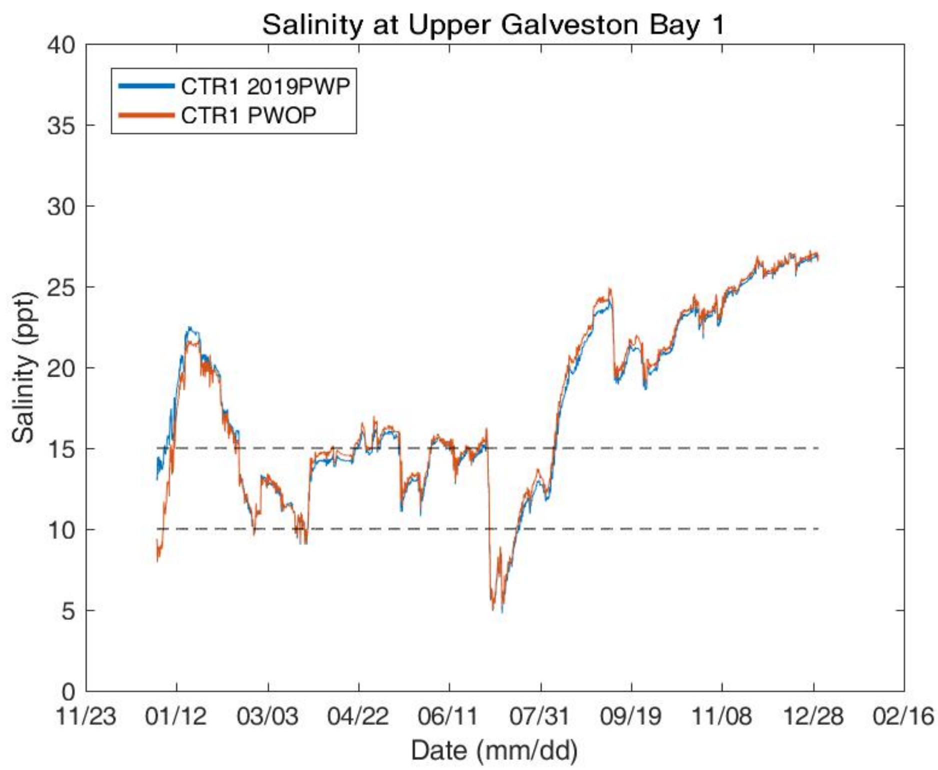

Mean Salinity Profiles at HSC at Entrance
Depth (m)
Salinity (ppt)
0
-5
-10
-15
22
23
24
25
26
27
28
29
30
31
CTR1 2019PWP
CTR1 PWOP

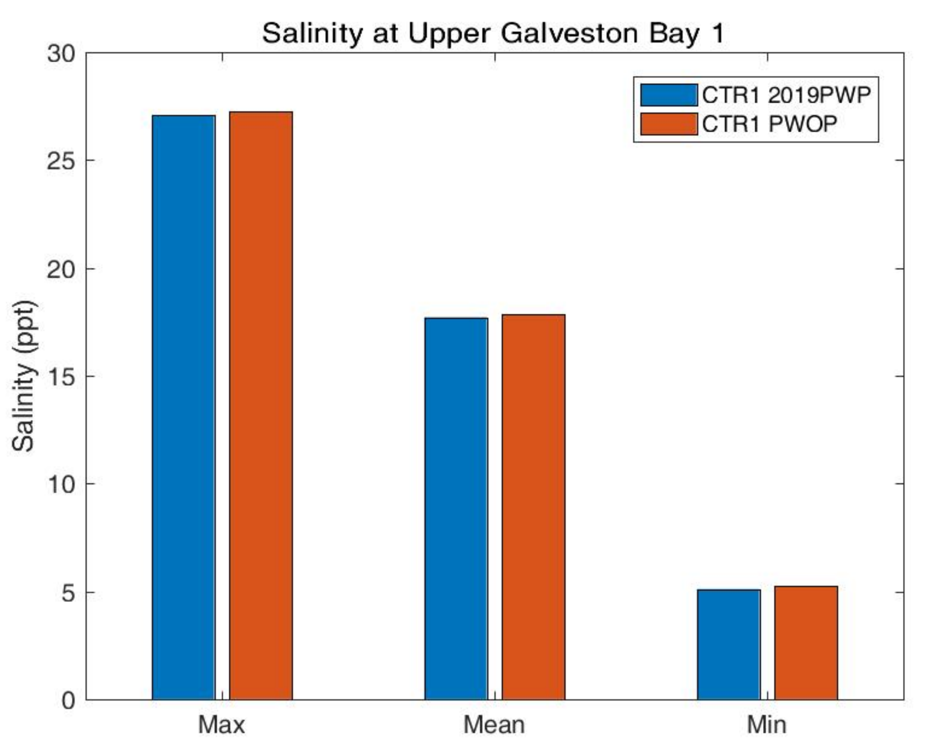

Salinity at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
40
35
30
25
20
15
10
5
0
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

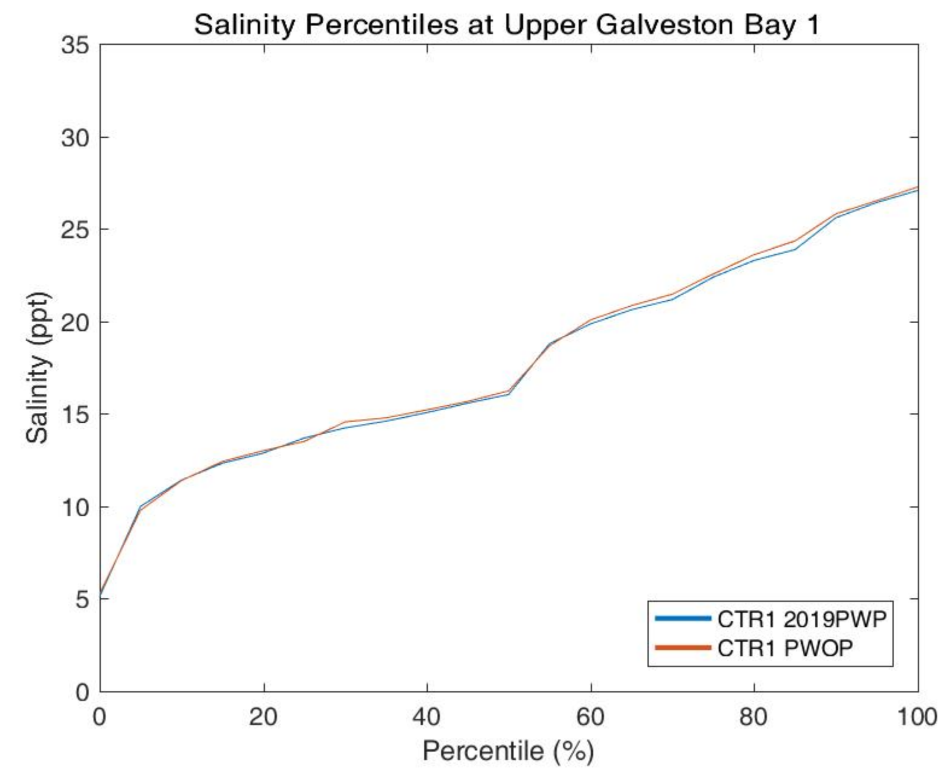

Bottom Salinity at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
40
35
30
25
20
15
10
5
0
Max
Mean
Min

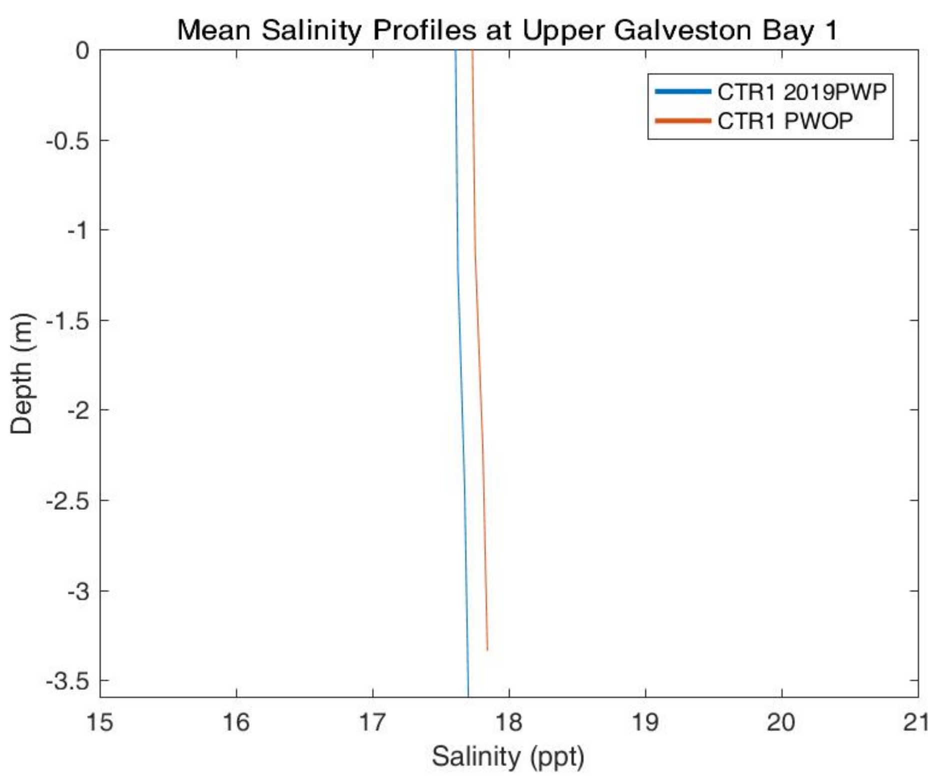

Bottom Salinity Percentiles at HSC at Gulf
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
35
30
25
20
15
10
5
0
0
20
40
60
80
100

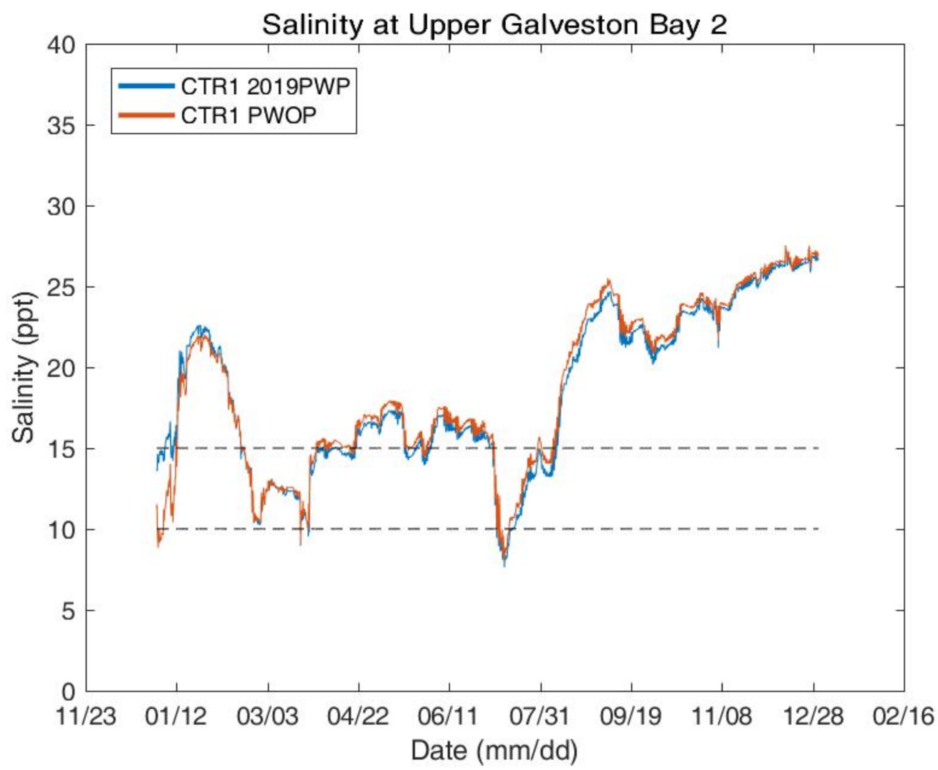

Mean Salinity Profiles at HSC at Gulf
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-2
-4
-6
-8
-10
-12
-14
-16
24
25
26
27
28
29
30
31
32
33

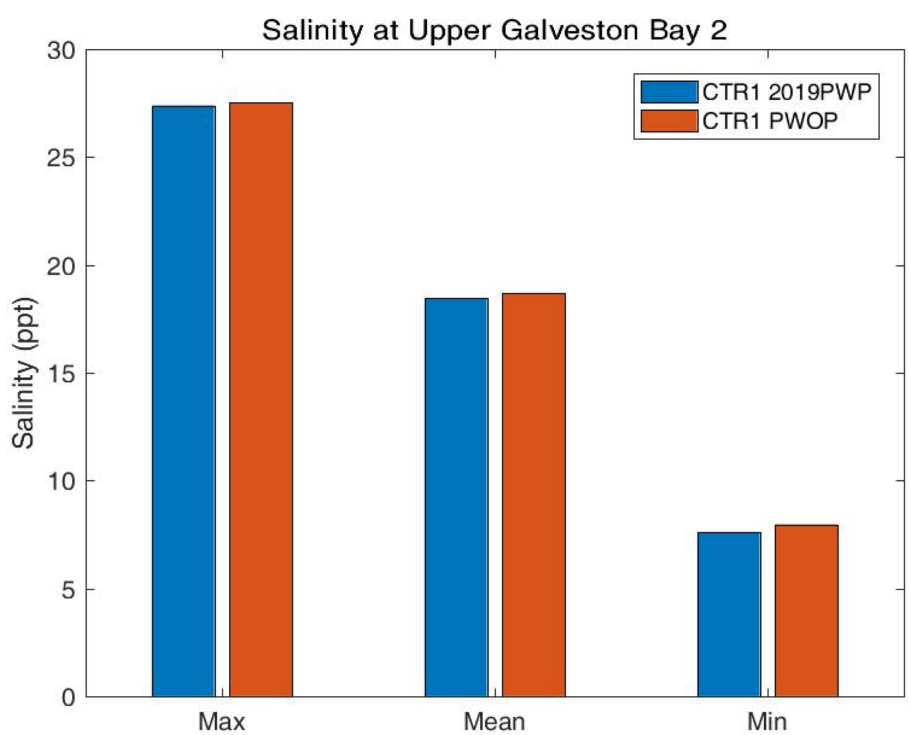

Salinity at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

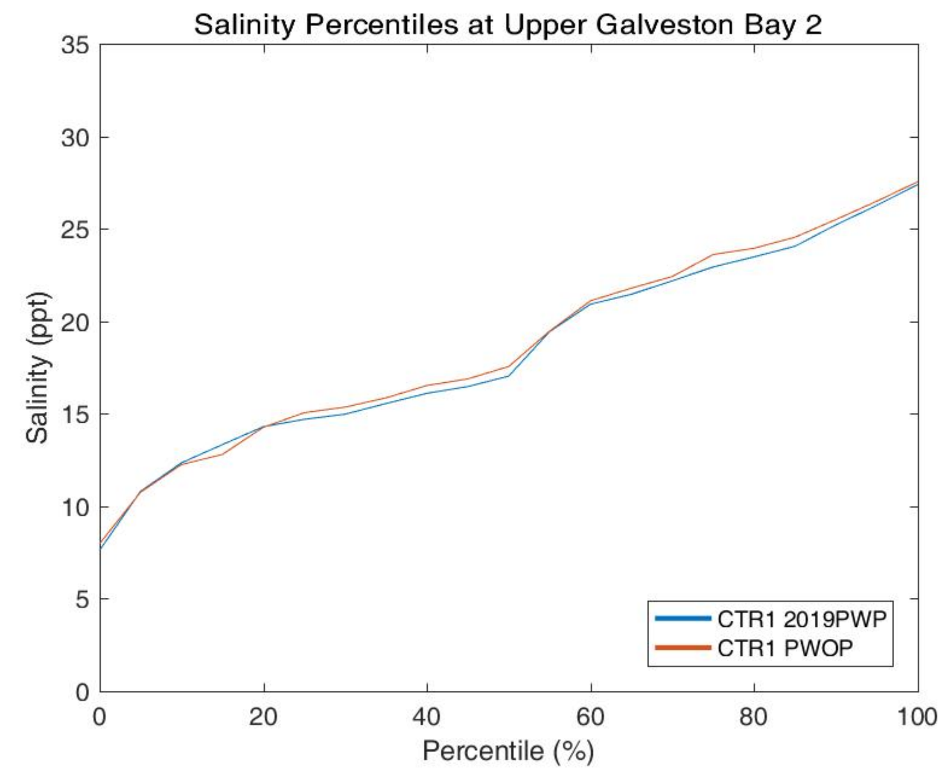

Salinity at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
Max
Mean
Min

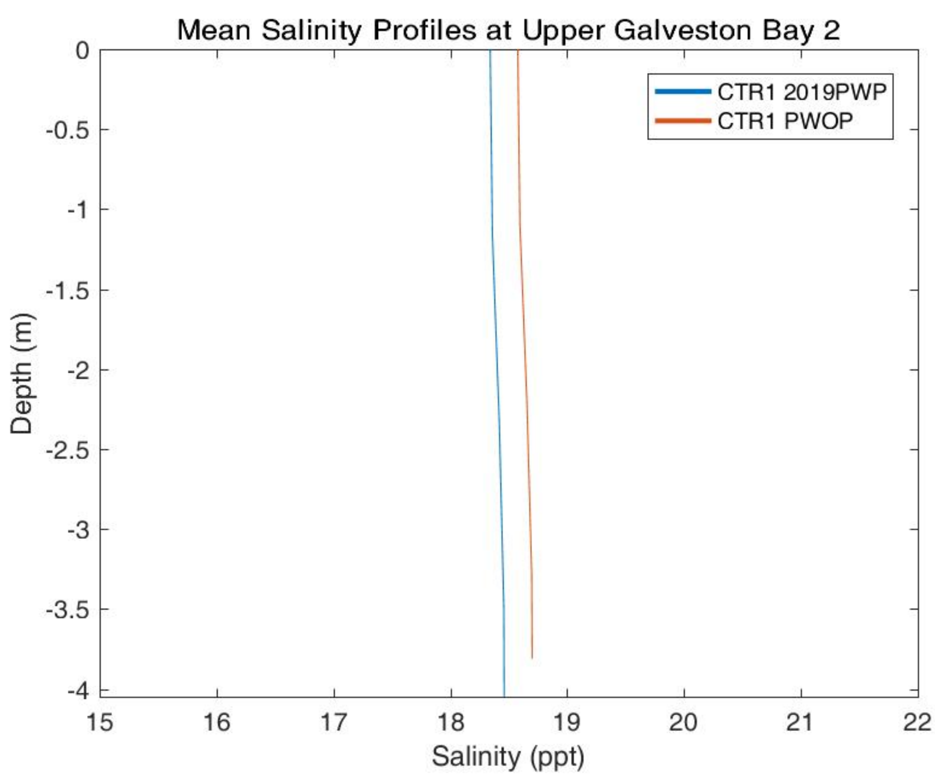

Salinity Percentiles at Upper Galveston Bay 1
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
35
30
25
20
15
10
5
0
0
20
40
60
80
100

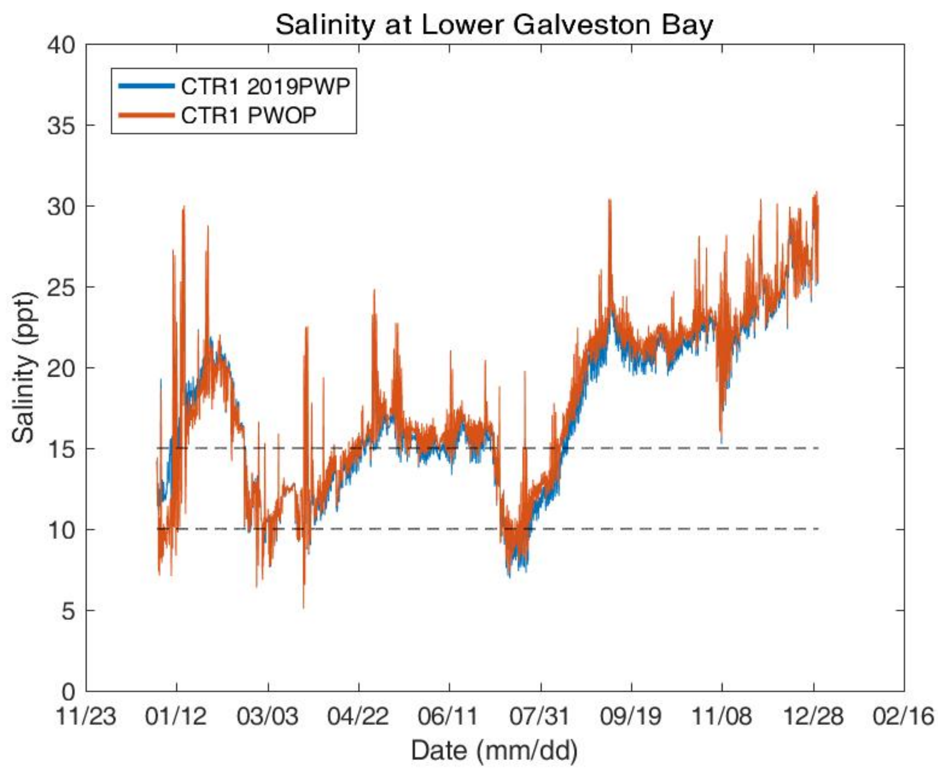

Mean Salinity Profiles at Upper Galveston Bay 1
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
15
16
17
18
19
20
21

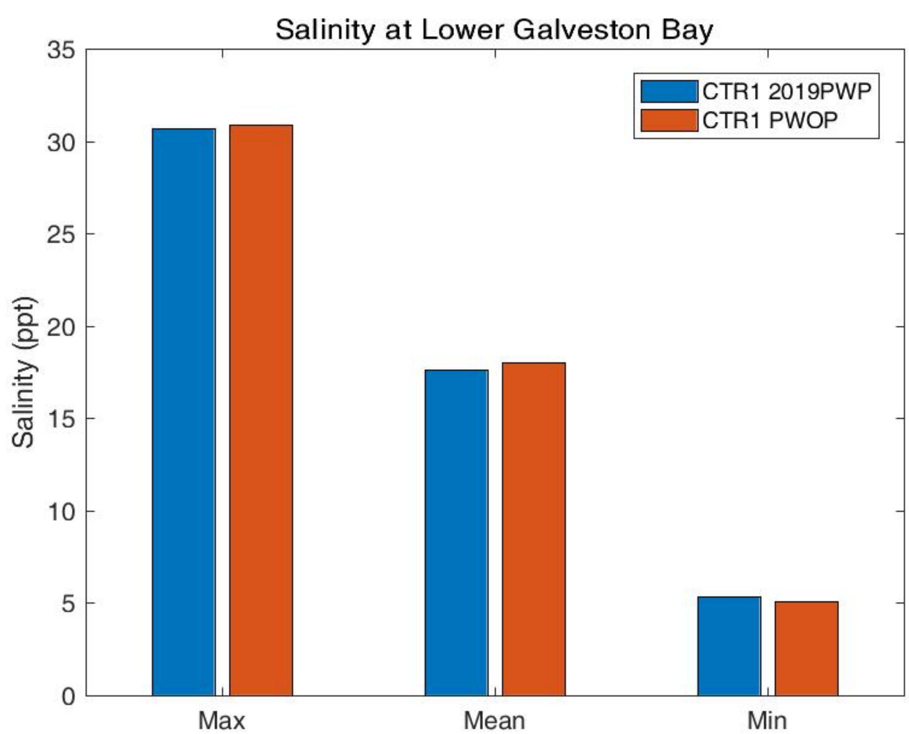

Salinity at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

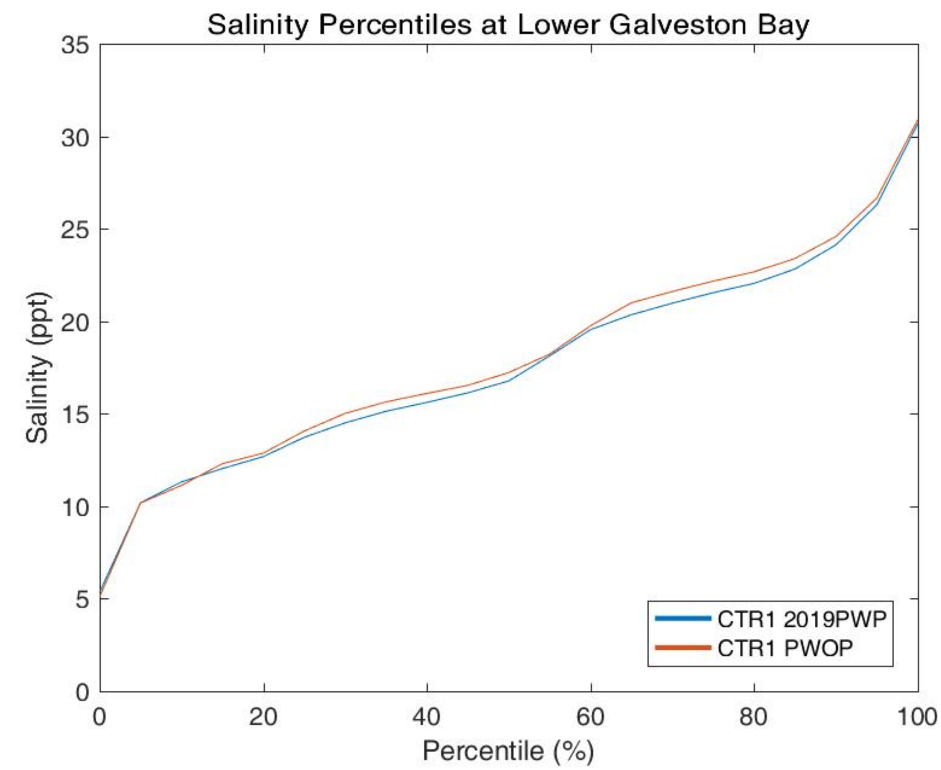

Salinity at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
Max
Mean
Min

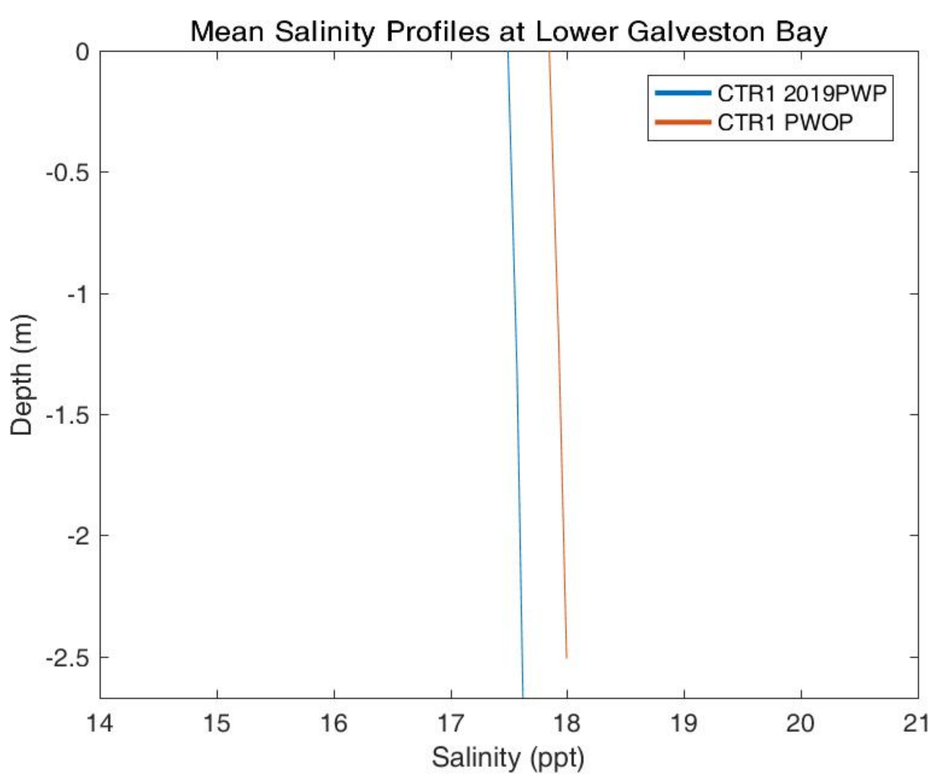

Salinity Percentiles at Upper Galveston Bay 2
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

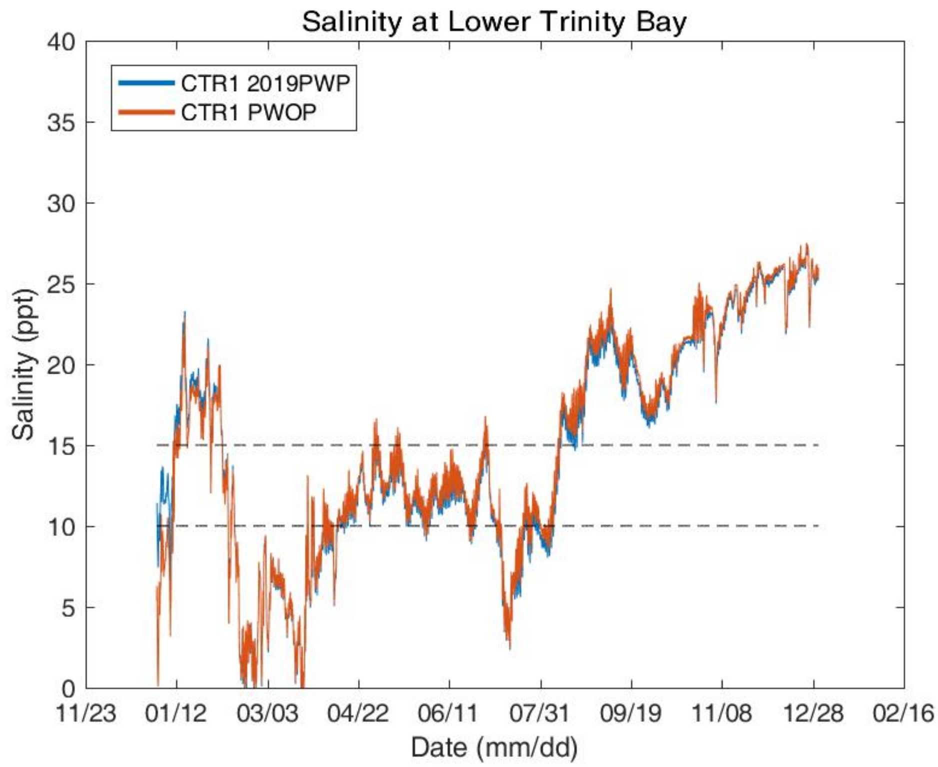

Mean Salinity Profiles at Upper Galveston Bay 2
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
15
16
17
18
19
20
21
22

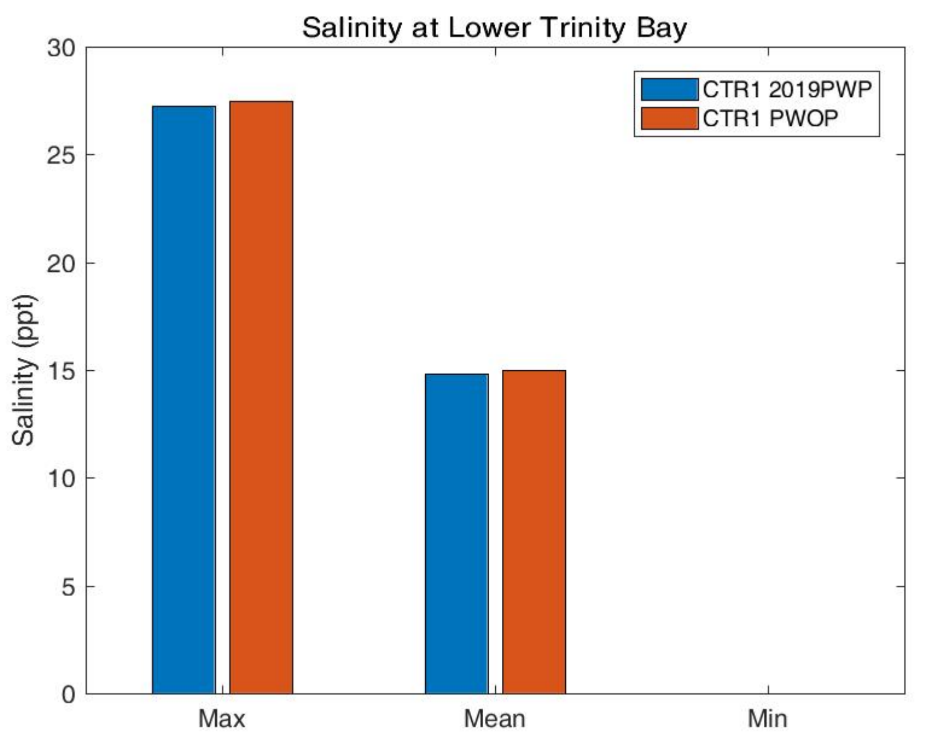

Salinity at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

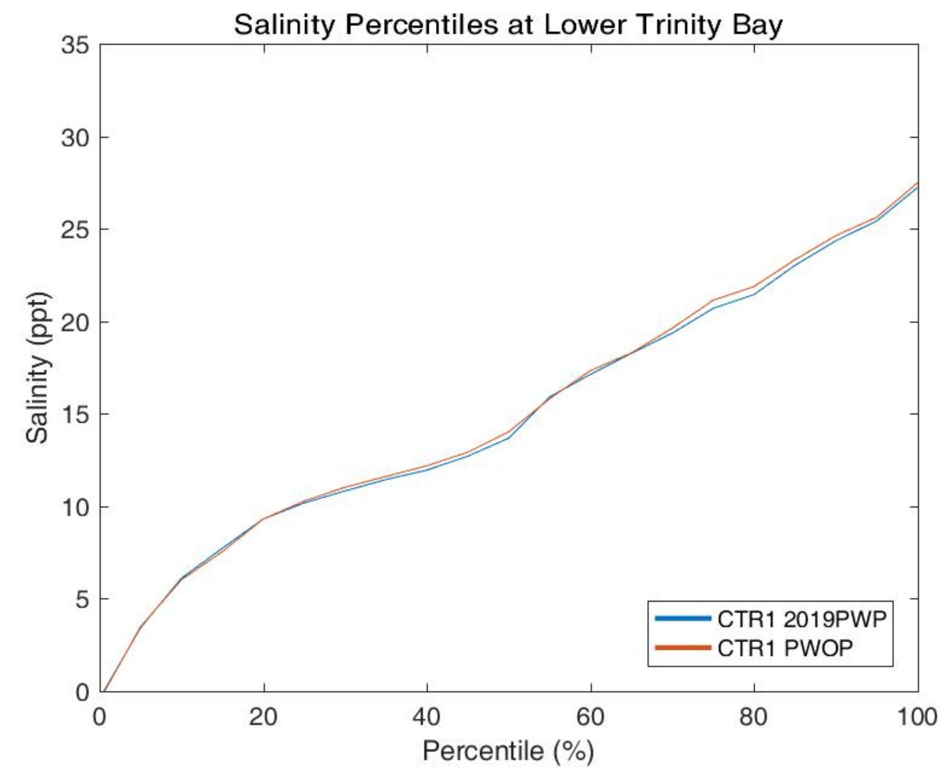

Salinity at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min

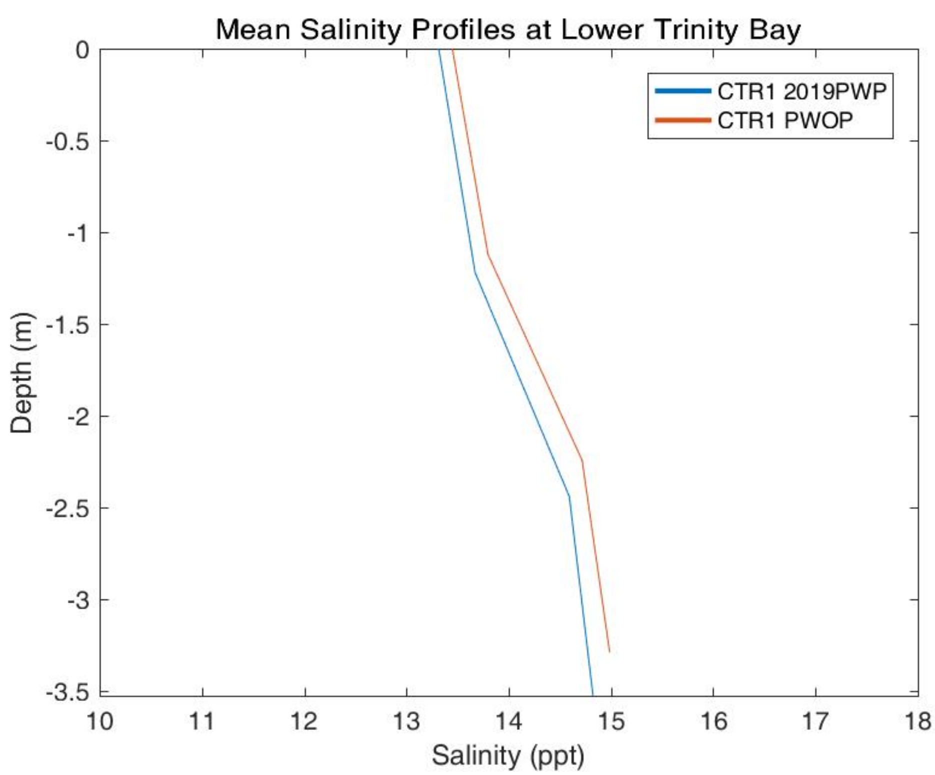

Salinity Percentiles at Lower Galveston Bay
Salinity (ppt)
Percentile (%)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
CTR1 2019PWP
CTR1 PWOP

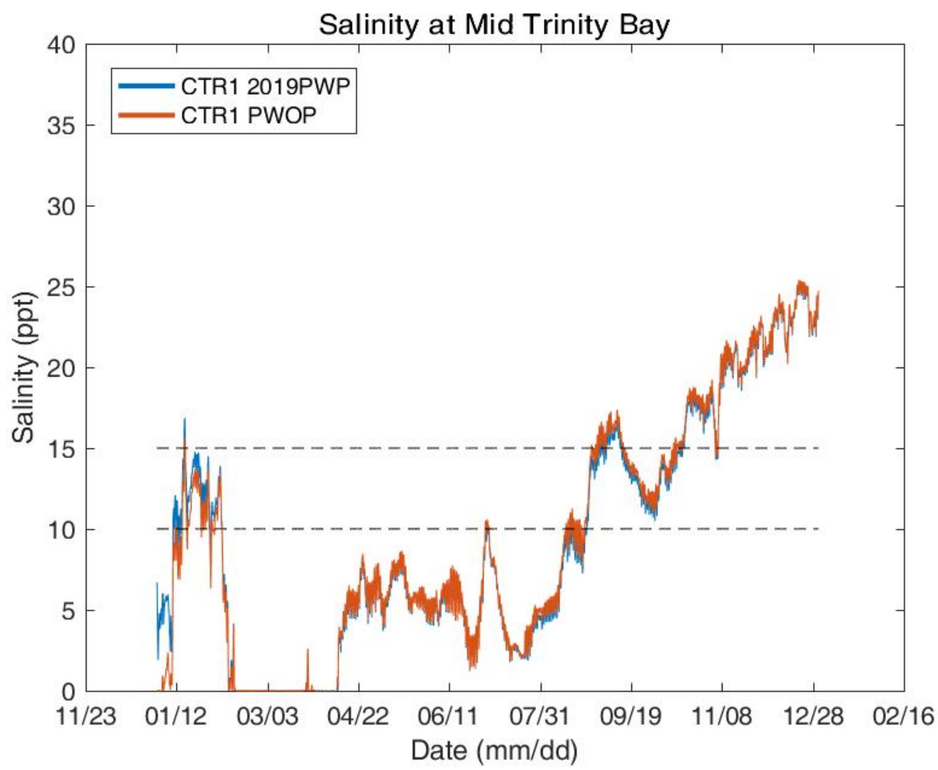

Mean Salinity Profiles at Lower Galveston Bay
Depth (m)
Salinity (ppt)
0
-0.5
-1
-1.5
-2
-2.5
14
15
16
17
18
19
20
21
CTR1 2019PWP
CTR1 PWOP

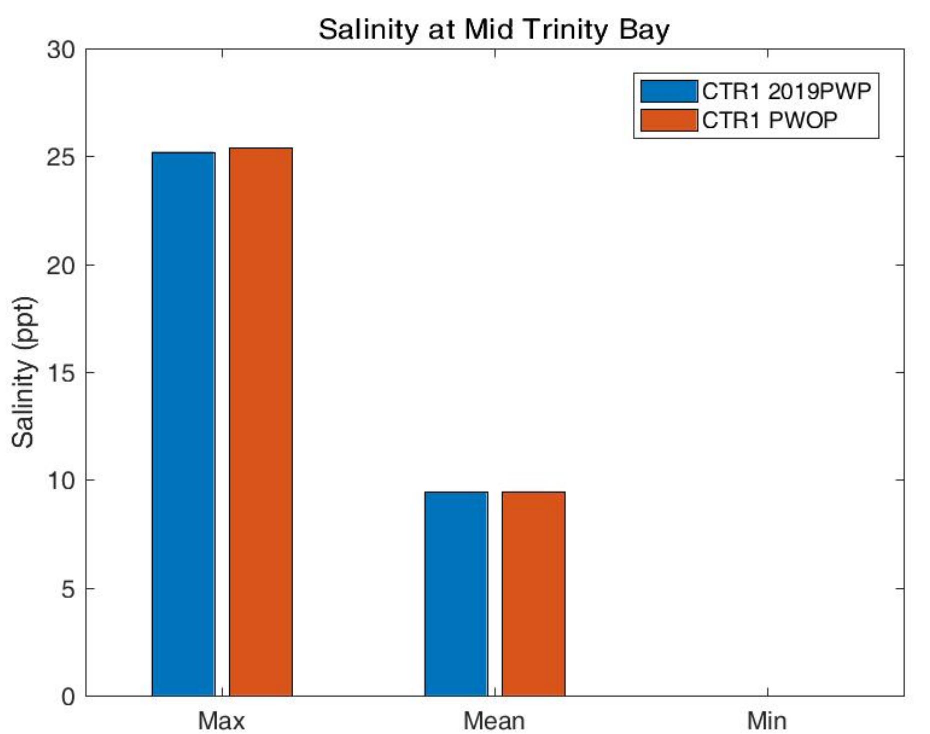

Salinity at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
40
35
30
25
20
15
10
5
0
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

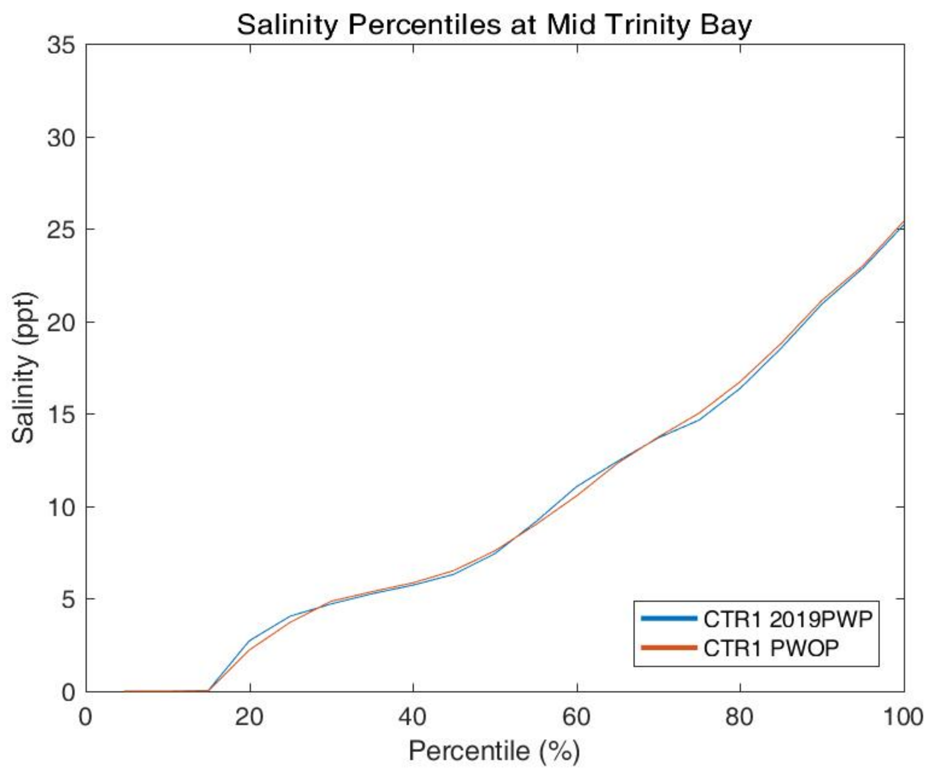

Salinity at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
30
25
20
15
10
5
0
Max
Mean
Min

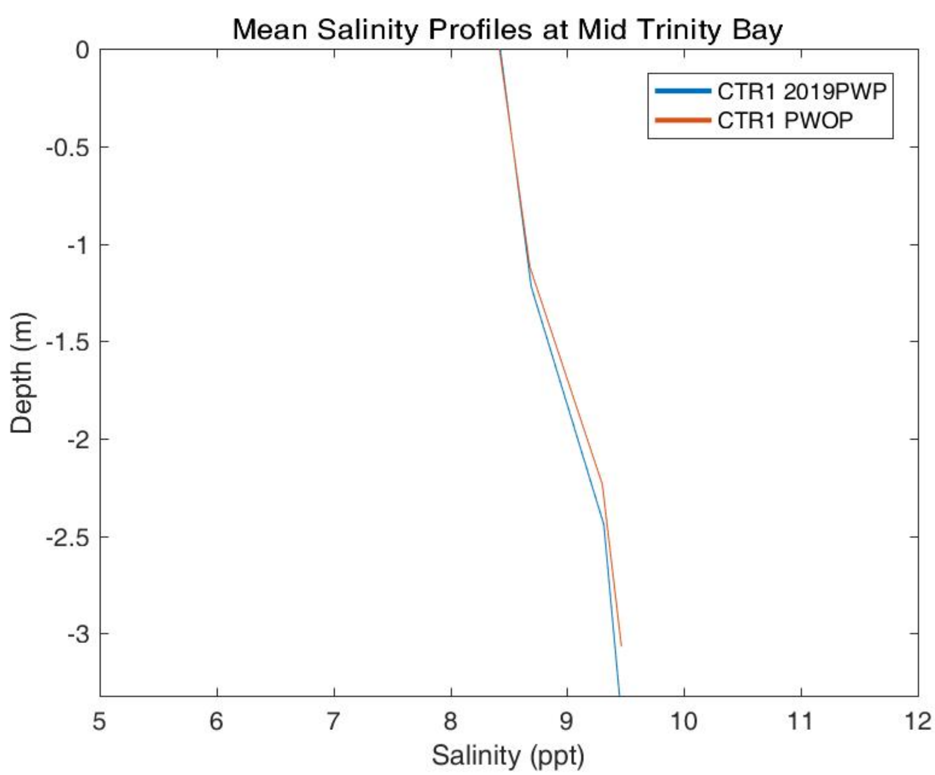

Salinity Percentiles at Lower Trinity Bay
35
30
25
20
15
10
5
0
Salinity (ppt)
0
20
40
60
80
100
Percentile (%)
CTR1 2019PWP
CTR1 PWOP

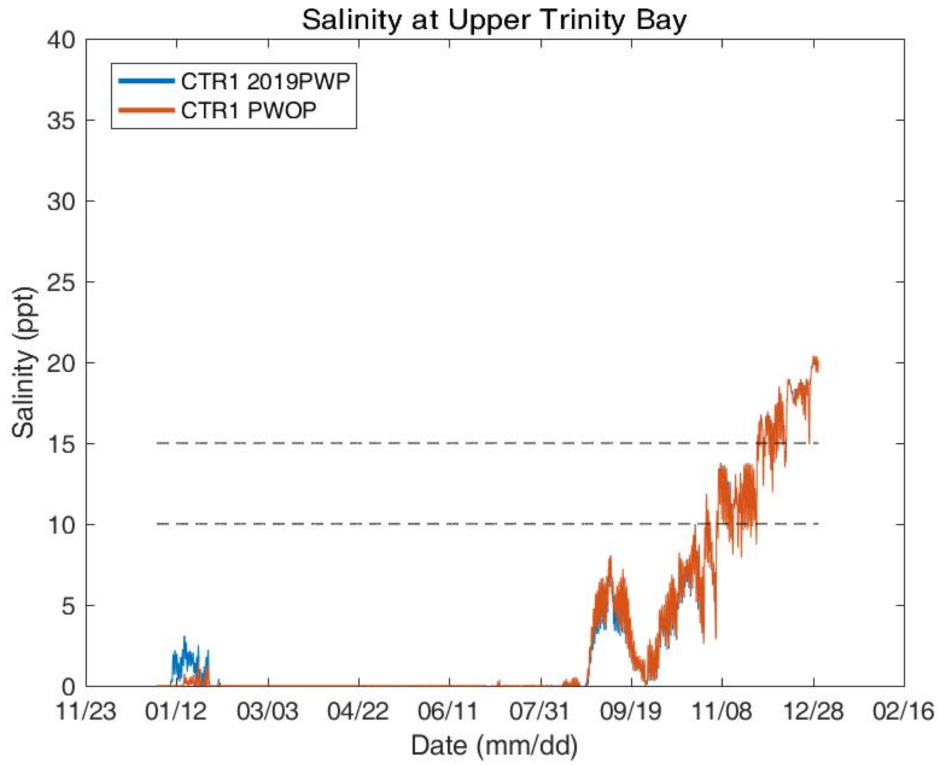

Mean Salinity Profiles at Lower Trinity Bay
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
Depth (m)
10
11
12
13
14
15
16
17
18
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP

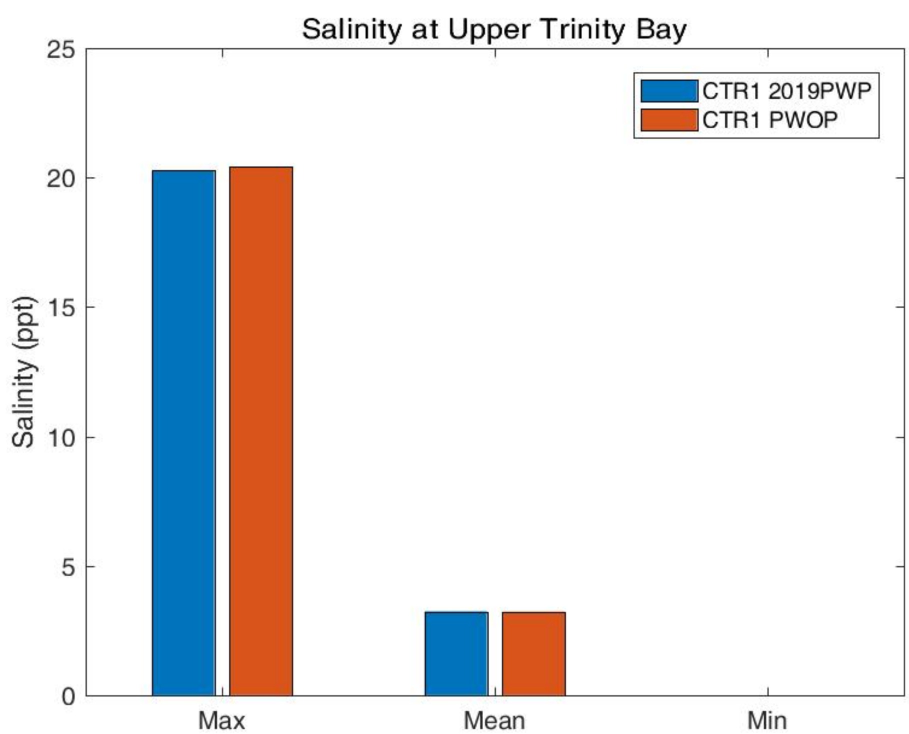

Salinity at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
0
5
10
15
20
25
30
35
40

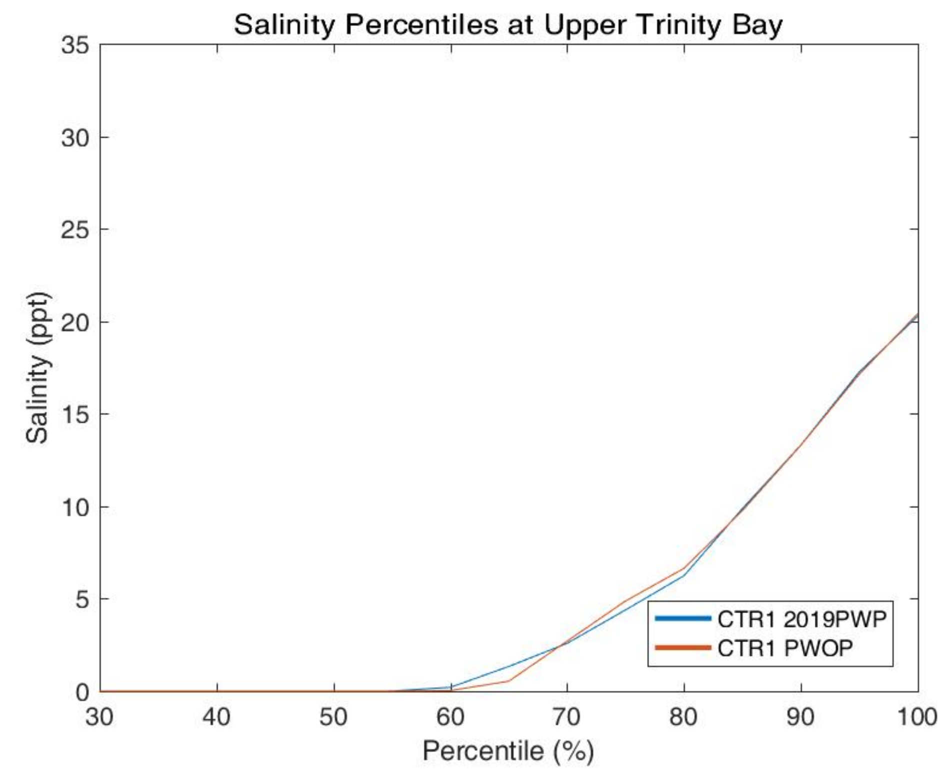

Salinity at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Max
Mean
Min
0
5
10
15
20
25
30

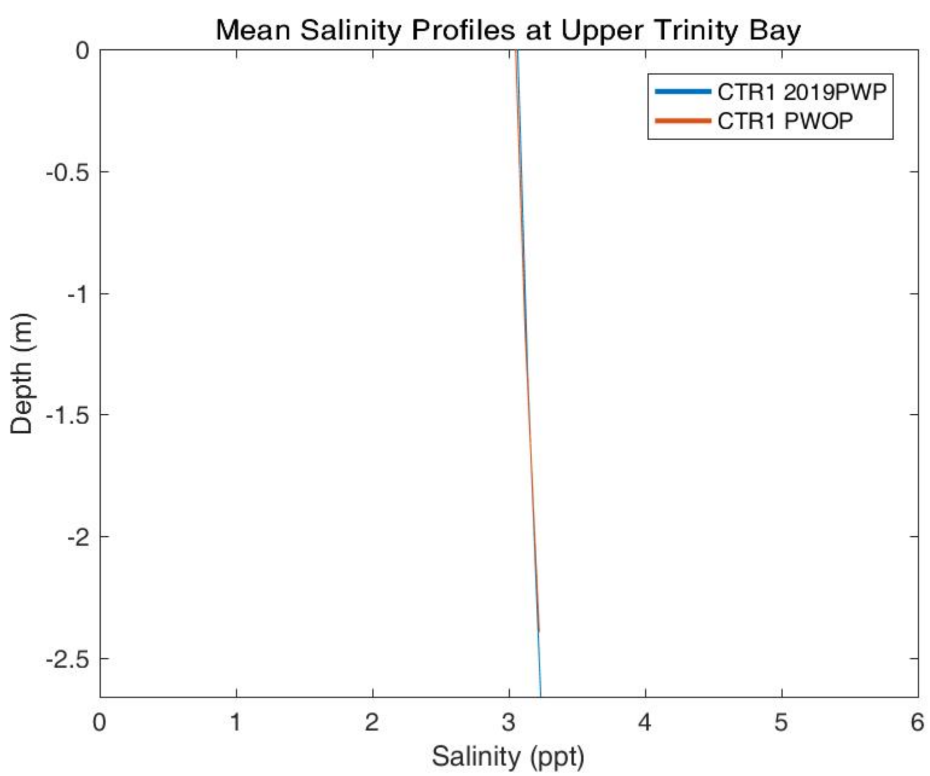

Salinity Percentiles at Mid Trinity Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

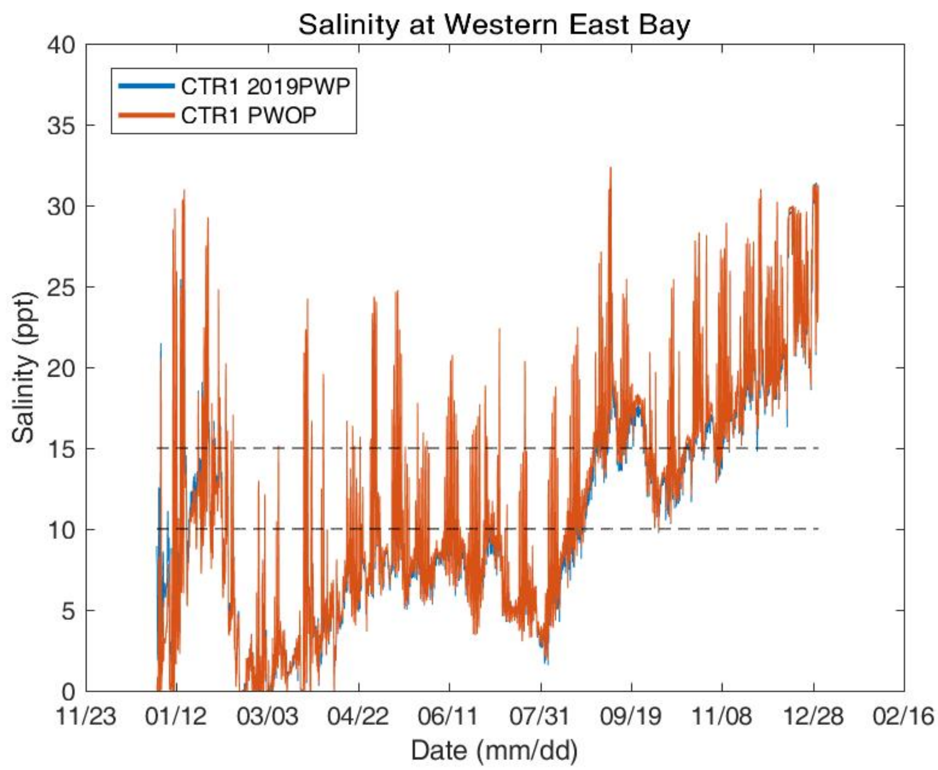

Mean Salinity Profiles at Mid Trinity Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
-3
5
6
7
8
9
10
11
12

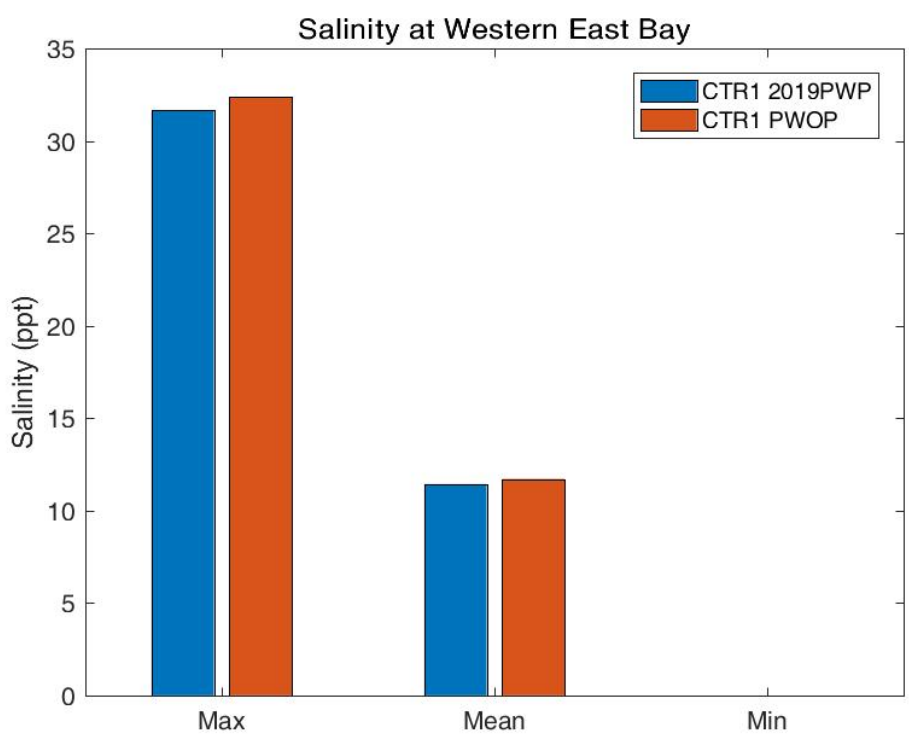

Salinity at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

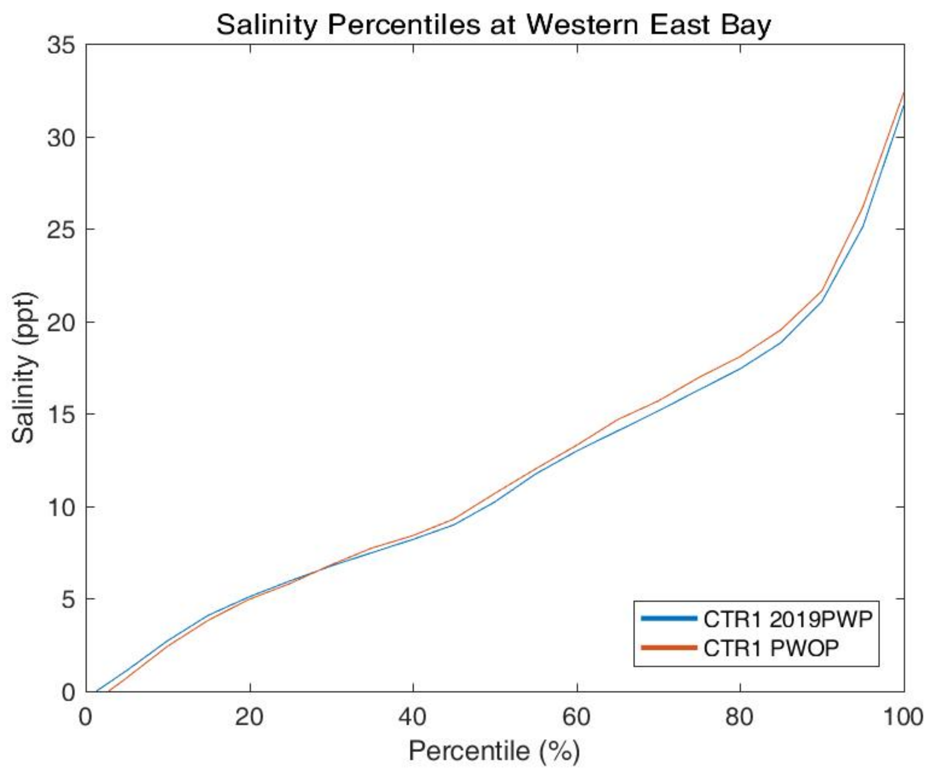

Salinity at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
Max
Mean
Min

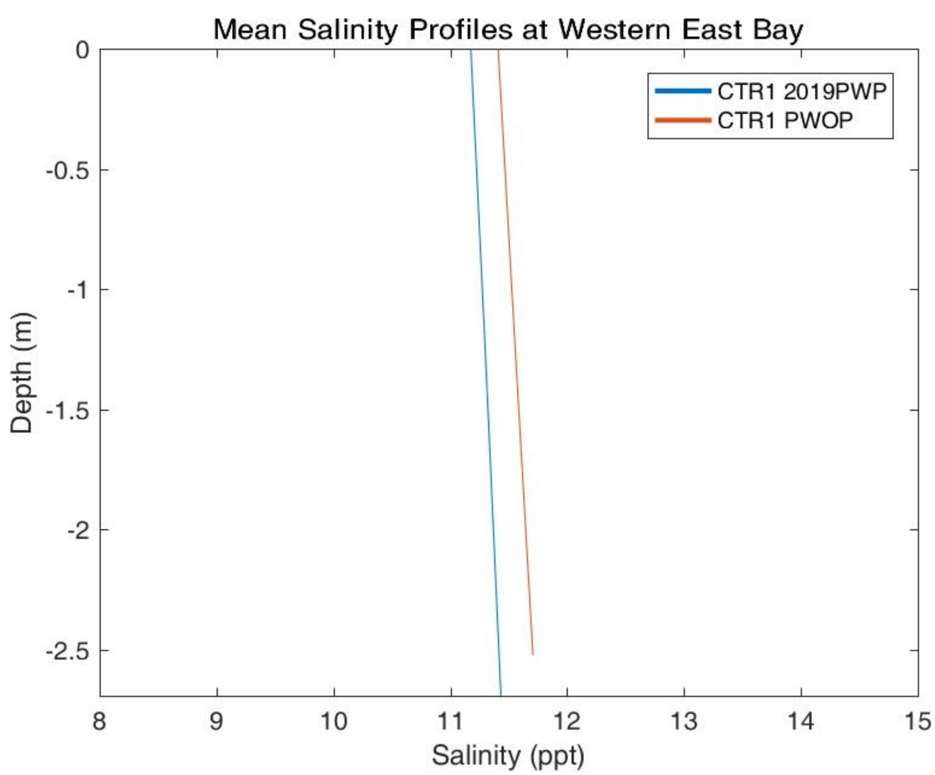

Salinity Percentiles at Upper Trinity Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
35
30
25
20
15
10
5
0
30
40
50
60
70
80
90
100

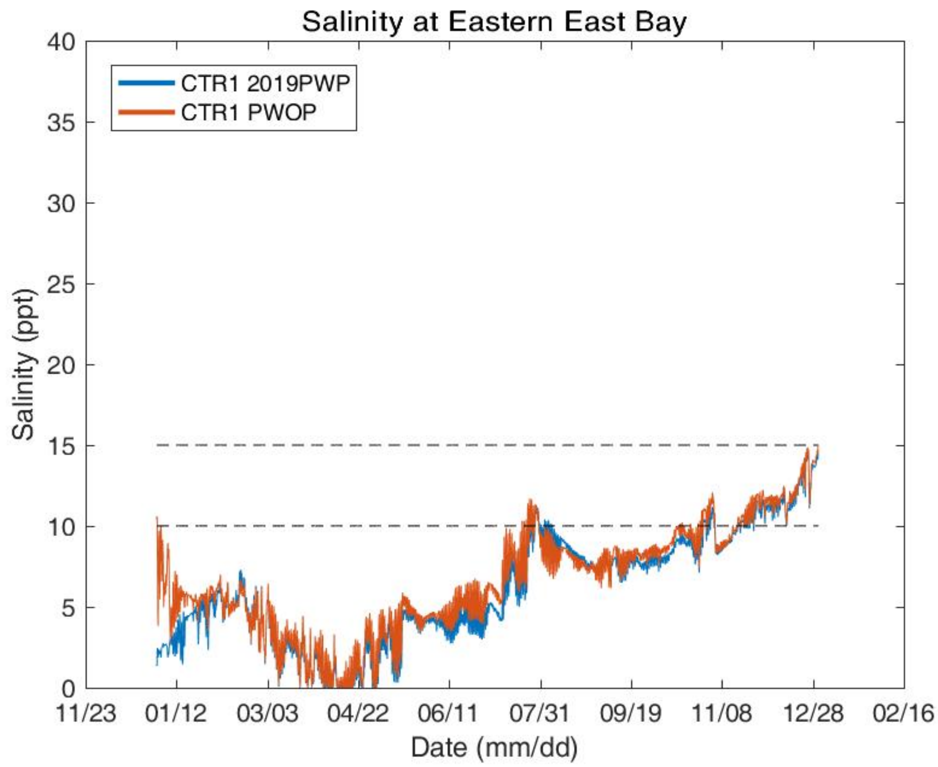

Mean Salinity Profiles at Upper Trinity Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
0
1
2
3
4
5
6

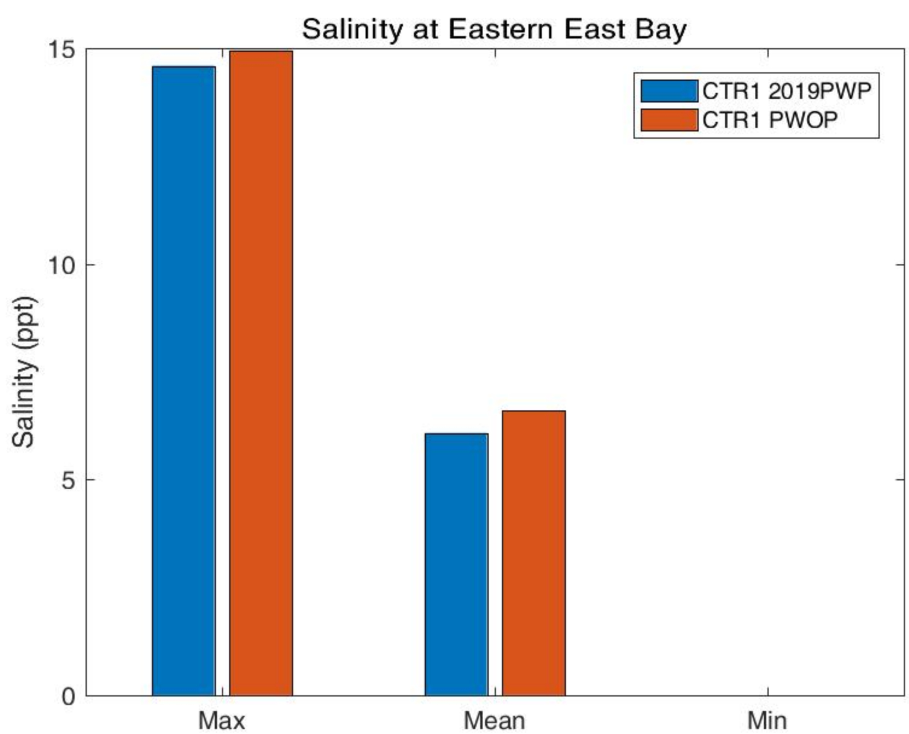

Salinity at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

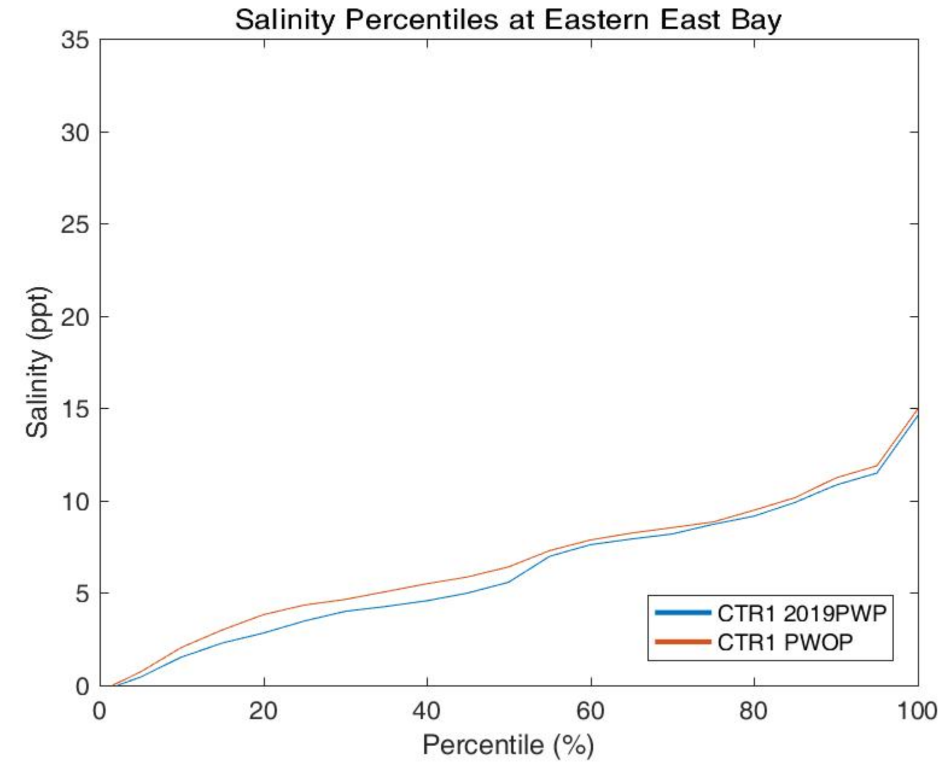

Salinity at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min

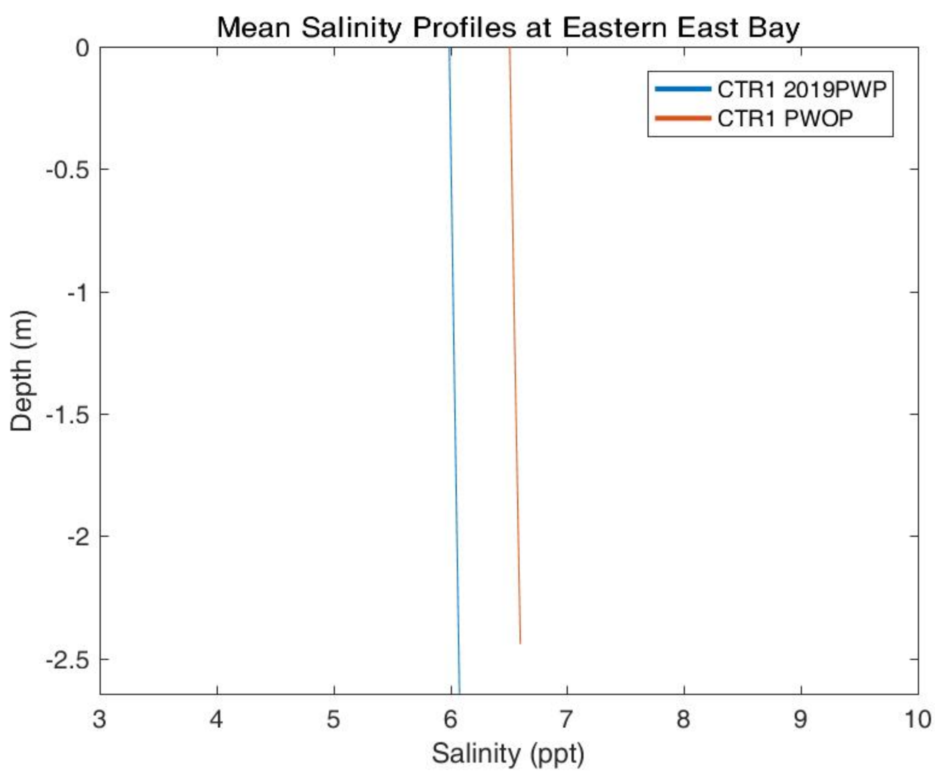

Salinity Percentiles at Western East Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
35
30
25
20
15
10
5
0
0
20
40
60
80
100

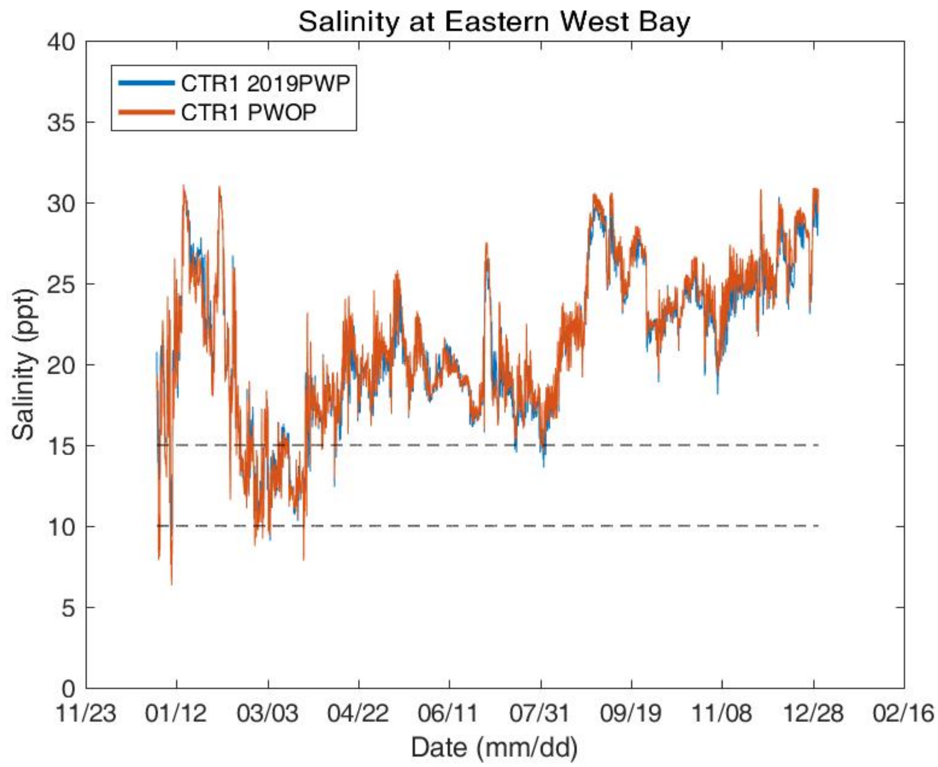

Mean Salinity Profiles at Western East Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
8
9
10
11
12
13
14
15

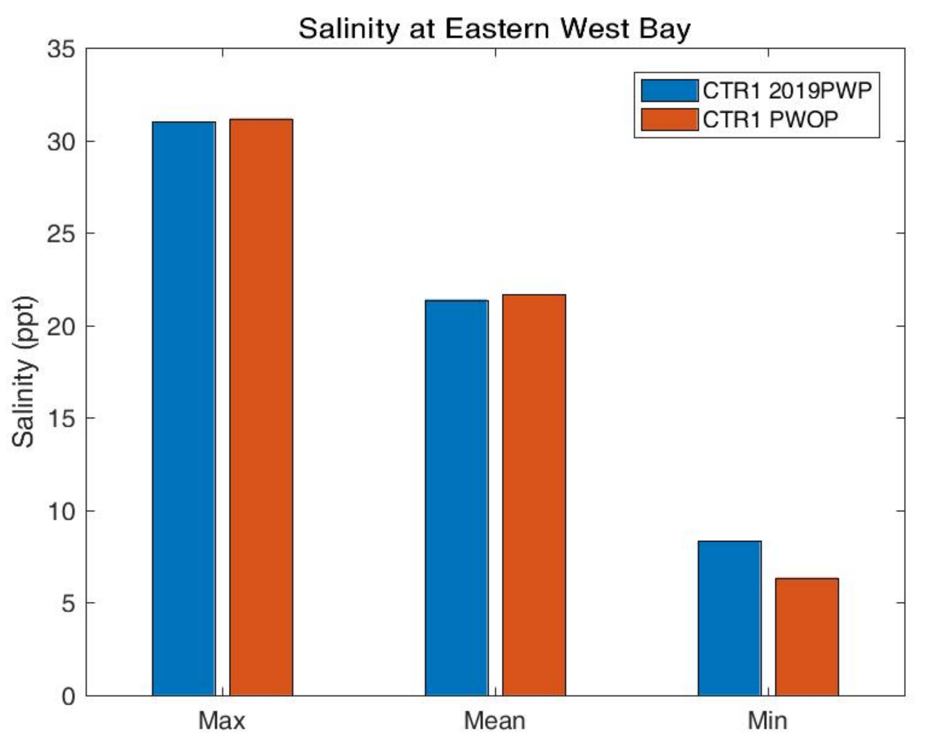

Salinity at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

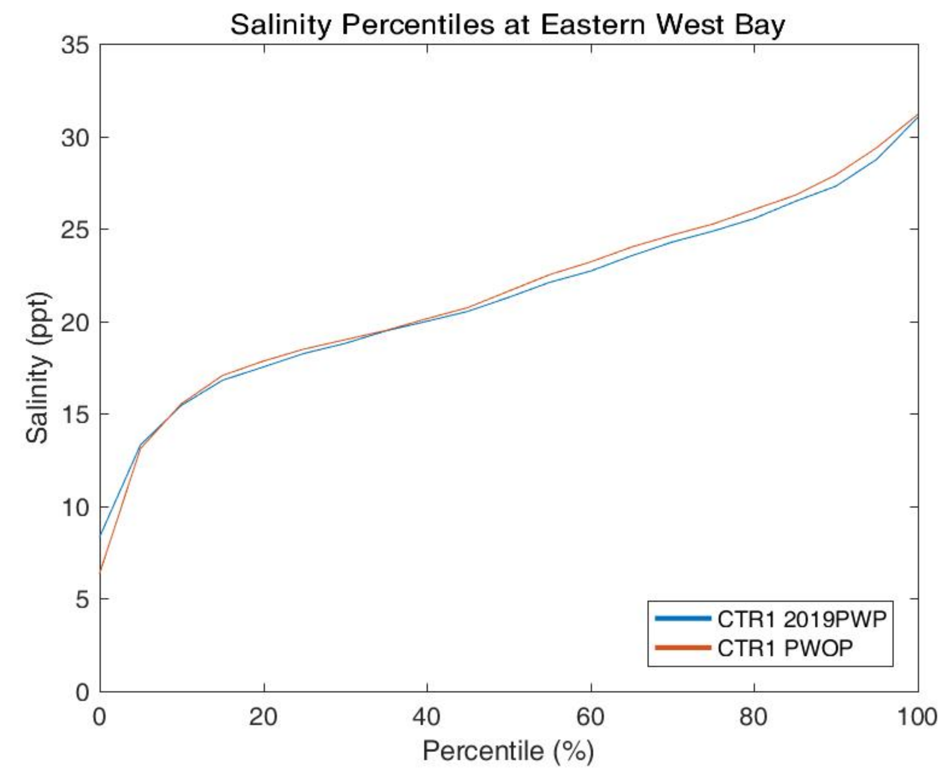

Salinity at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
Max
Mean
Min

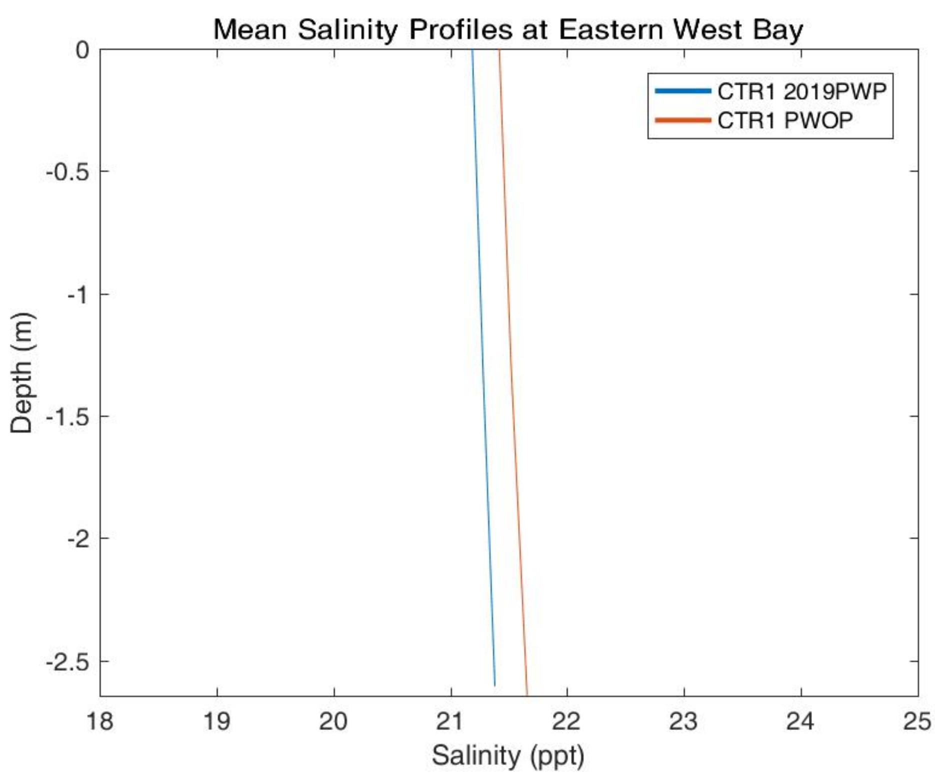

Salinity Percentiles at Eastern East Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
35
30
25
20
15
10
5
0
0
20
40
60
80
100

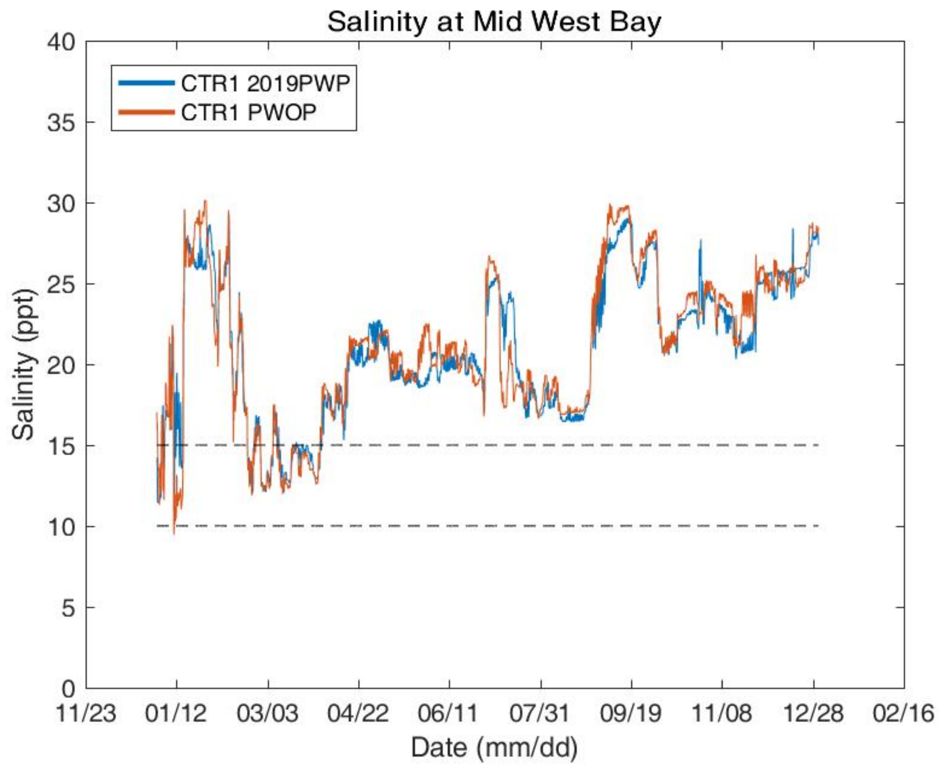

Mean Salinity Profiles at Eastern East Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
3
4
5
6
7
8
9
10

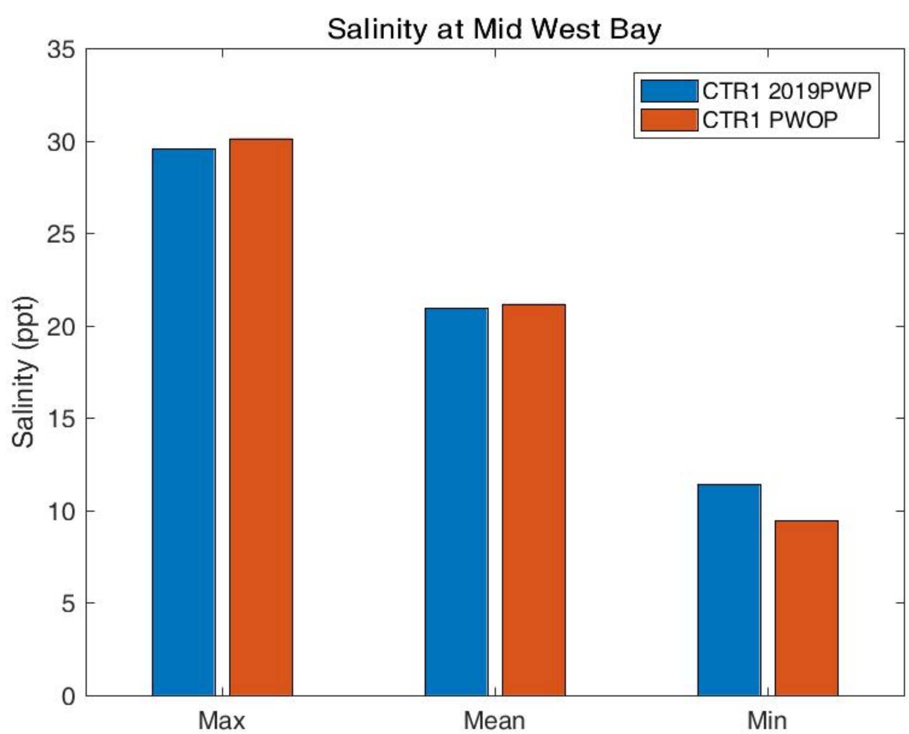

Salinity at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

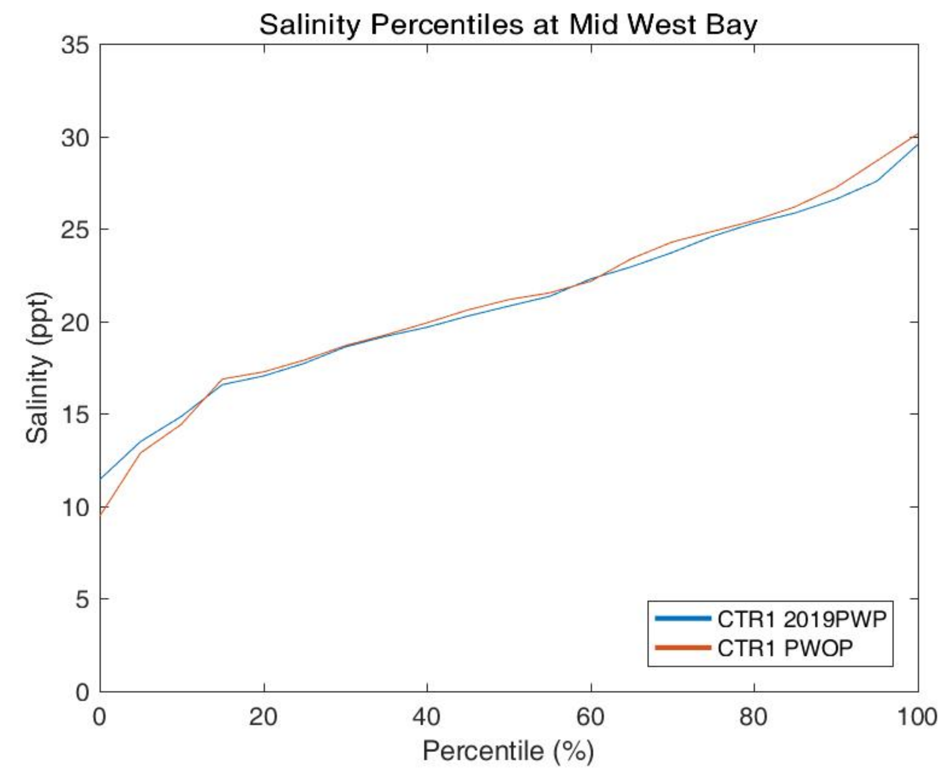

Salinity at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min

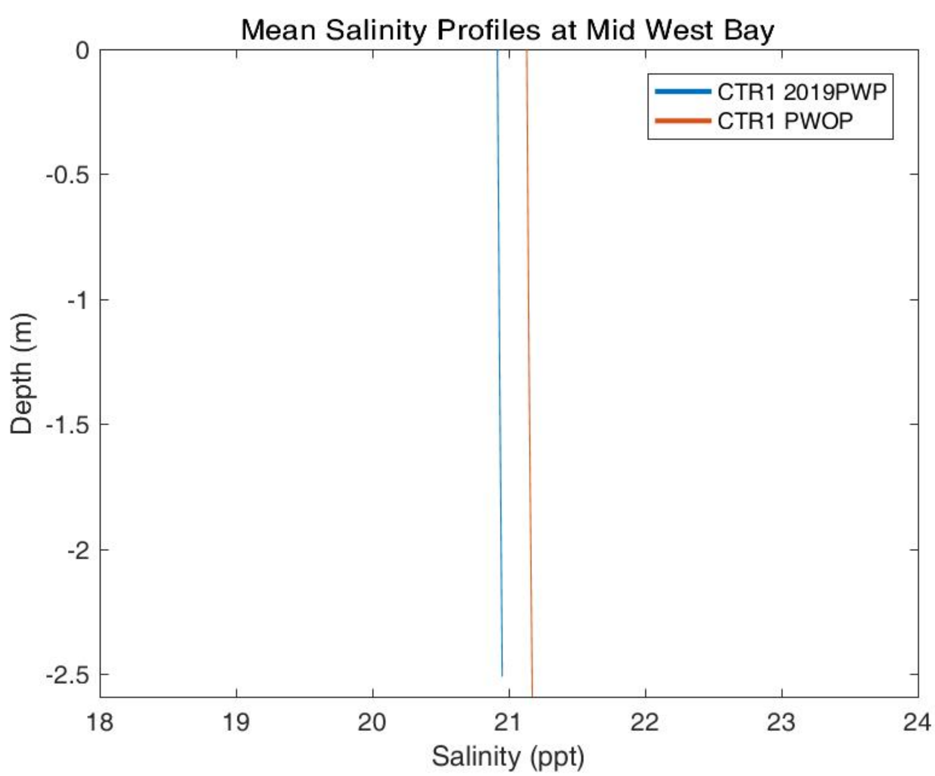

Salinity Percentiles at Eastern West Bay
Salinity (ppt)
Percentile (%)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
CTR1 2019PWP
CTR1 PWOP

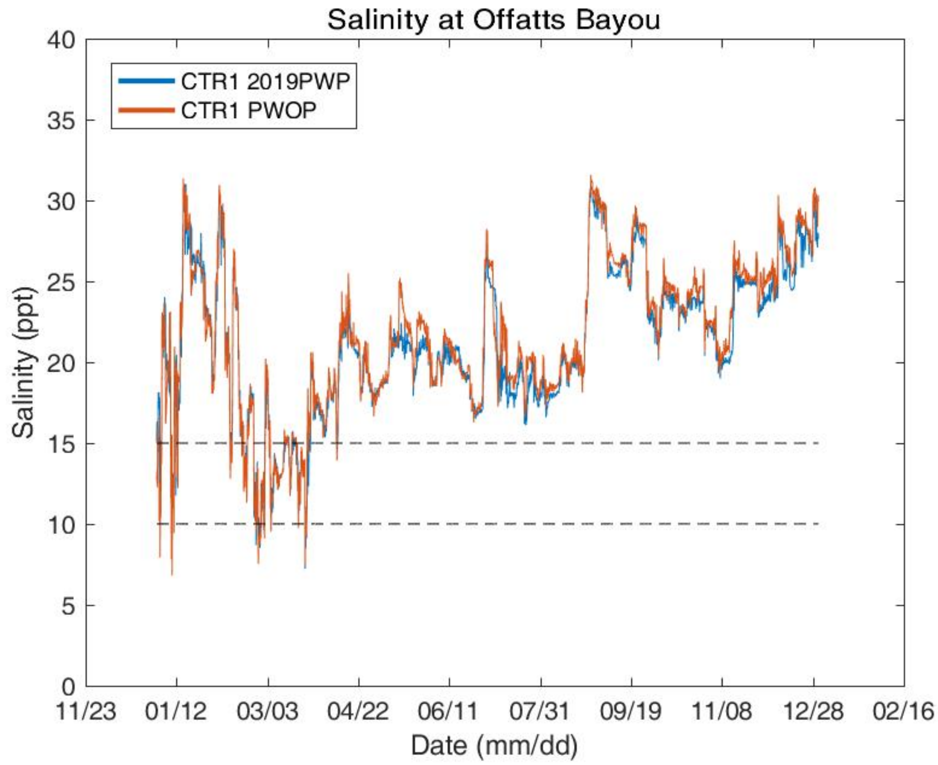

Mean Salinity Profiles at Eastern West Bay
Depth (m)
Salinity (ppt)
0
-0.5
-1
-1.5
-2
-2.5
18
19
20
21
22
23
24
25
CTR1 2019PWP
CTR1 PWOP

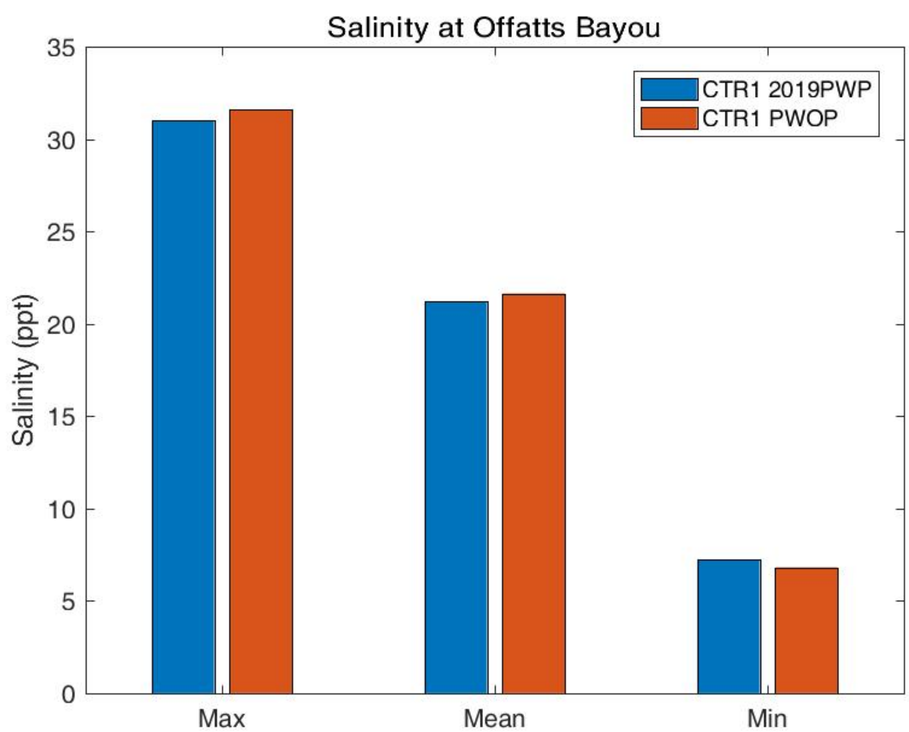

Salinity at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

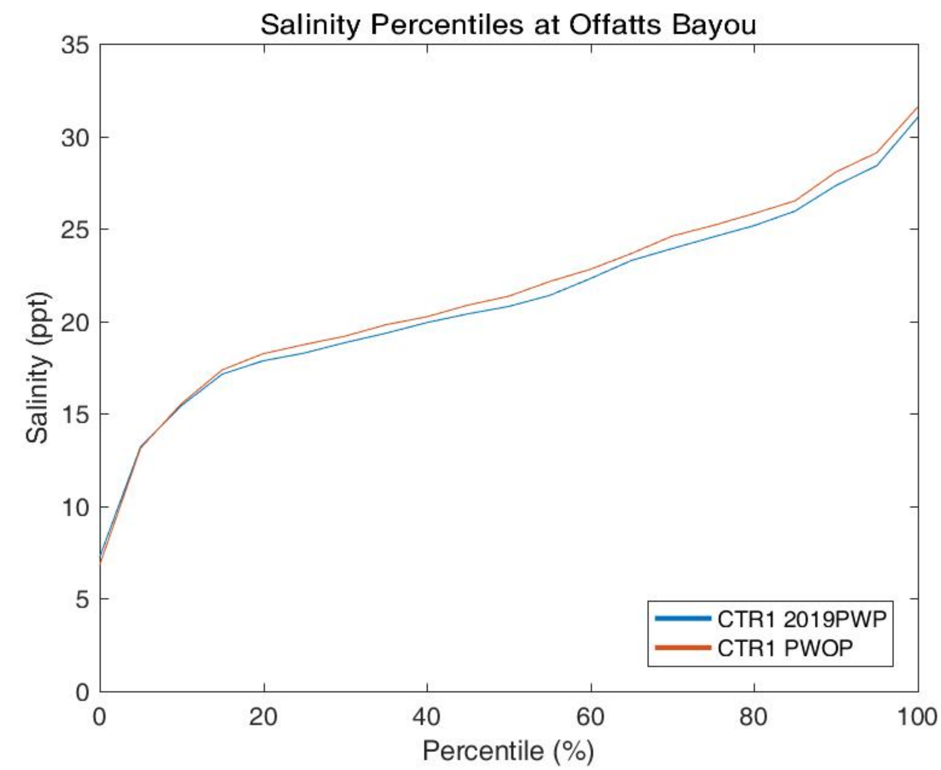

Salinity at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min

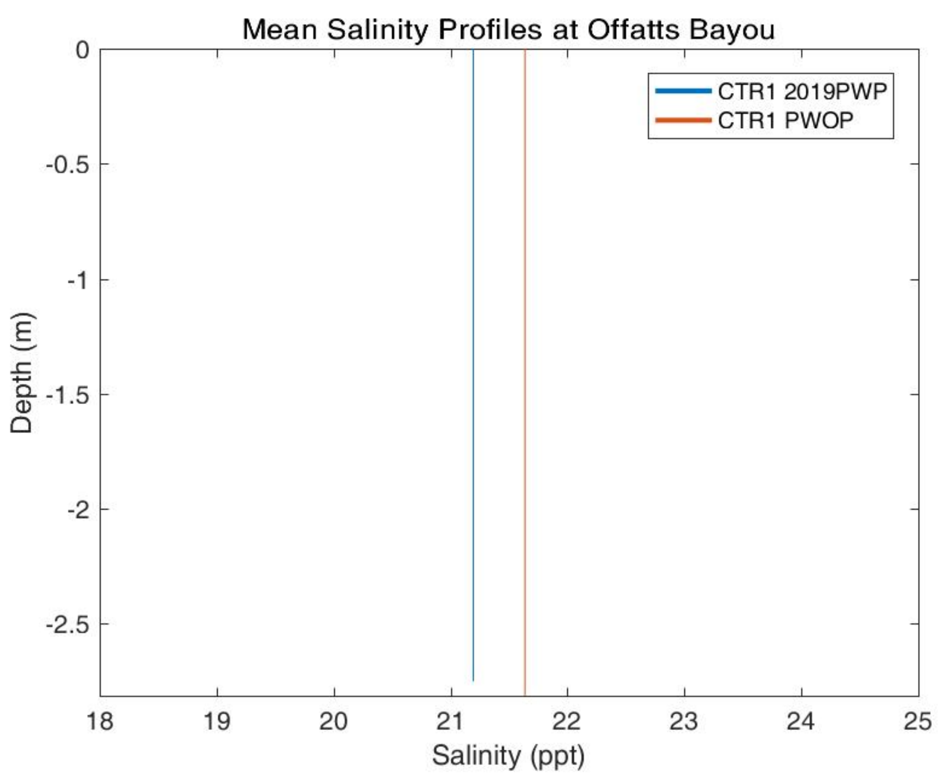

Salinity Percentiles at Mid West Bay
Salinity (ppt)
35
30
25
20
15
10
5
0
0
20
40
60
80
100
Percentile (%)
CTR1 2019PWP
CTR1 PWOP

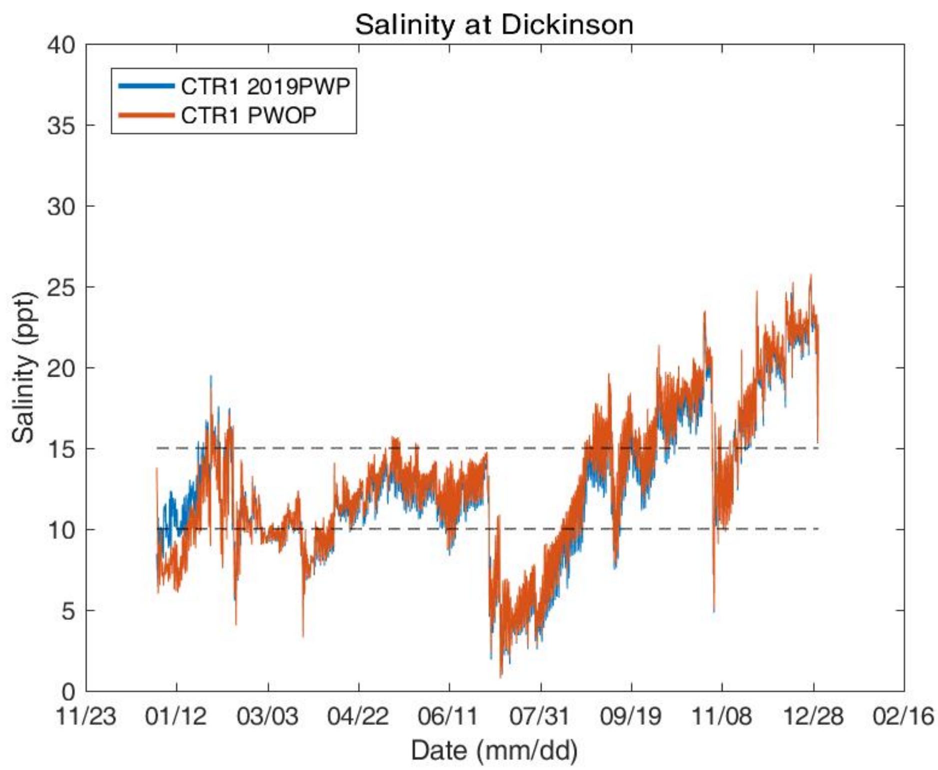

Mean Salinity Profiles at Mid West Bay
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
18
19
20
21
22
23
24
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP

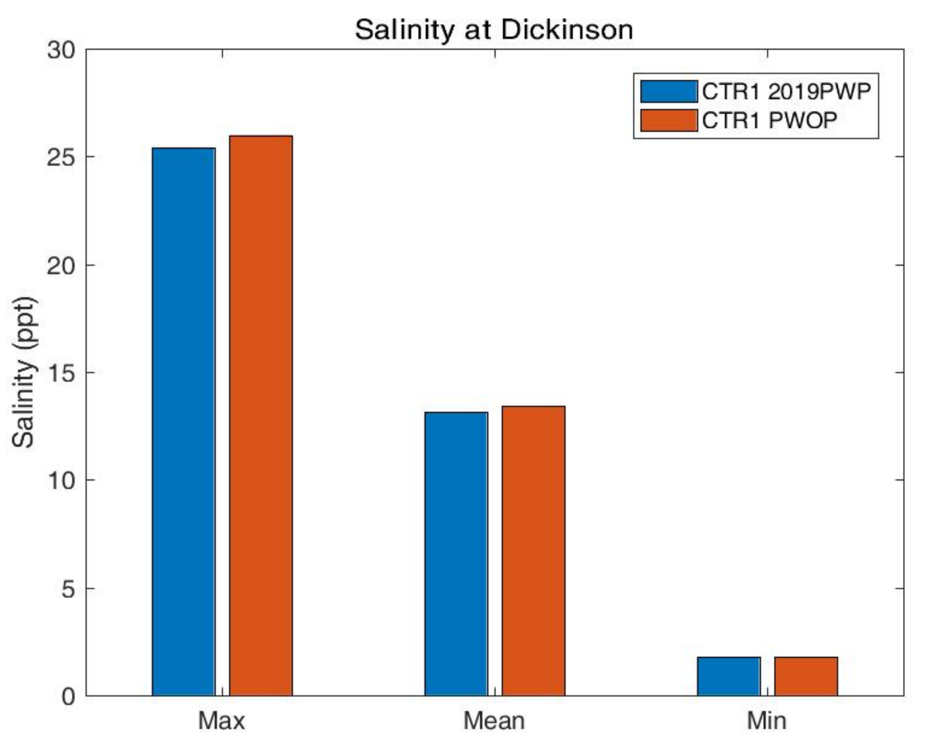

Salinity at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16
Date (mm/dd)

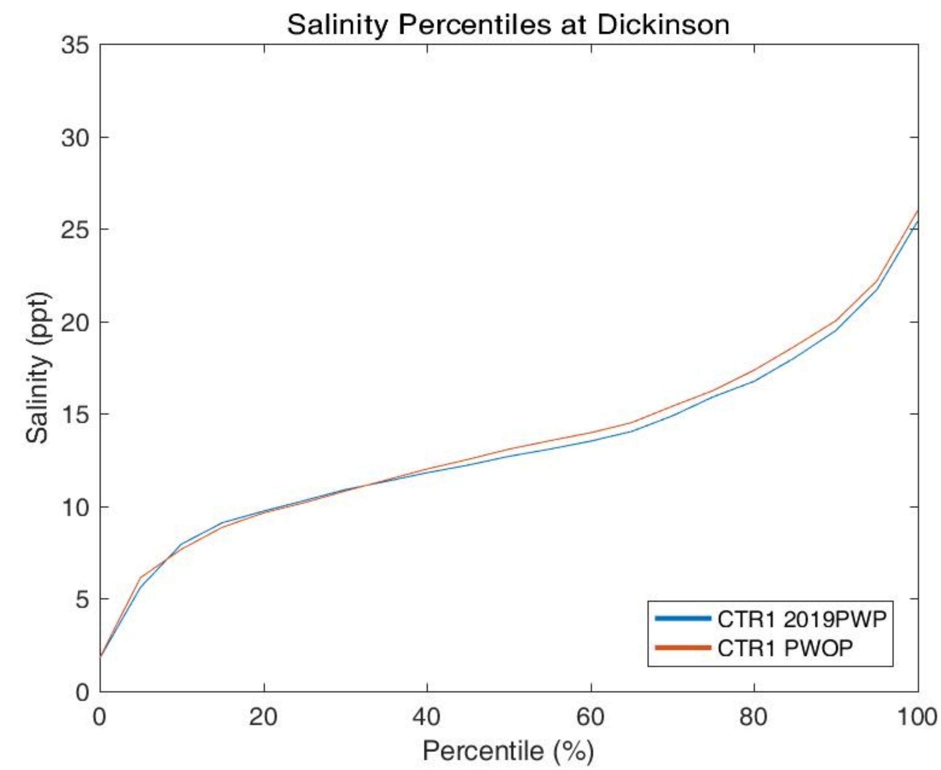

Salinity at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
35
Max
Mean
Min

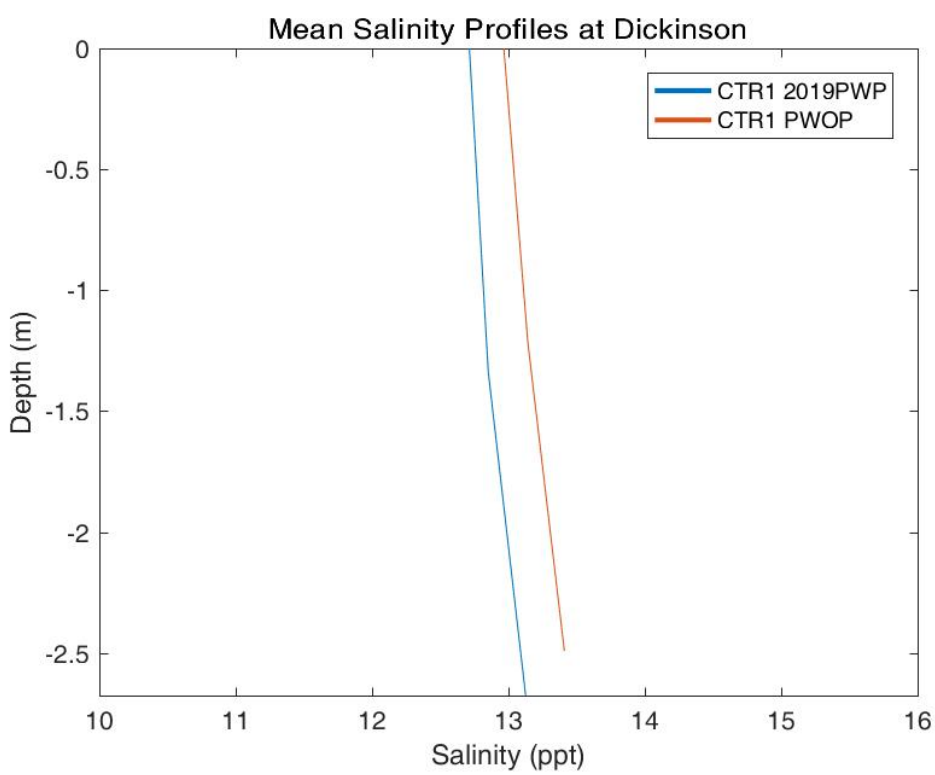

Salinity Percentiles at Offatts Bayou
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

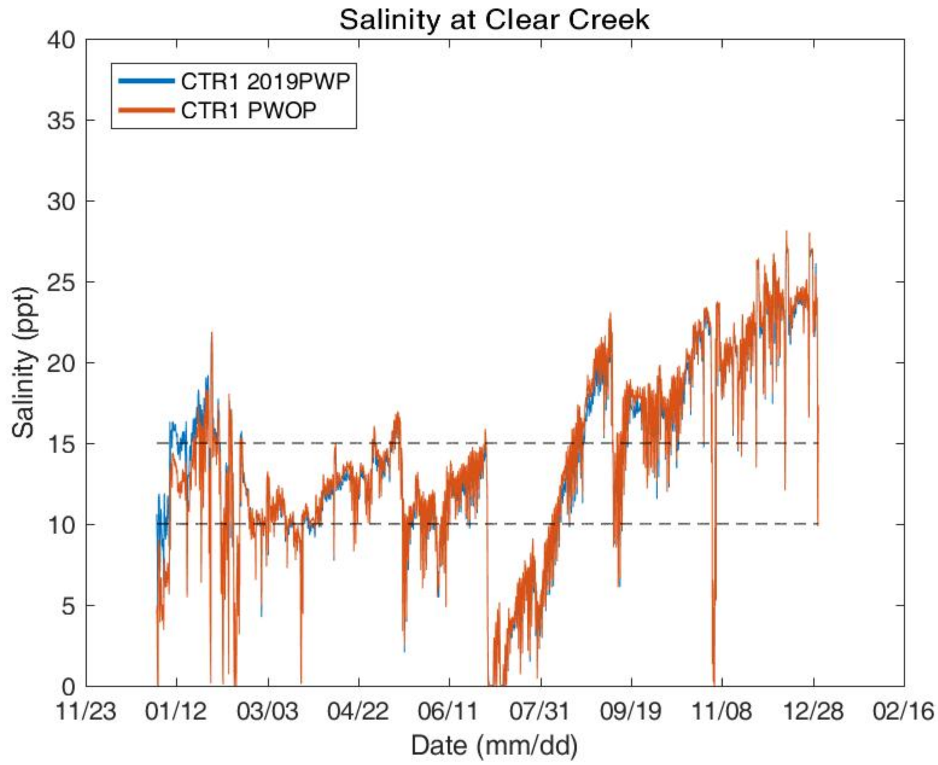

Mean Salinity Profiles at Offatts Bayou
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
18
19
20
21
22
23
24
25

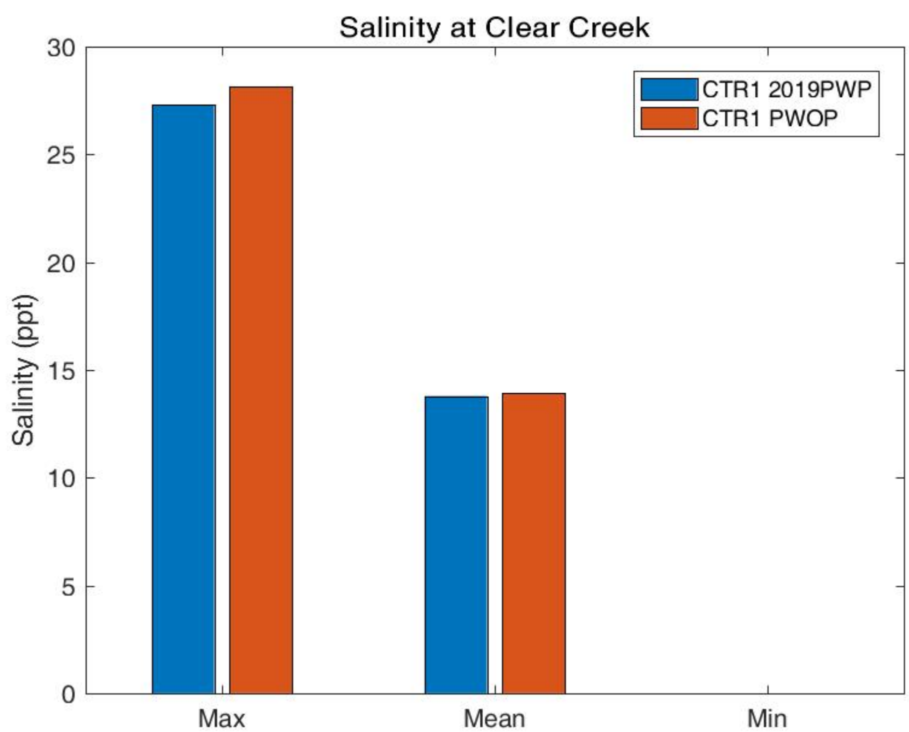

Salinity at Dickinson
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

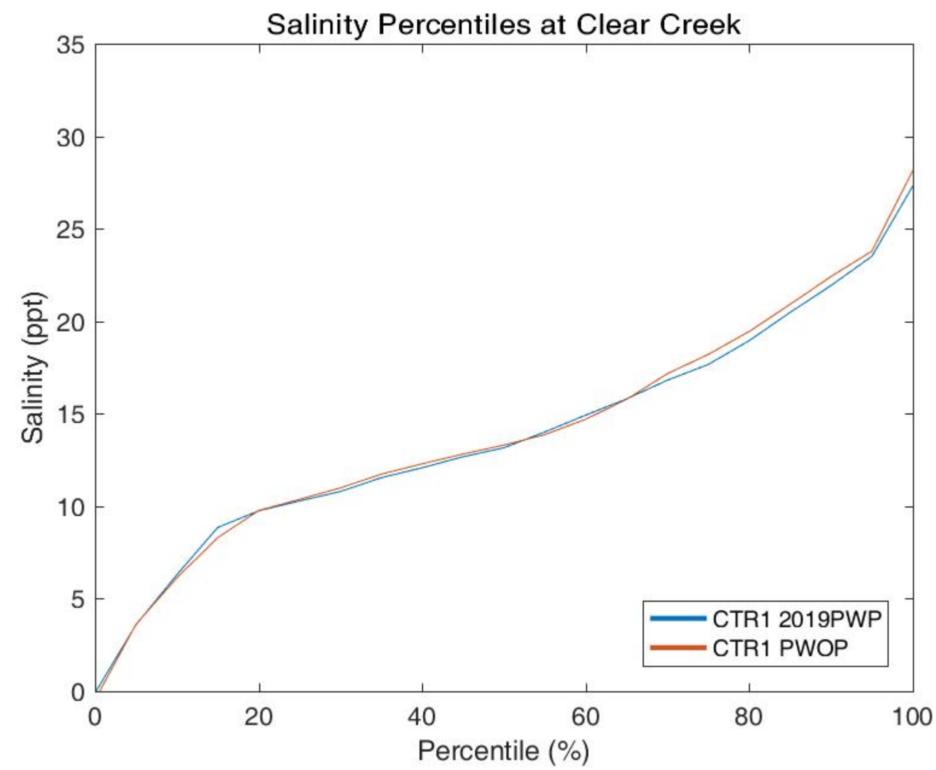

Salinity at Dickinson
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
Max
Mean
Min

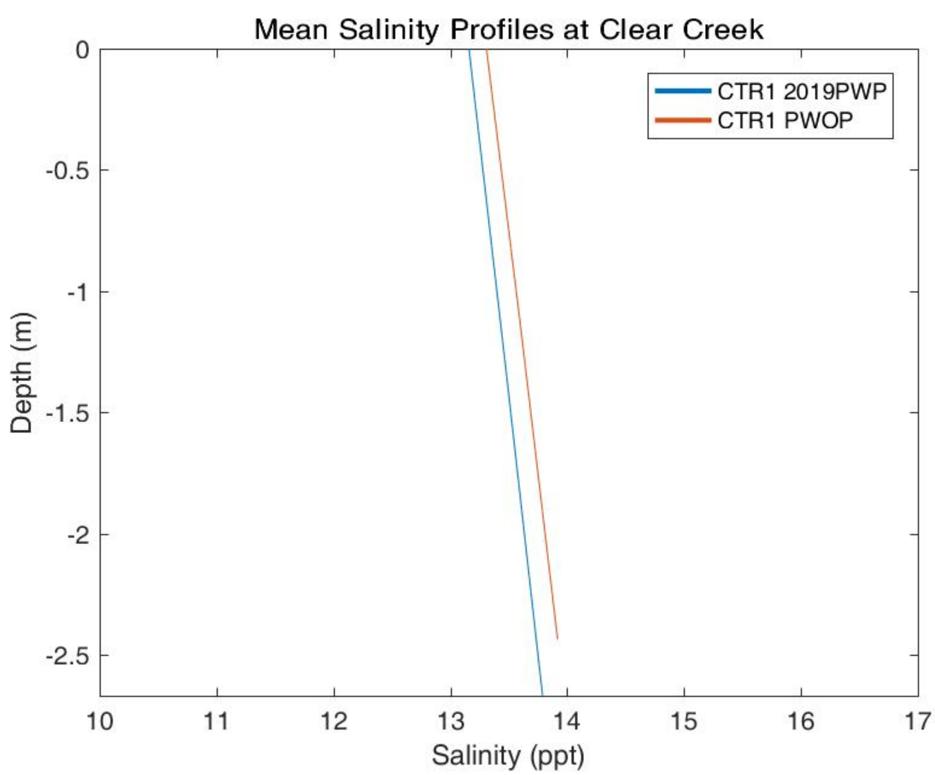

Salinity Percentiles at Dickinson
Salinity (ppt)
Percentile (%)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
CTR1 2019PWP
CTR1 PWOP

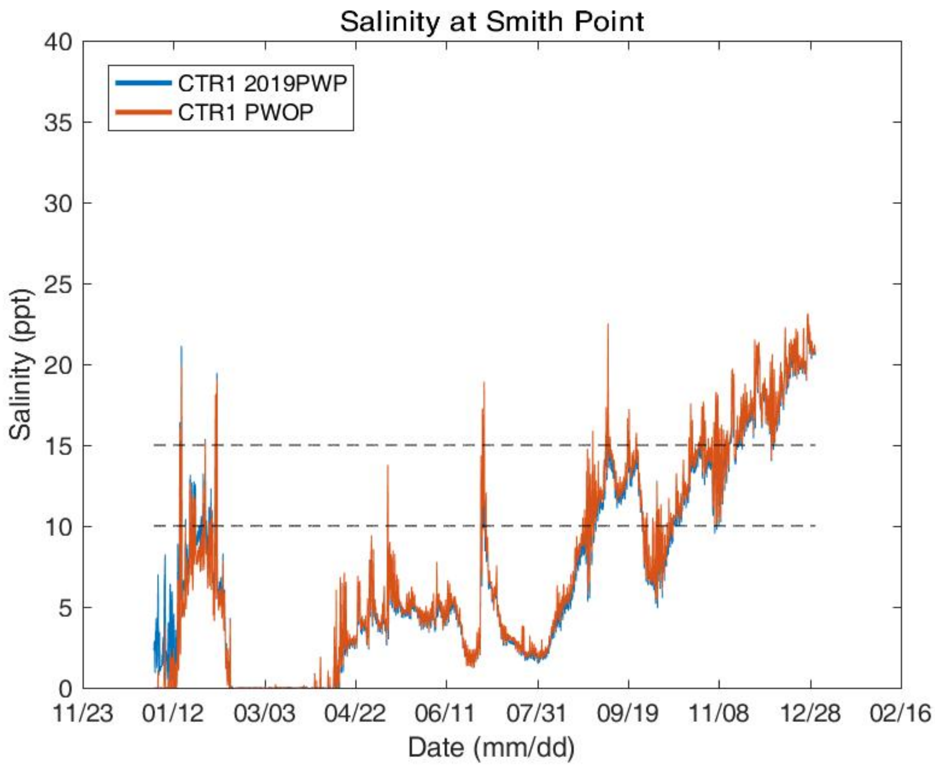

Mean Salinity Profiles at Dickinson
Depth (m)
Salinity (ppt)
0
-0.5
-1
-1.5
-2
-2.5
10
11
12
13
14
15
16
CTR1 2019PWP
CTR1 PWOP

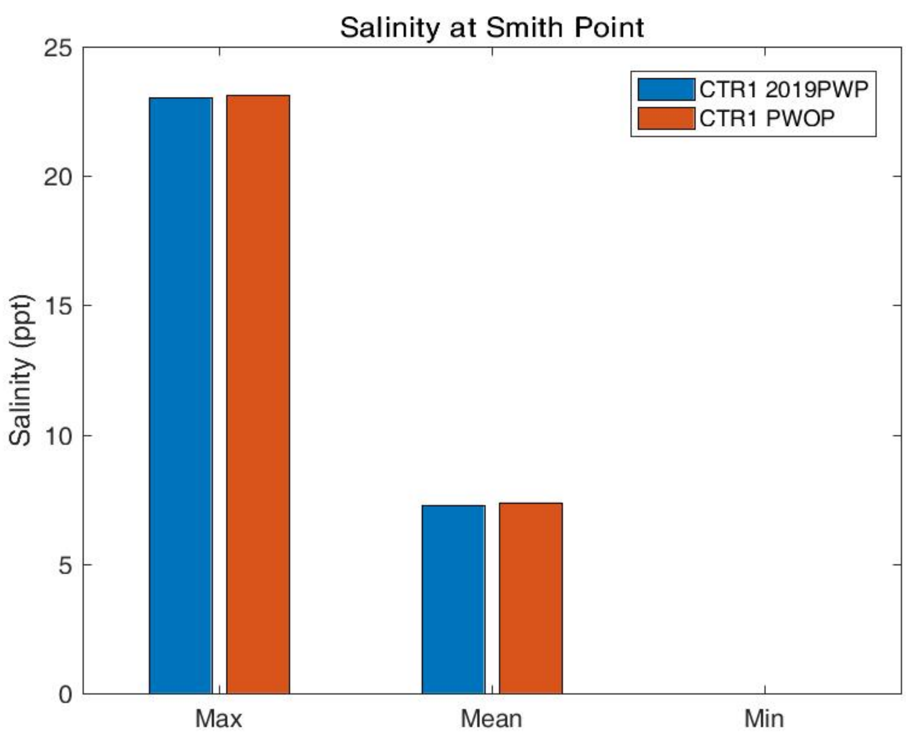

Salinity at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
40
35
30
25
20
15
10
5
0
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

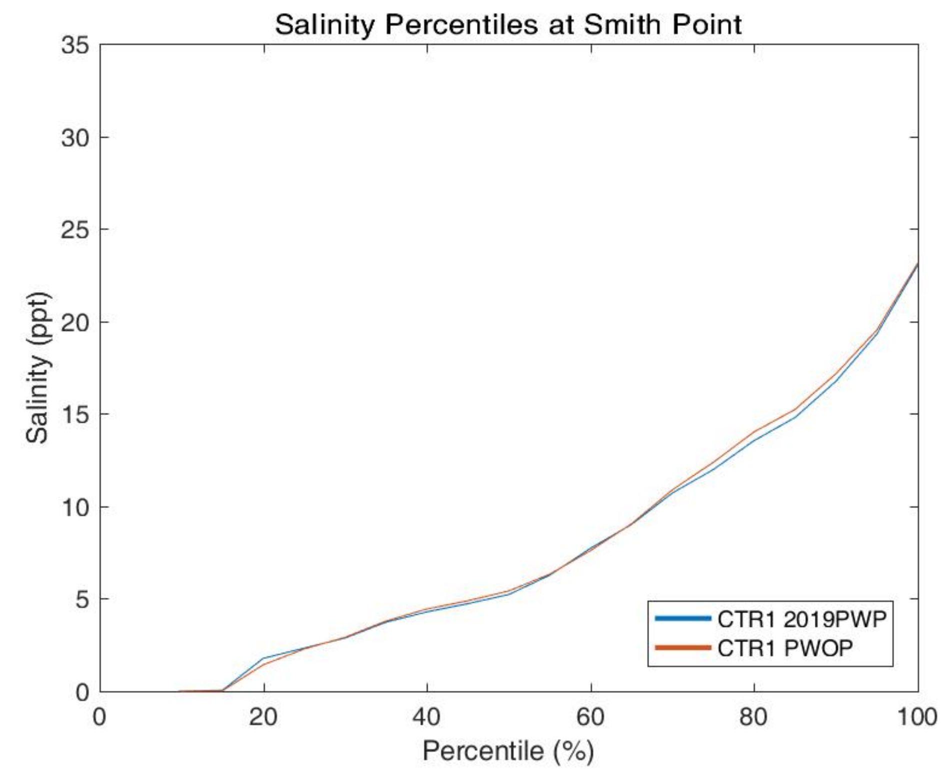

Salinity at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
30
25
20
15
10
5
0
Max
Mean
Min


Salinity Percentiles at Clear Creek
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
0
20
40
60
80
100

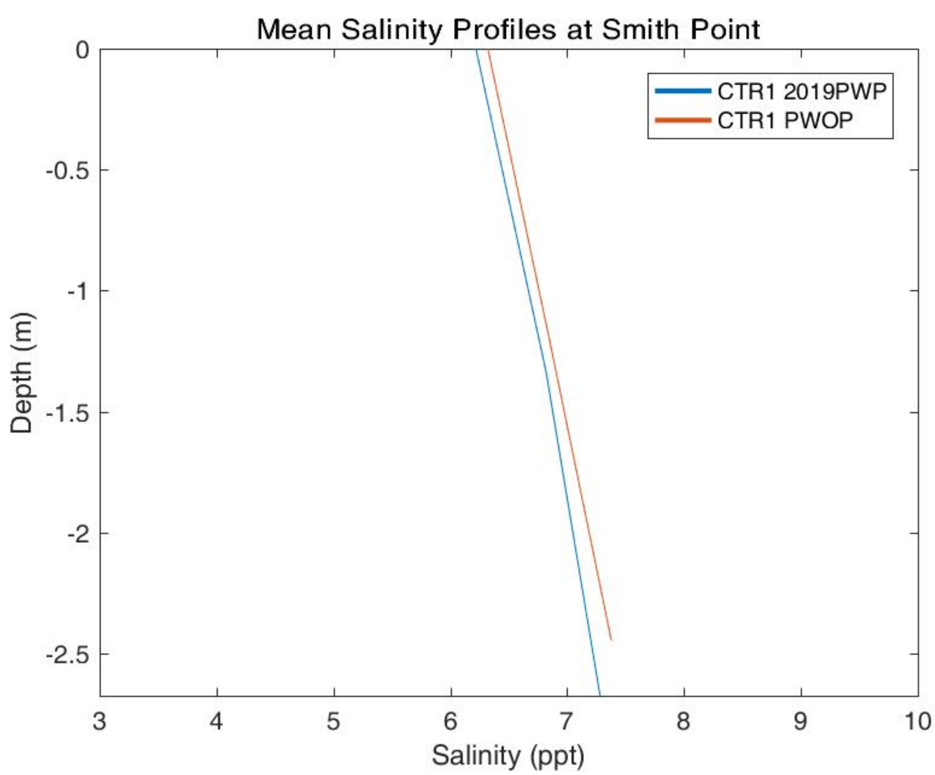

Mean Salinity Profiles at Clear Creek
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
10
11
12
13
14
15
16
17


Salinity at Smith Point
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

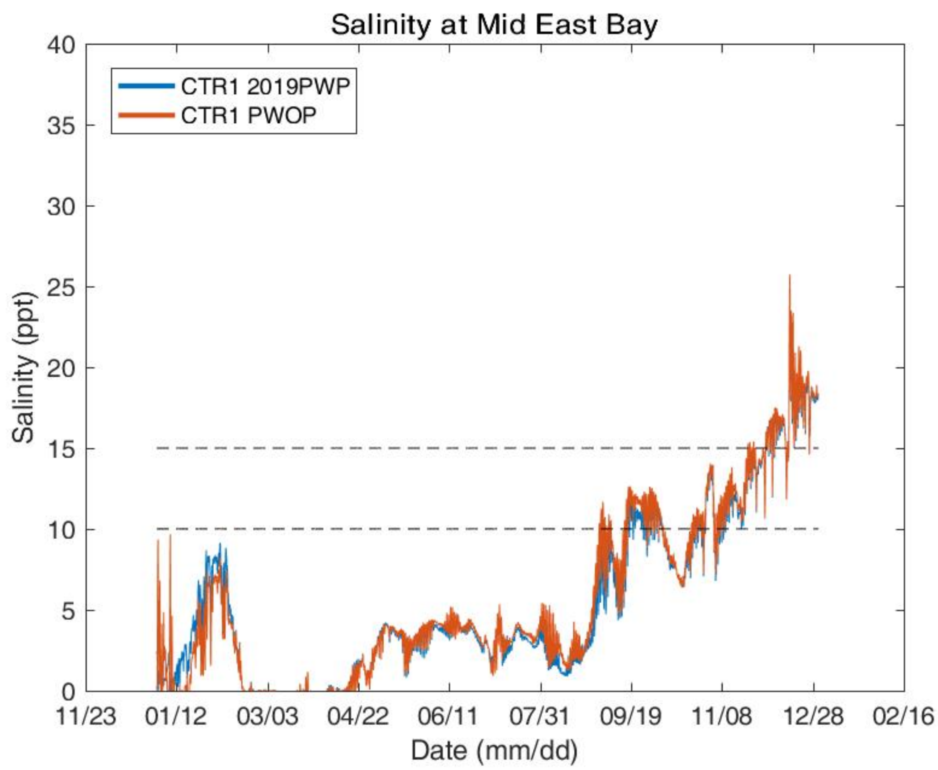

Salinity at Smith Point
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
Max
Mean
Min

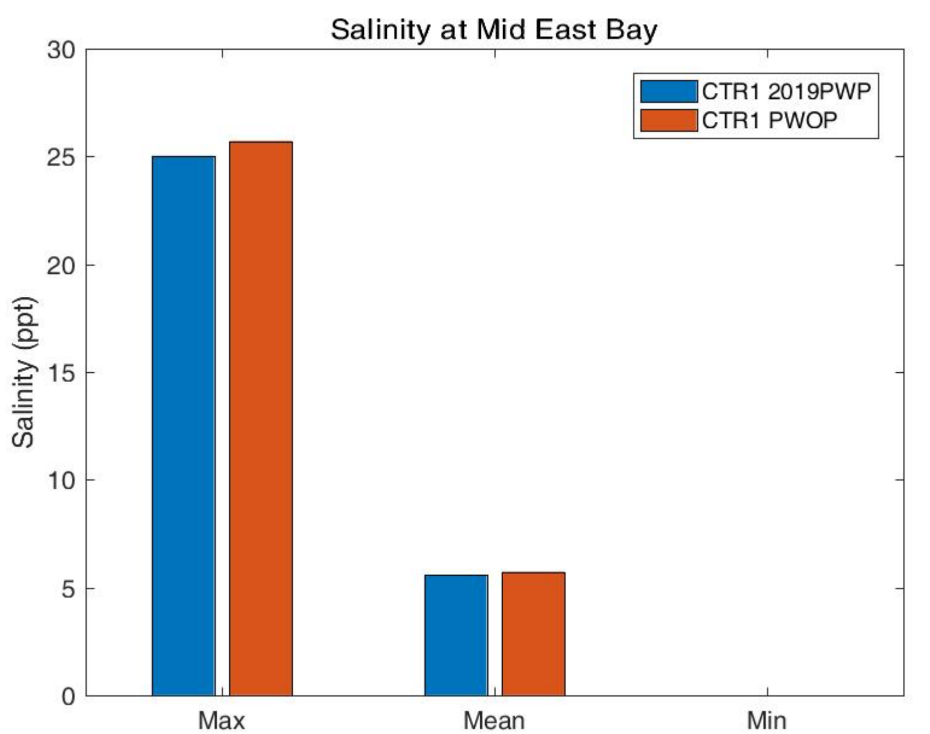


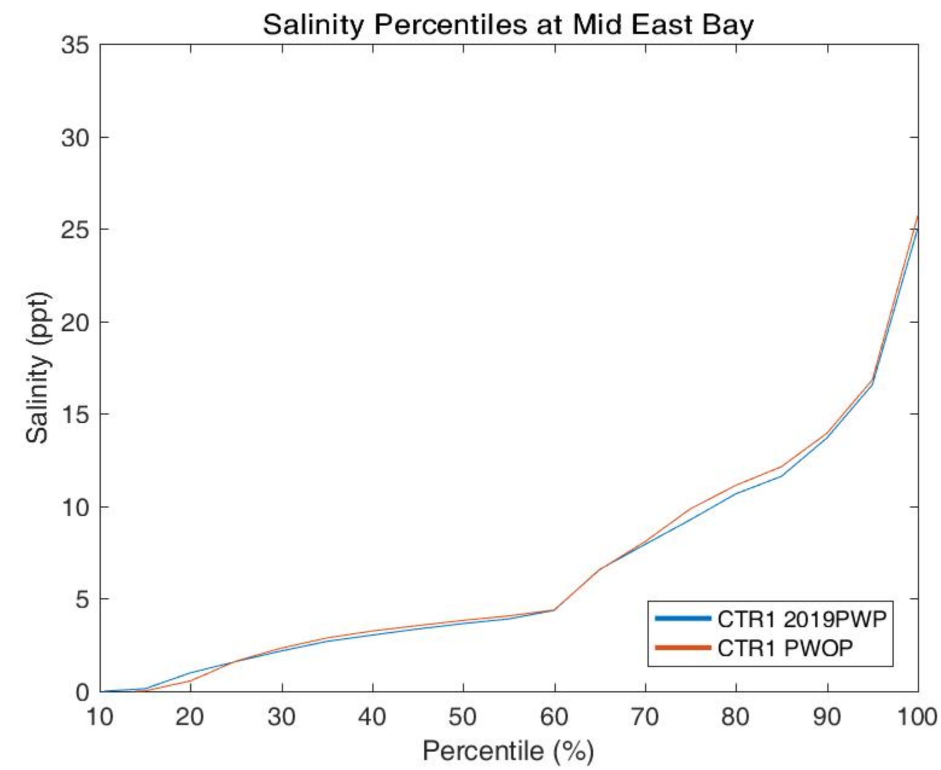
Salinity Percentiles at Smith Point
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP

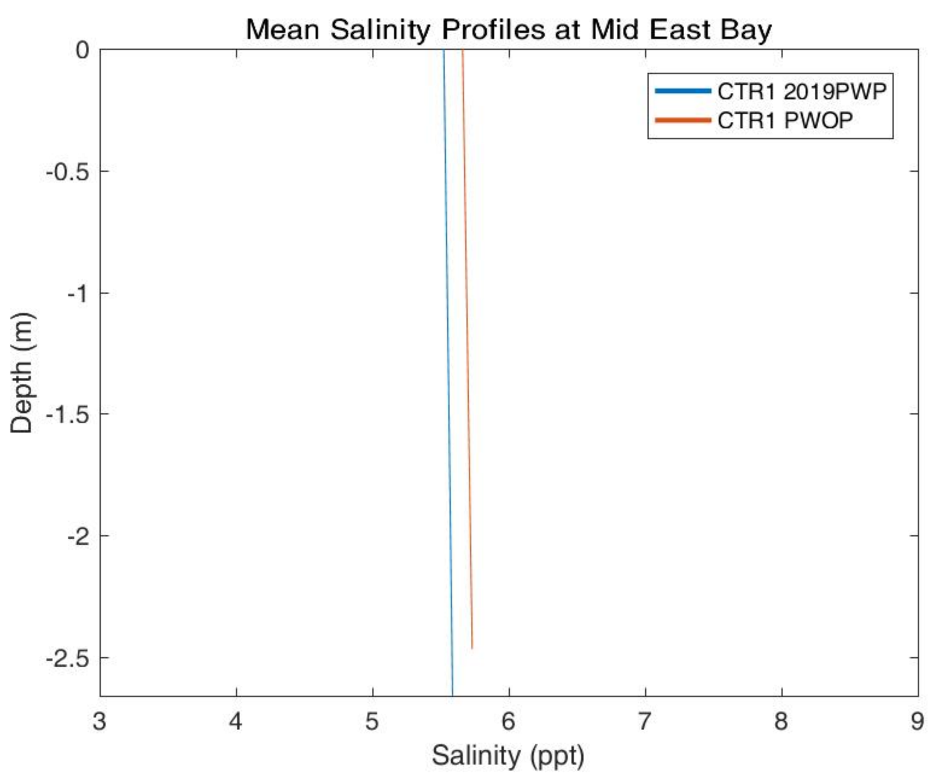


Mean Salinity Profiles at Smith Point
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP

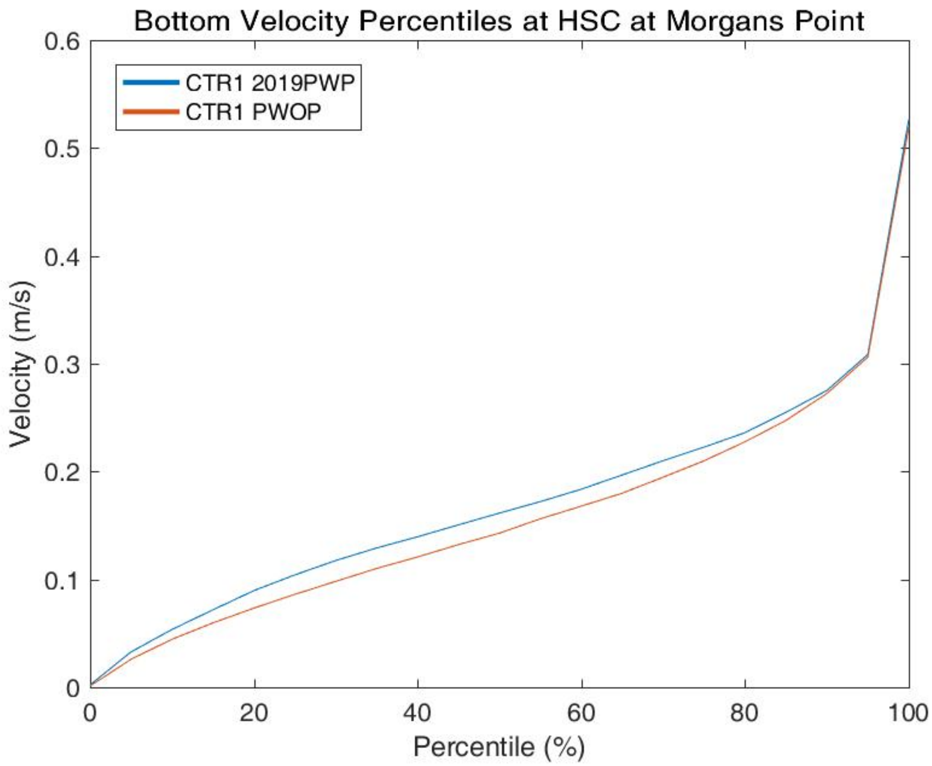

Salinity at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
Date (mm/dd)
0
5
10
15
20
25
30
35
40
11/23
01/12
03/03
04/22
06/11
07/31
09/19
11/08
12/28
02/16

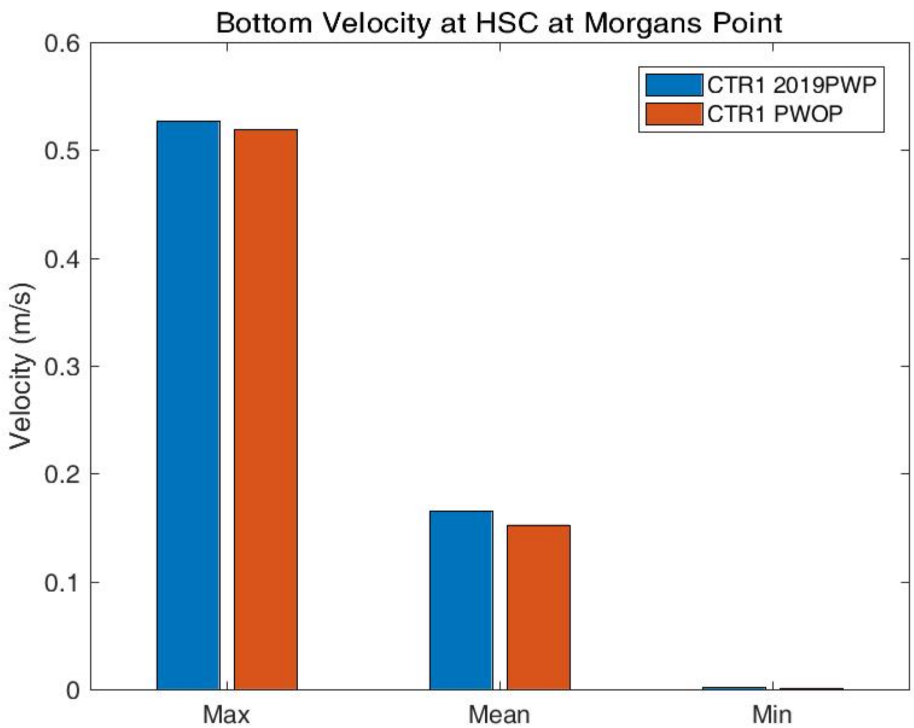

Salinity at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Salinity (ppt)
0
5
10
15
20
25
30
Max
Mean
Min

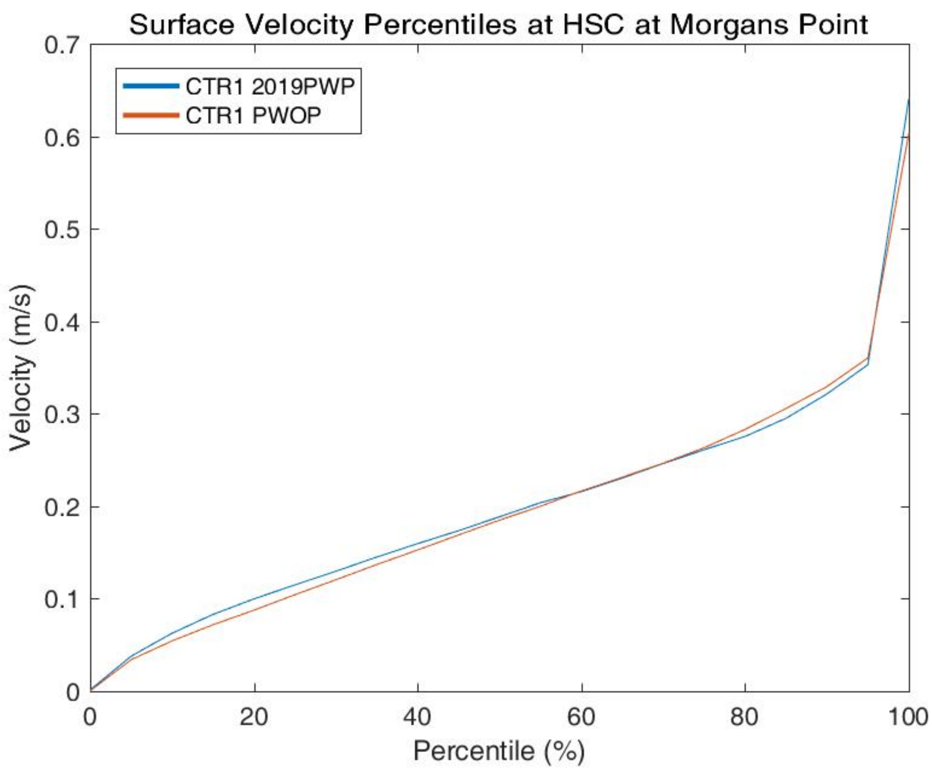

Salinity Percentiles at Mid East Bay
Salinity (ppt)
Percentile (%)
CTR1 2019PWP
CTR1 PWOP
0
5
10
15
20
25
30
35
10
20
30
40
50
60
70
80
90
100

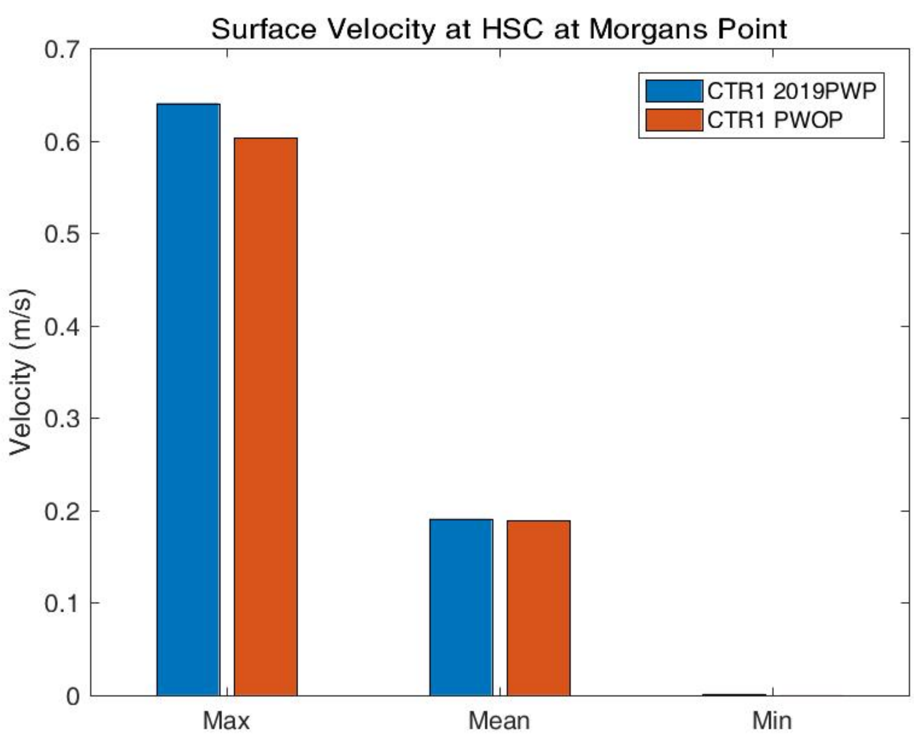

Mean Salinity Profiles at Mid East Bay
Depth (m)
Salinity (ppt)
CTR1 2019PWP
CTR1 PWOP
0
-0.5
-1
-1.5
-2
-2.5
3
4
5
6
7
8
9

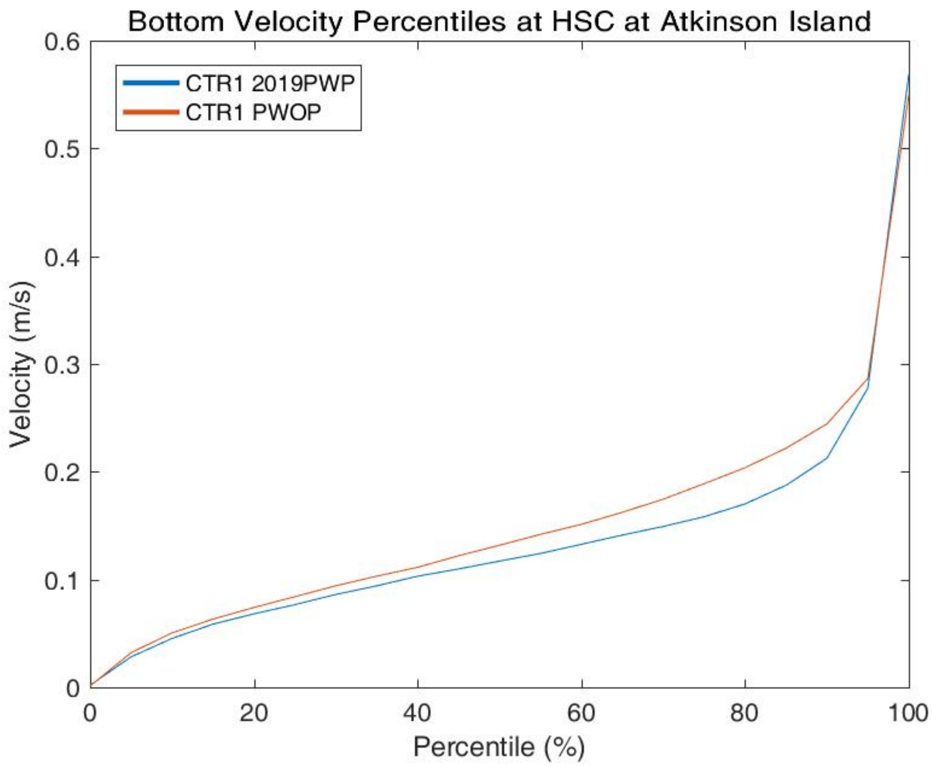
Appendix B: Velocity Magnitude Point Analysis

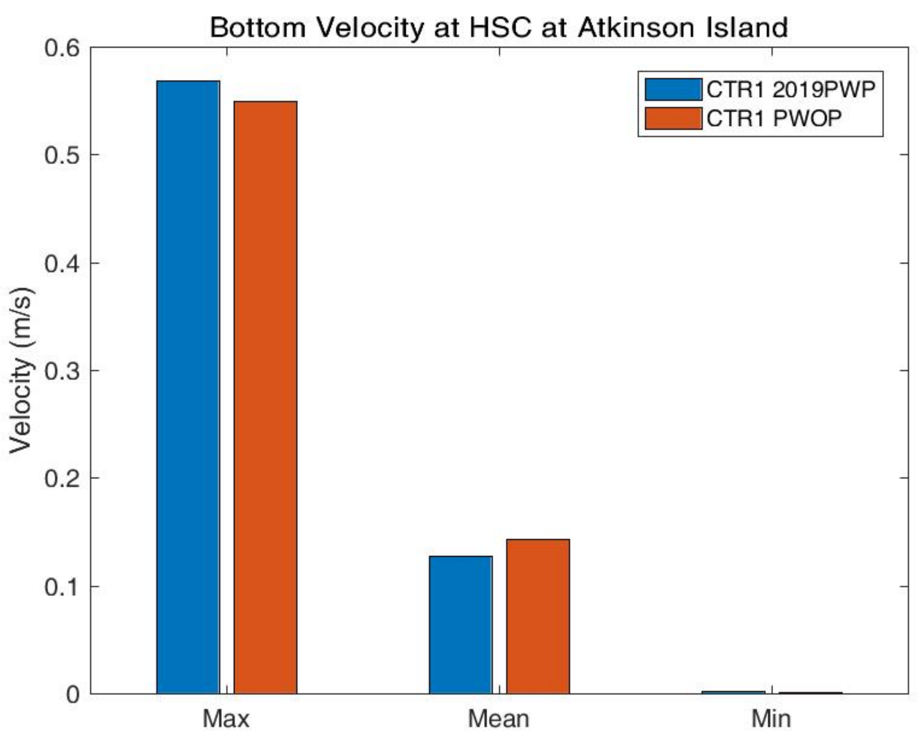


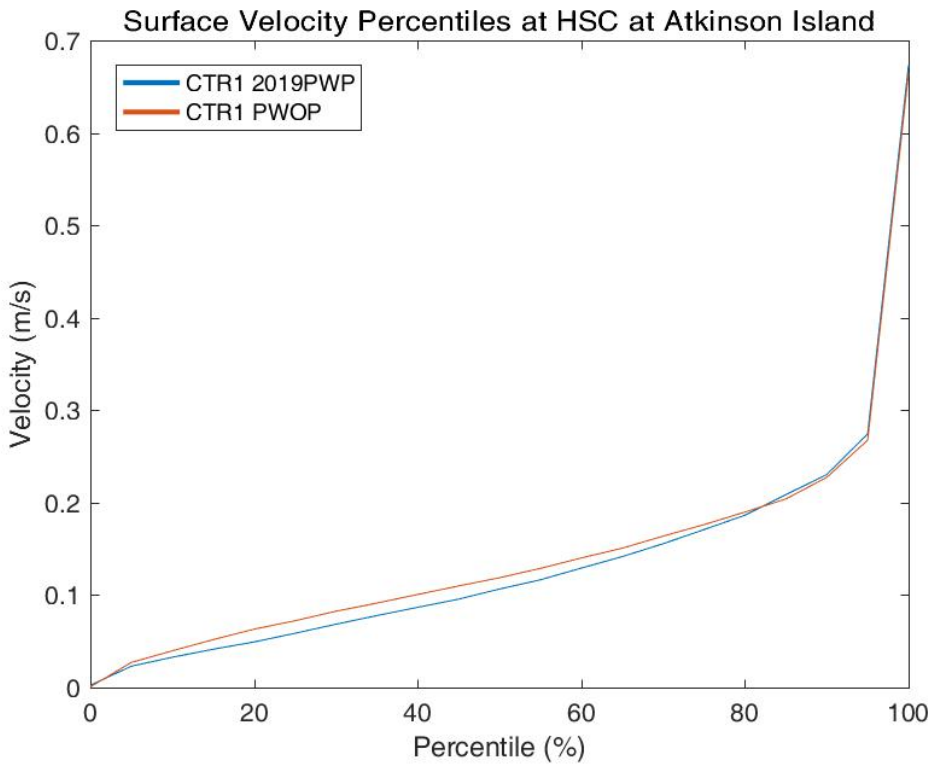

Bottom Velocity at HSC at Morgans Point
Velocity (m/s)
0.6
0.5
0.4
0.3
0.2
0.1
0
Max
Mean
Min
CTR1 2019PWP
CTR1 PWOP

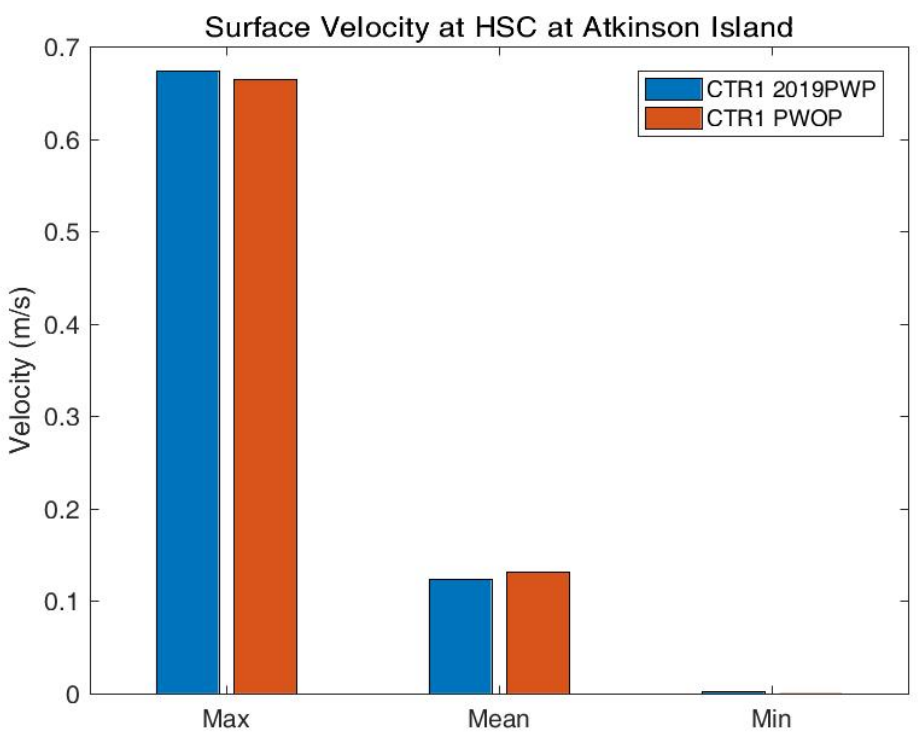

Surface Velocity Percentiles at HSC at Morgans Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Percentile (%)
0
20
40
60
80
100

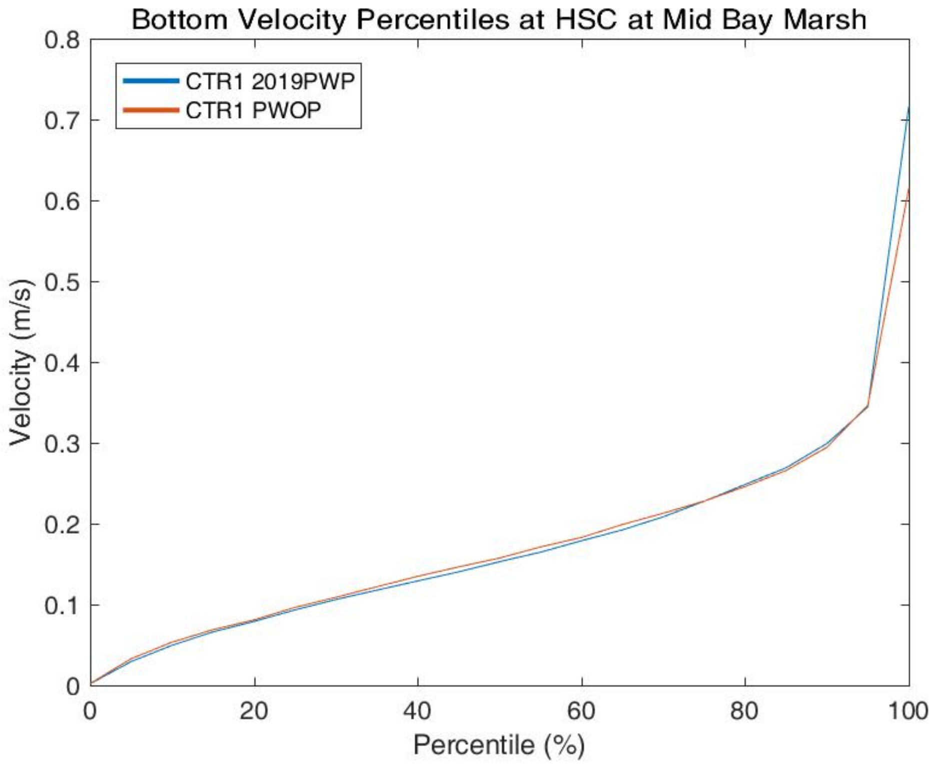

Surface Velocity at HSC at Morgans Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Max
Mean
Min

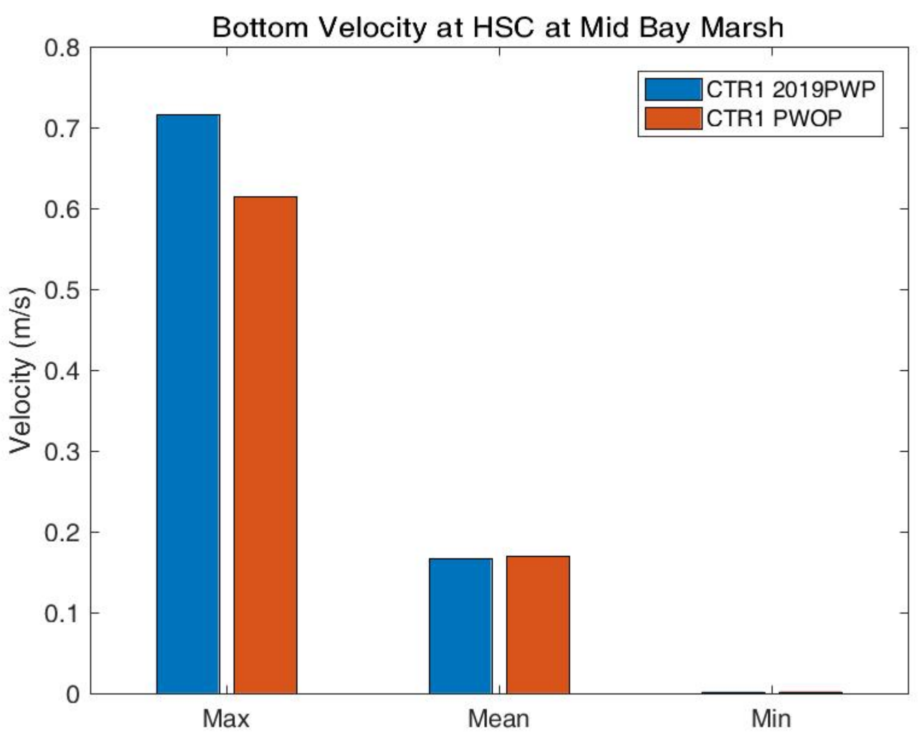

Bottom Velocity Percentiles at HSC at Atkinson Island
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100

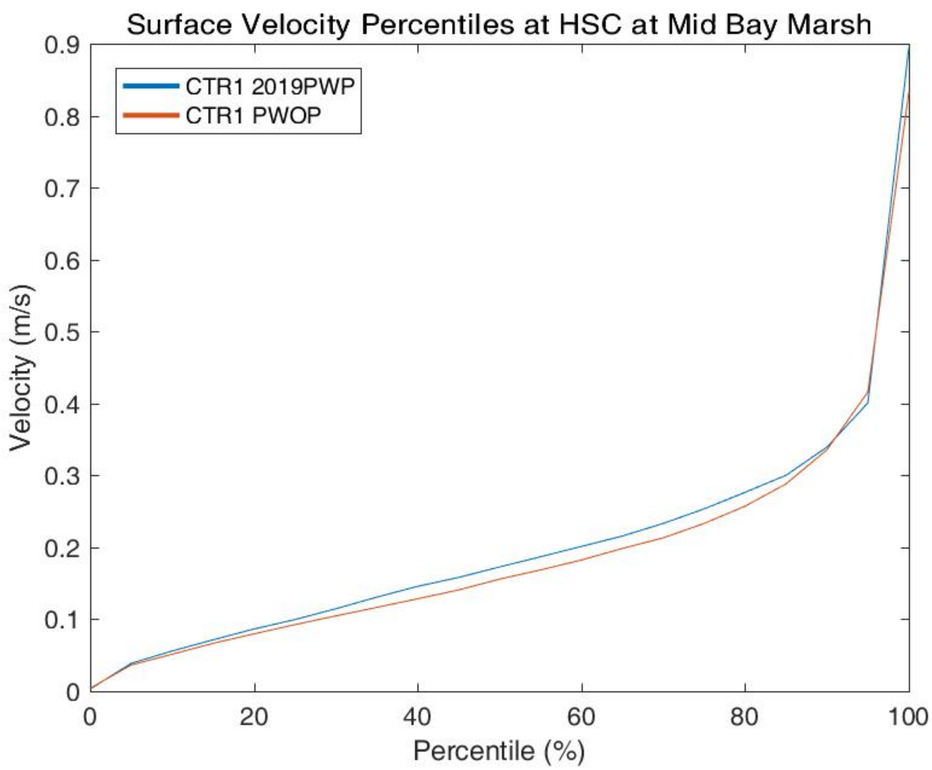

Bottom Velocity at HSC at Atkinson Island
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
Max
Mean
Min

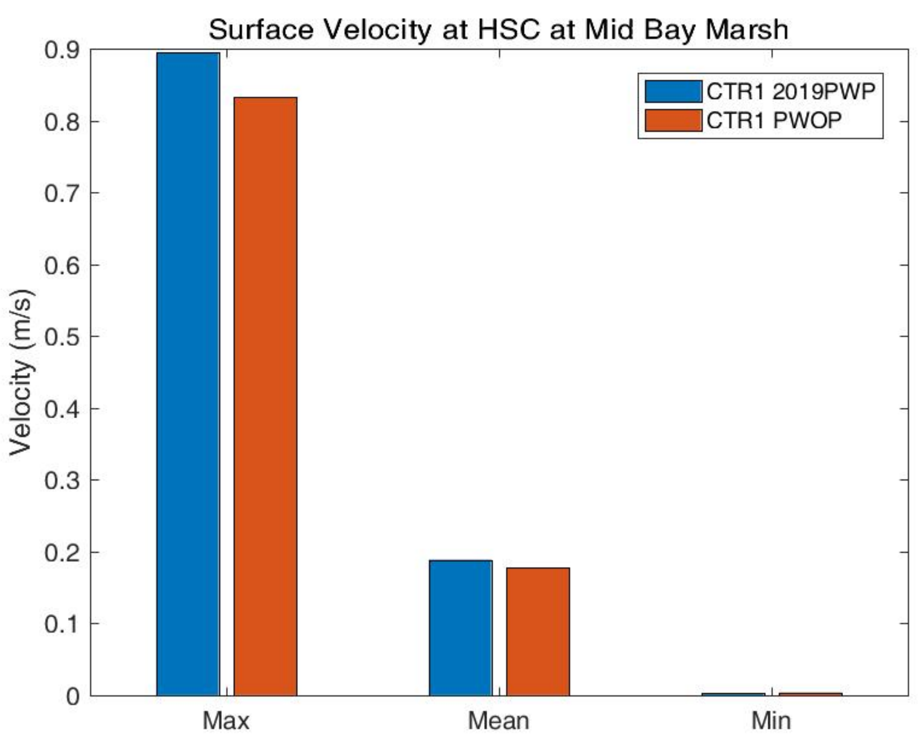

Surface Velocity Percentiles at HSC at Atkinson Island
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
20
40
60
80
100

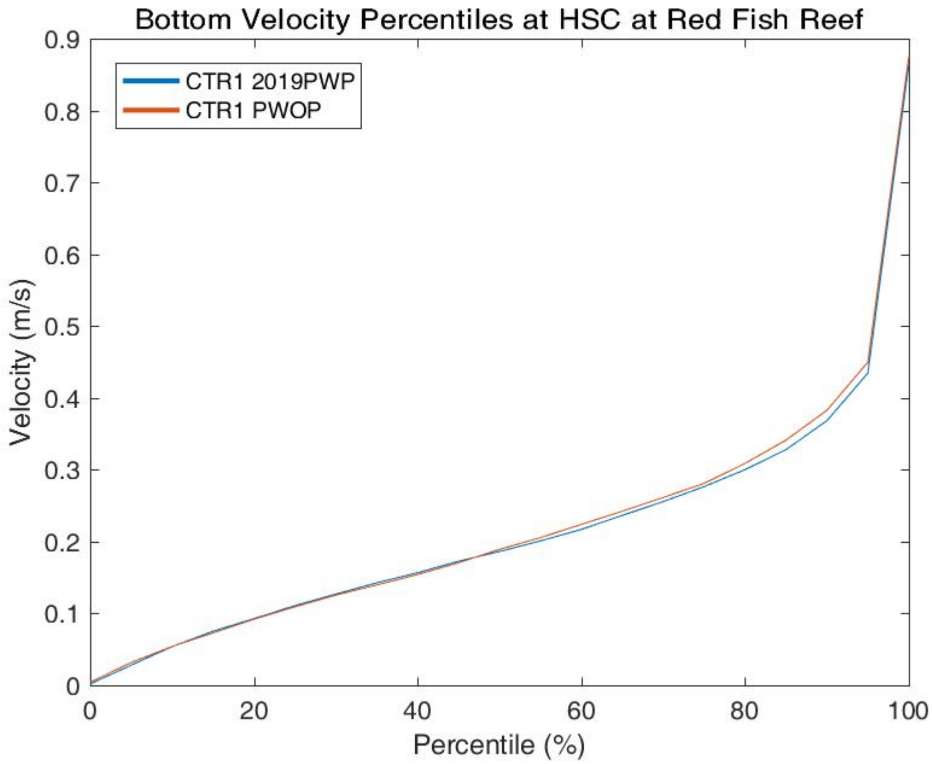

Surface Velocity at HSC at Atkinson Island
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Max
Mean
Min

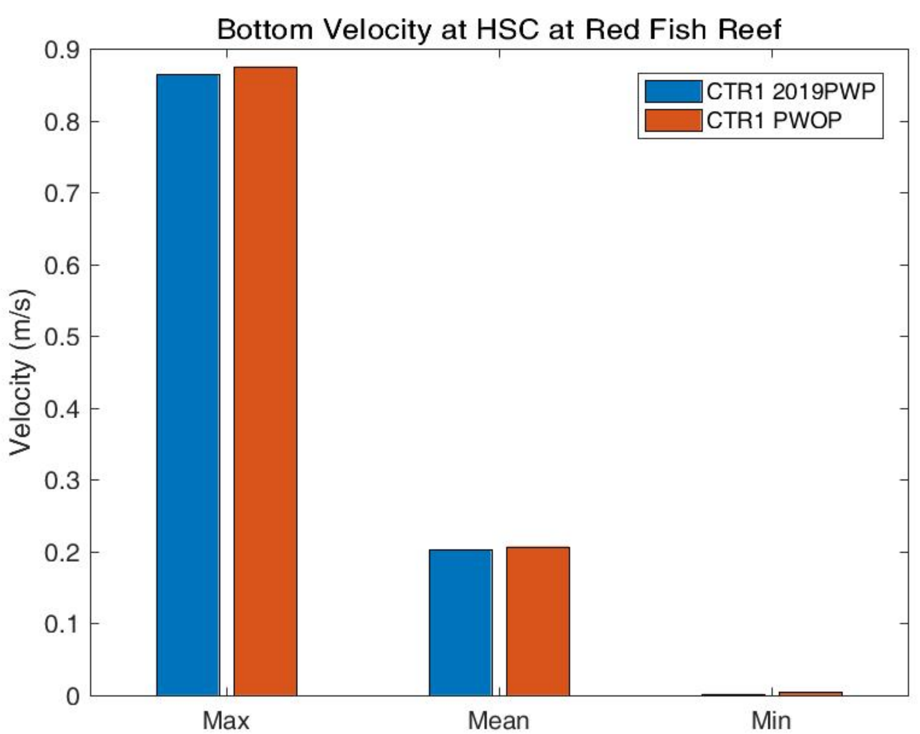

Bottom Velocity Percentiles at HSC at Mid Bay Marsh
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
20
40
60
80
100

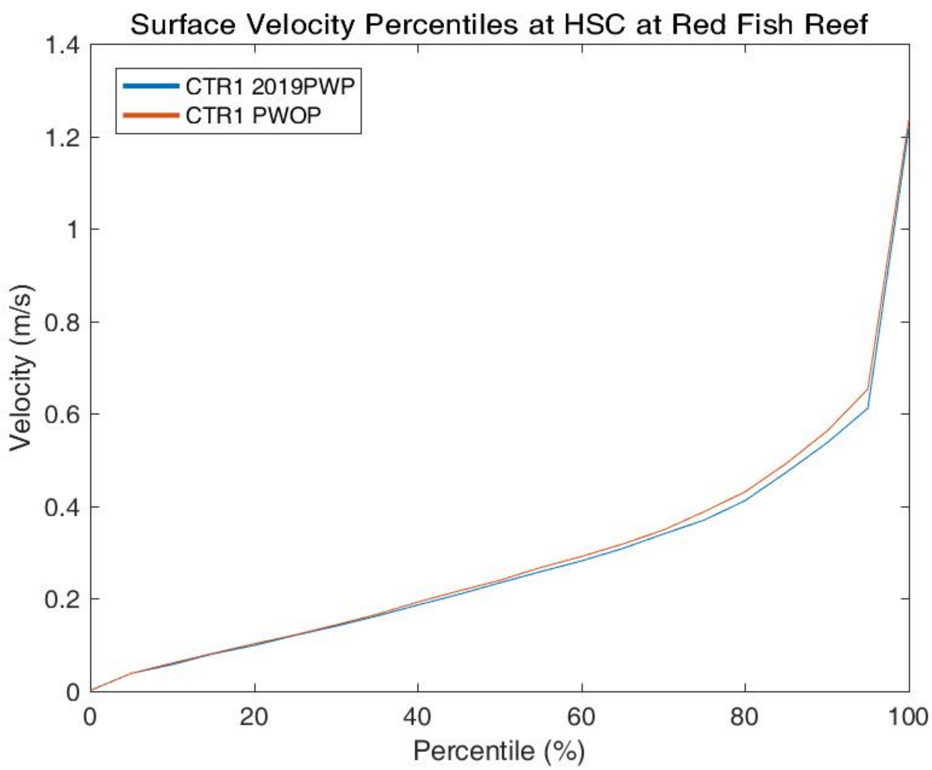

Bottom Velocity at HSC at Mid Bay Marsh
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Max
Mean
Min

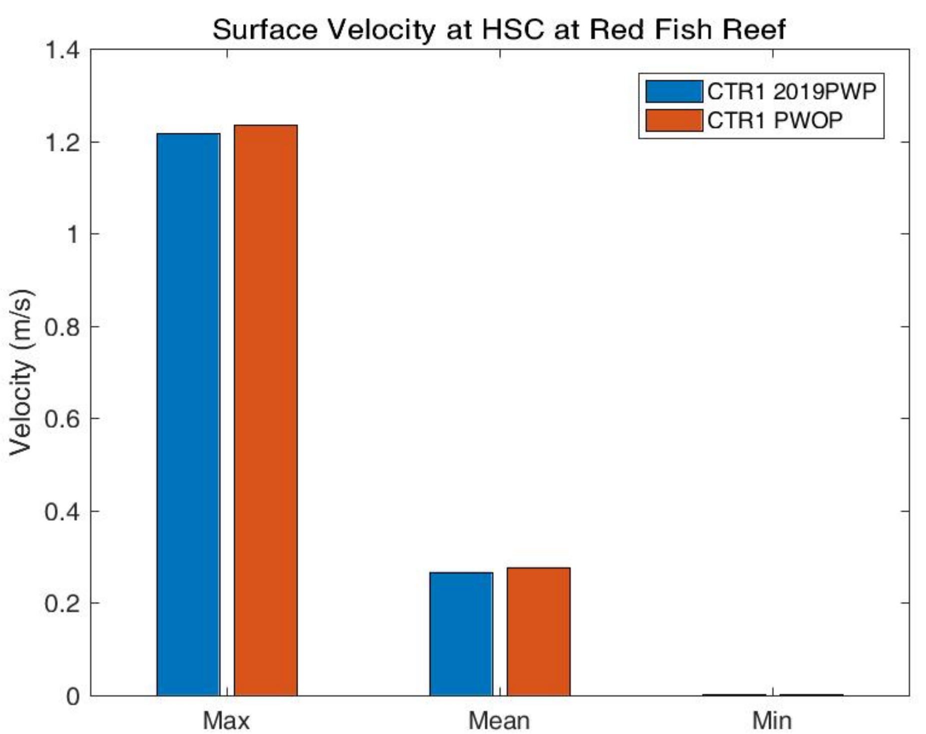

Surface Velocity Percentiles at HSC at Mid Bay Marsh
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20
40
60
80
100

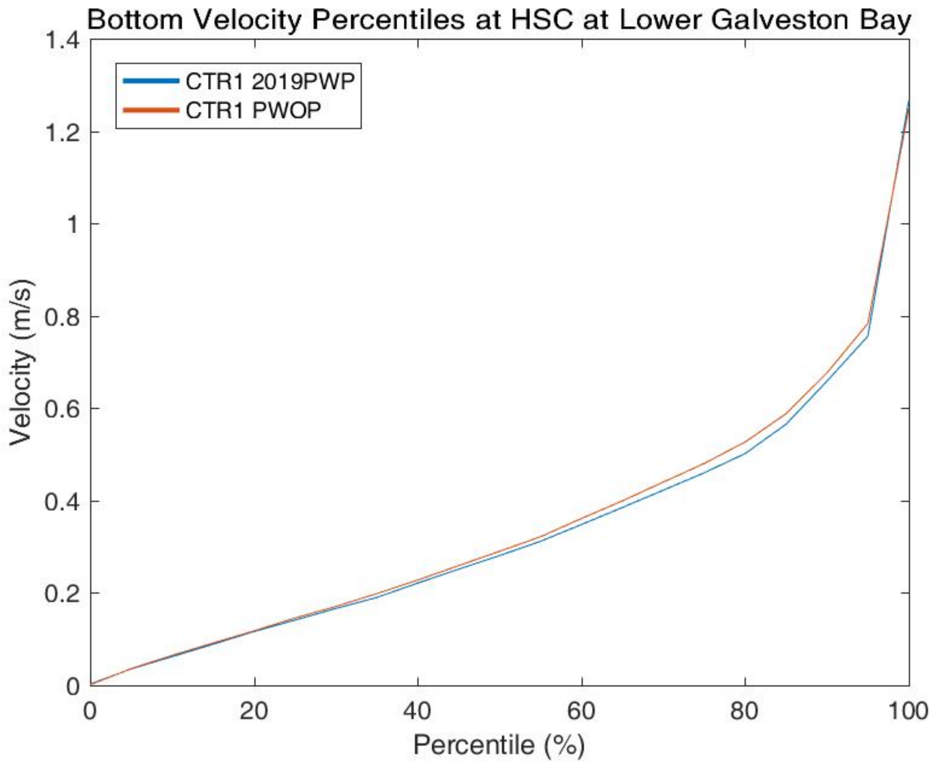

Surface Velocity at HSC at Mid Bay Marsh
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Max
Mean
Min

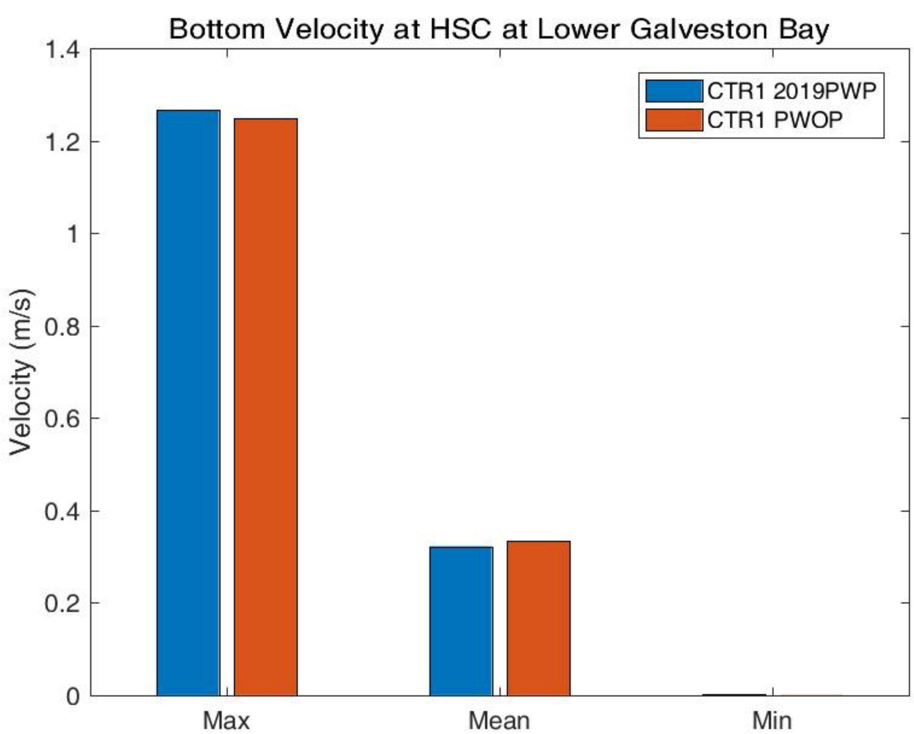

Bottom Velocity Percentiles at HSC at Red Fish Reef
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20
40
60
80
100

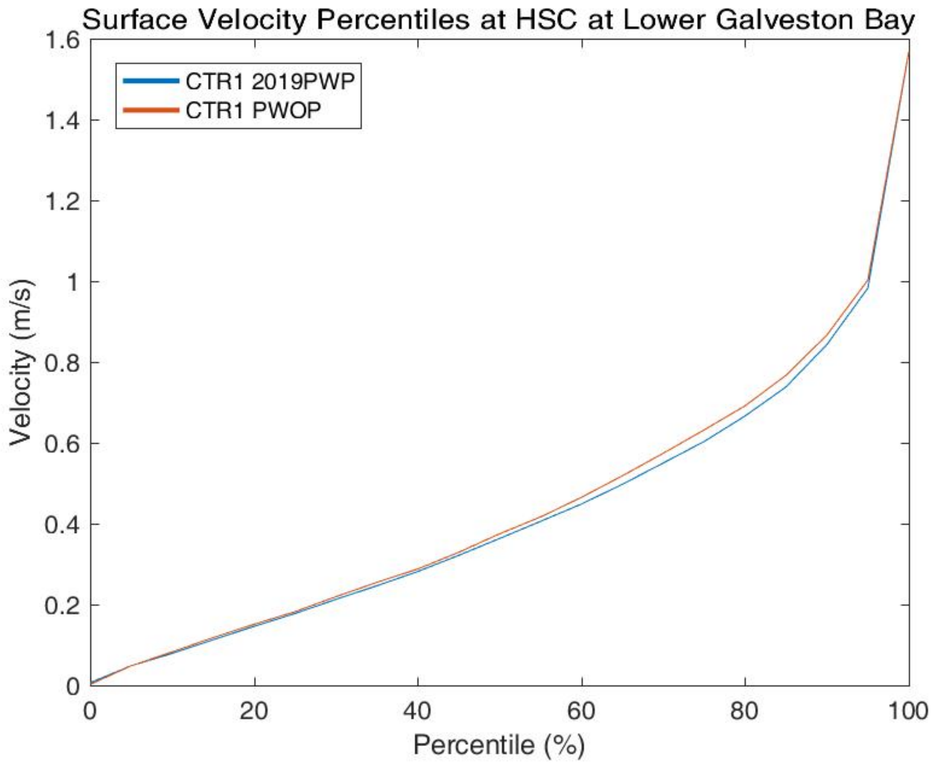

Bottom Velocity at HSC at Red Fish Reef
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Max
Mean
Min

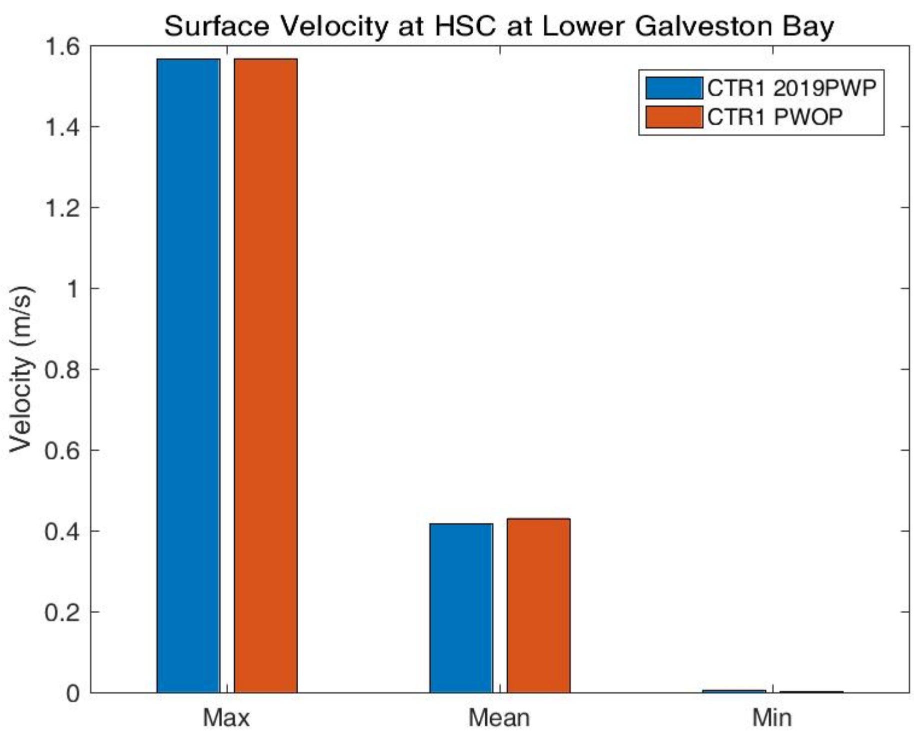

Surface Velocity Percentiles at HSC at Red Fish Reef
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
20
40
60
80
100

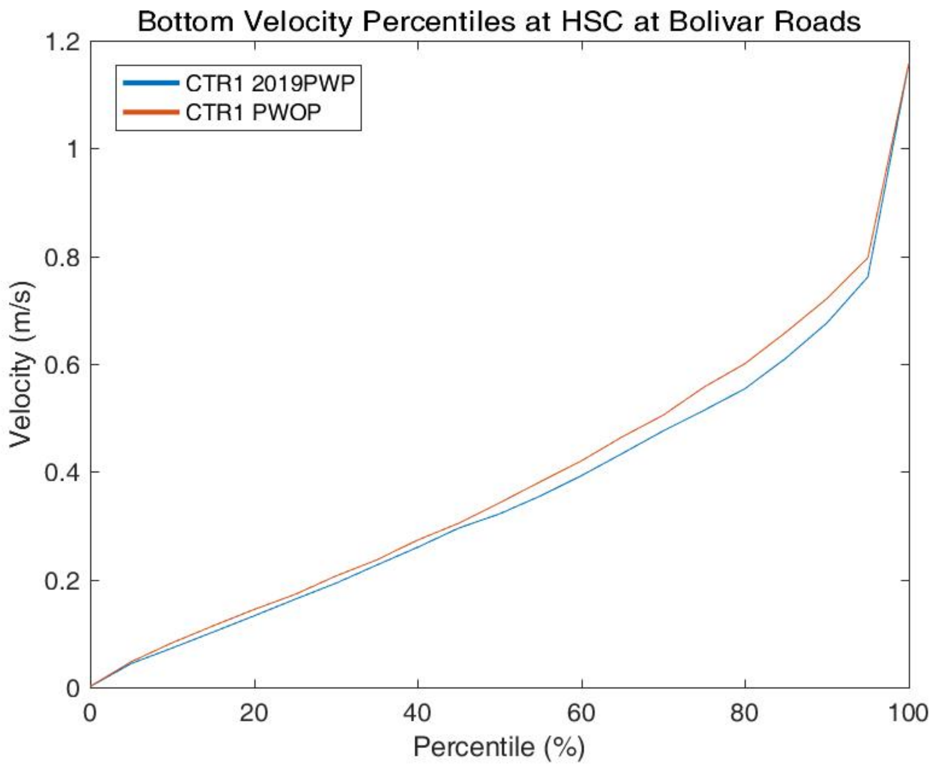

Surface Velocity at HSC at Red Fish Reef
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Max
Mean
Min

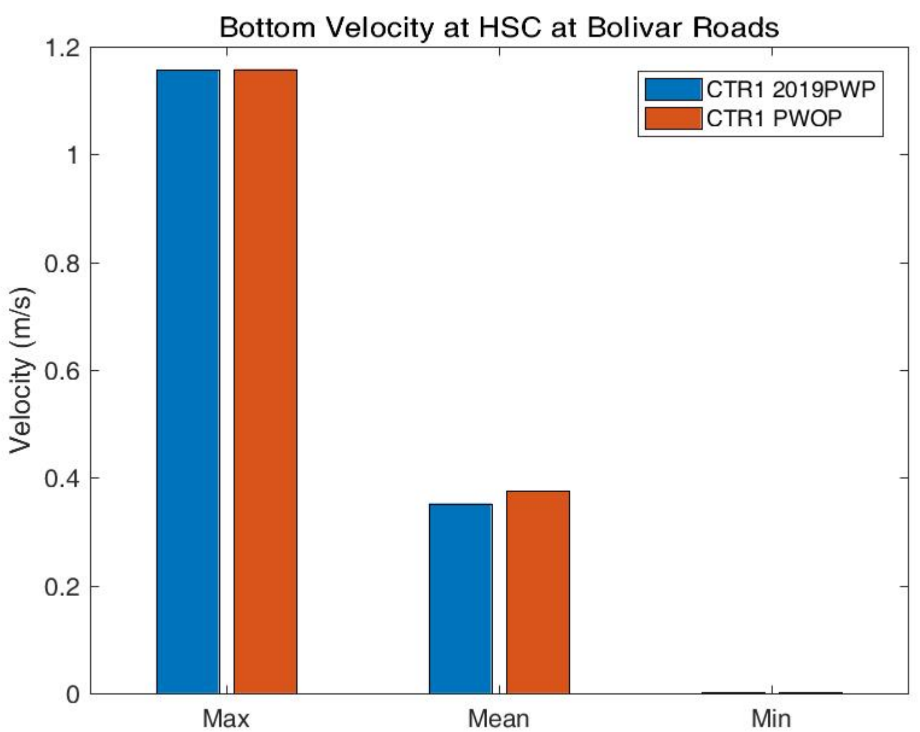

Bottom Velocity Percentiles at HSC at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
20
40
60
80
100

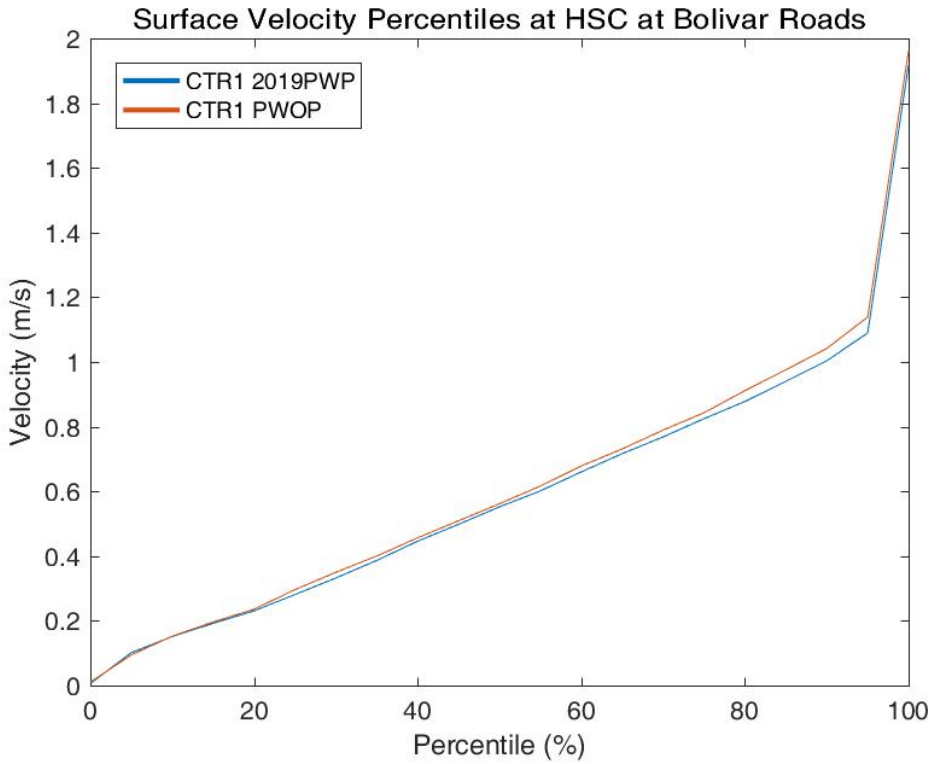

Bottom Velocity at HSC at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Max
Mean
Min

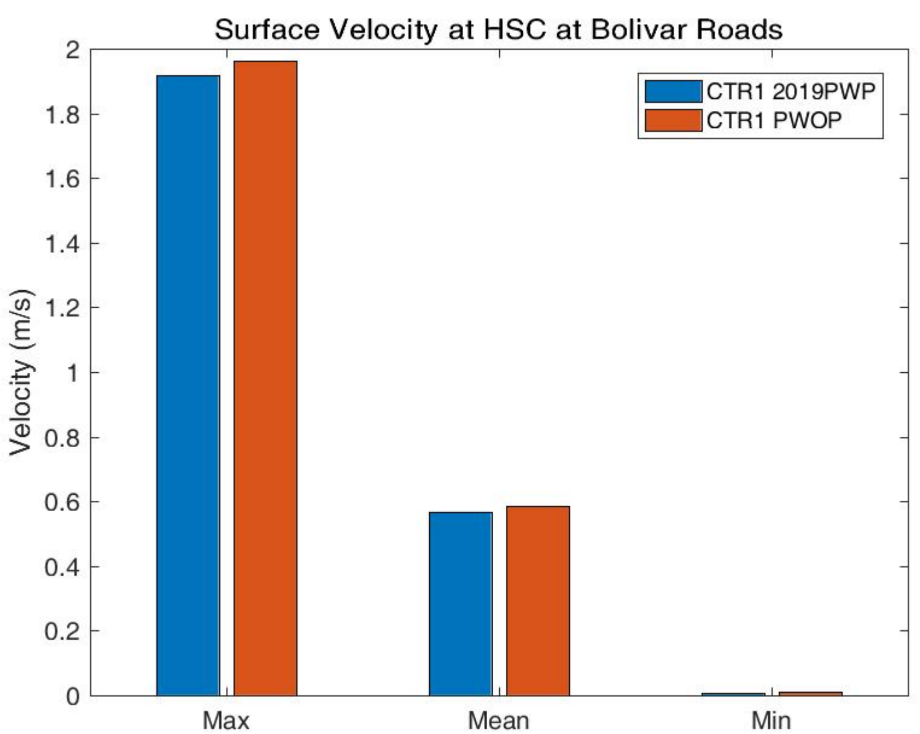

Surface Velocity Percentiles at HSC at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
20
40
60
80
100

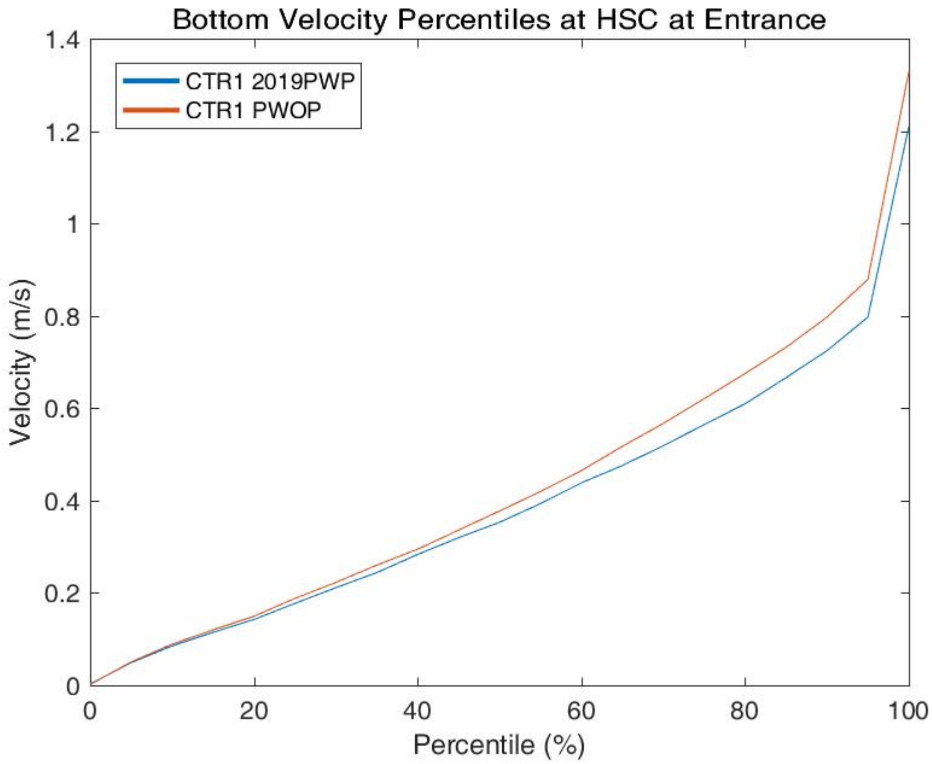

Surface Velocity at HSC at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Max
Mean
Min

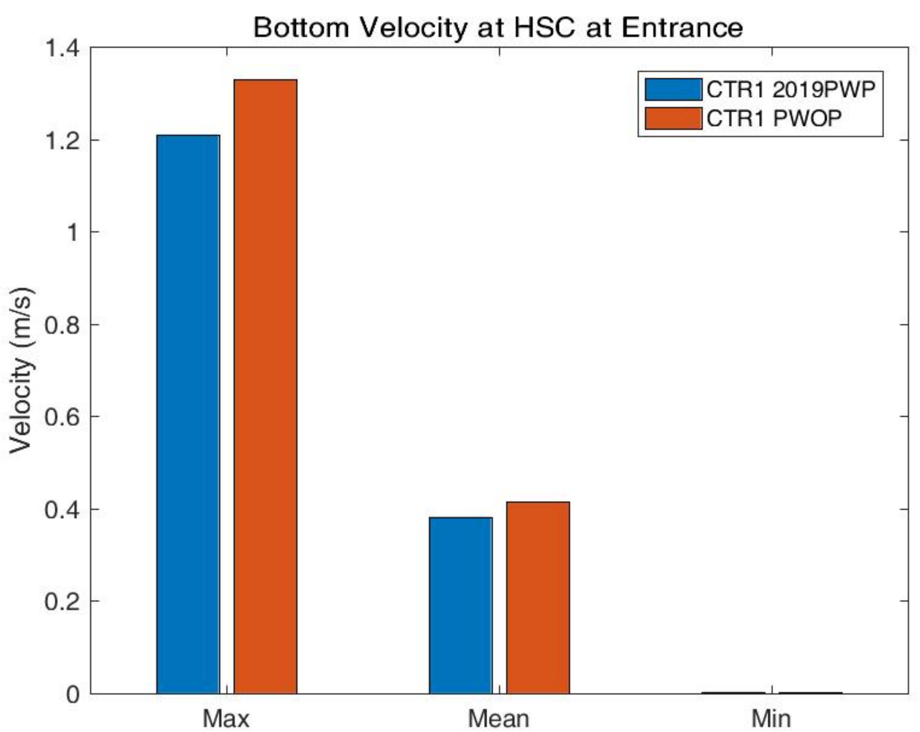

Bottom Velocity Percentiles at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80
100

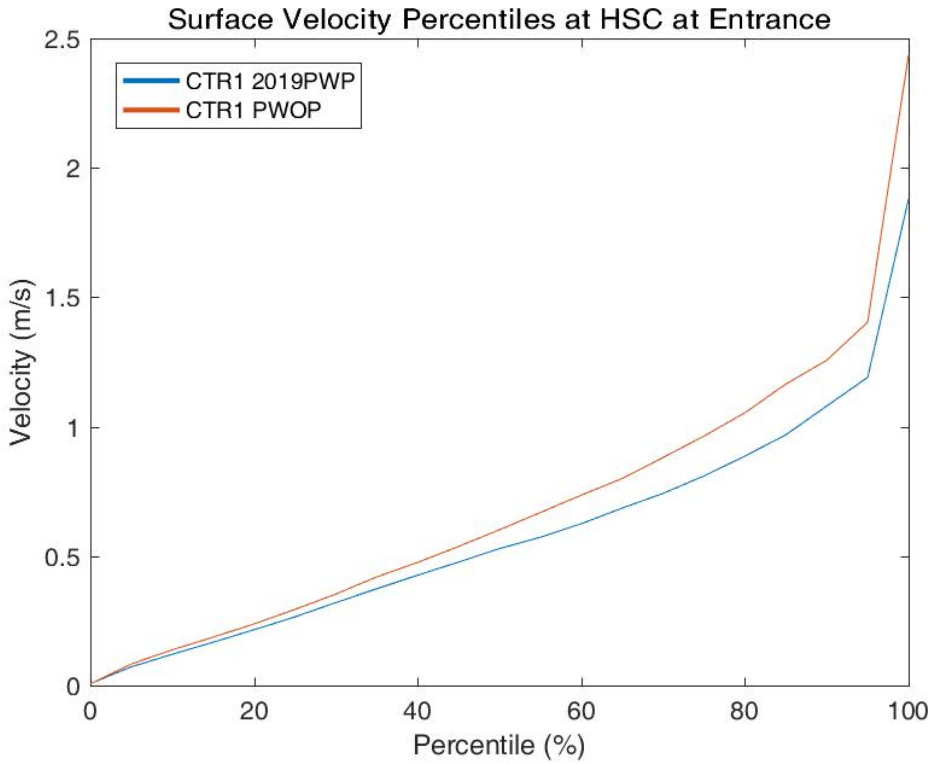

Bottom Velocity at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
Max
Mean
Min

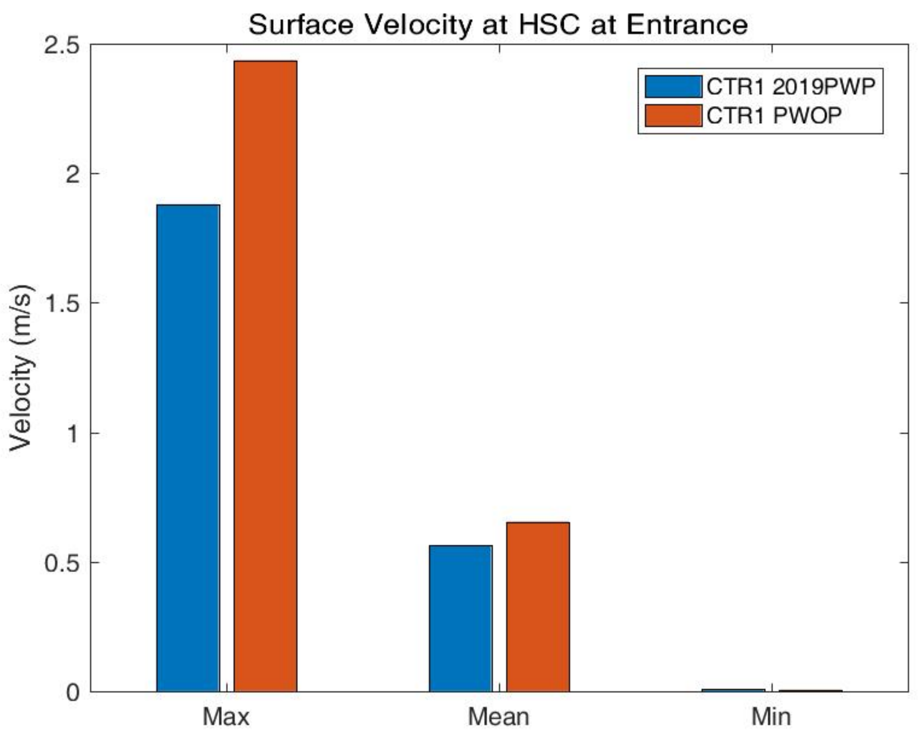

Surface Velocity Percentiles at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
20
40
60
80
100

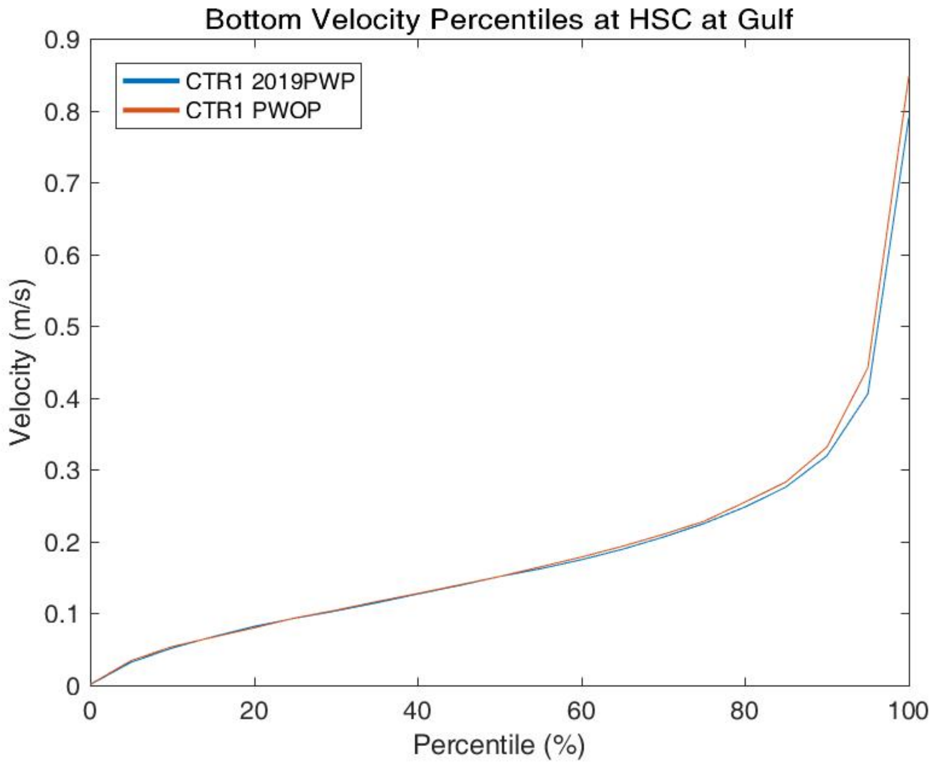

Surface Velocity at HSC at Bolivar Roads
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Max
Mean
Min

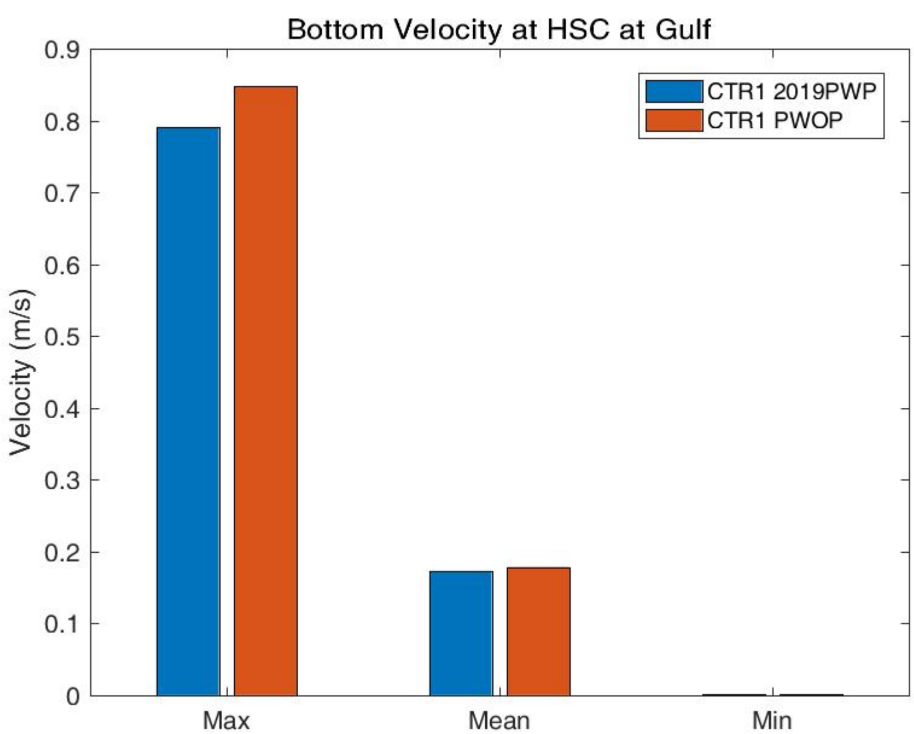

Bottom Velocity Percentiles at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
20
40
60
80
100

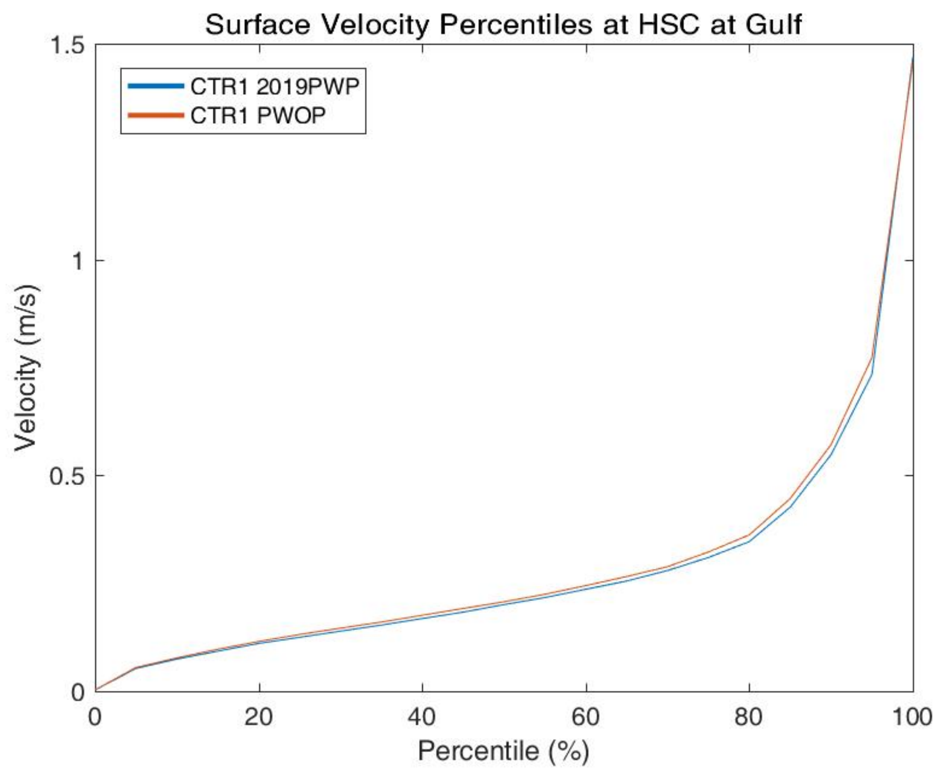

Bottom Velocity at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Max
Mean
Min

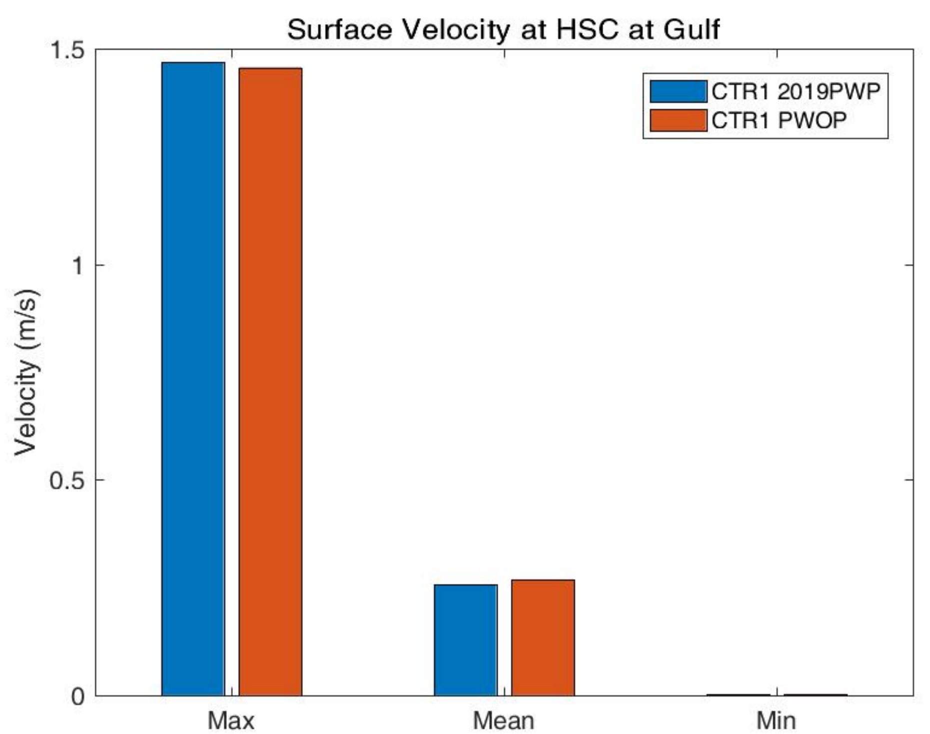

Surface Velocity Percentiles at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.5
1
1.5
2
2.5
0
20
40
60
80
100

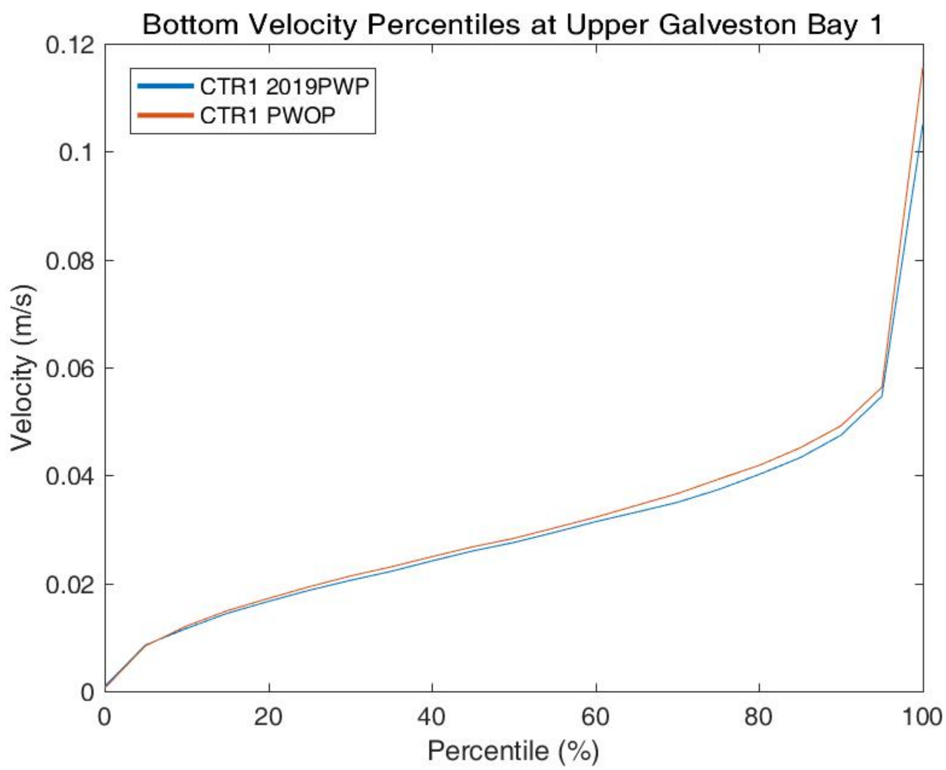

Surface Velocity at HSC at Entrance
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.5
1
1.5
2
2.5
Max
Mean
Min

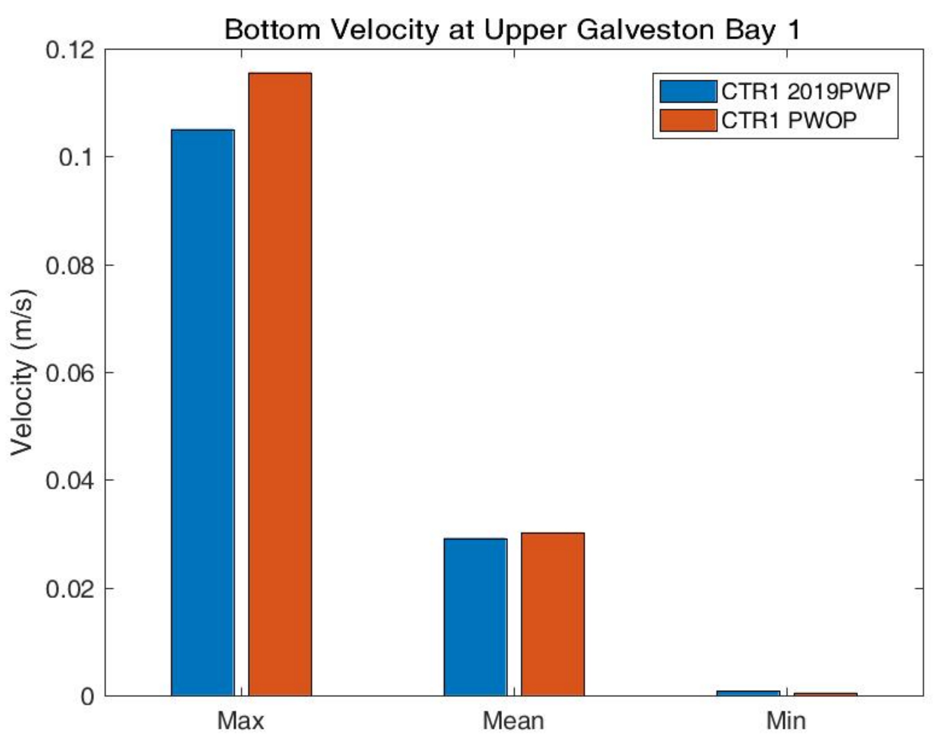

Bottom Velocity Percentiles at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
20
40
60
80
100

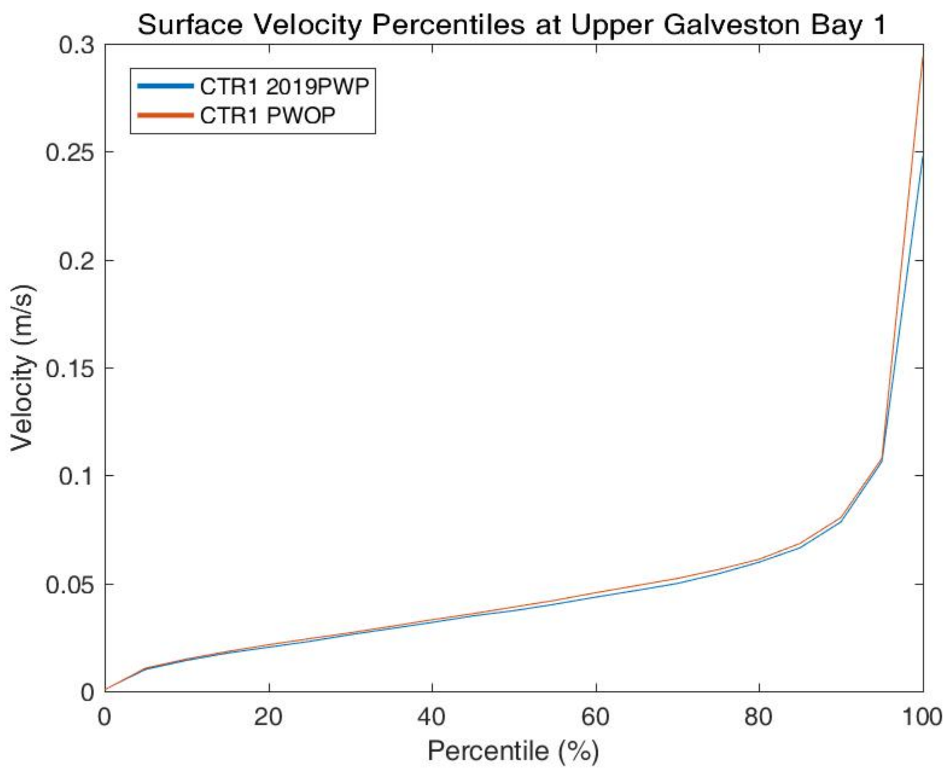

Bottom Velocity at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Max
Mean
Min

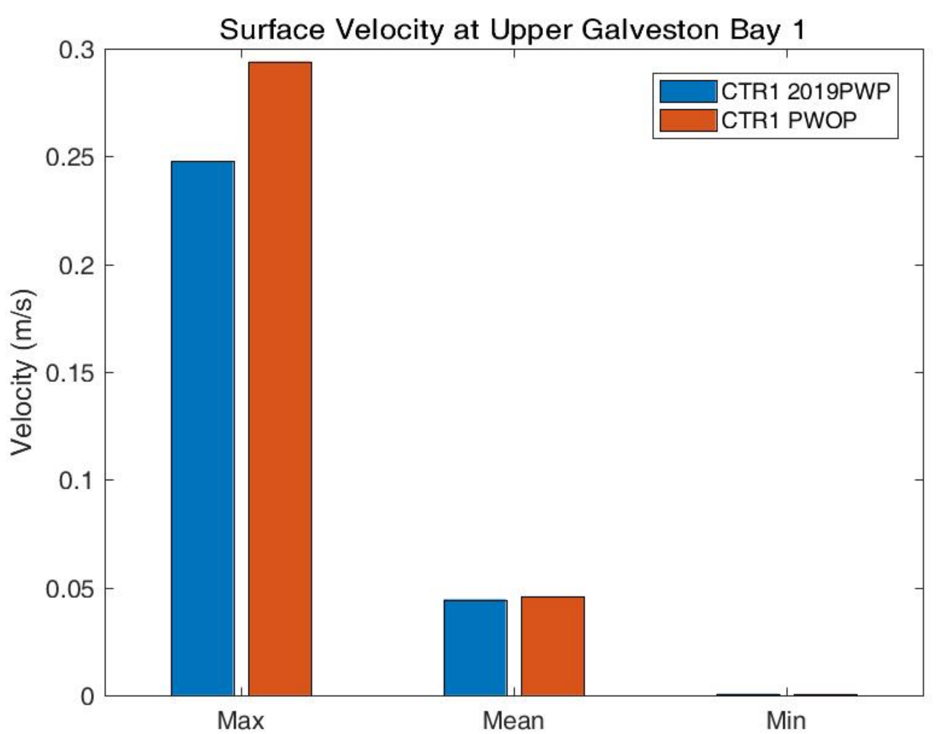

Surface Velocity Percentiles at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.5
1
1.5
0
20
40
60
80
100

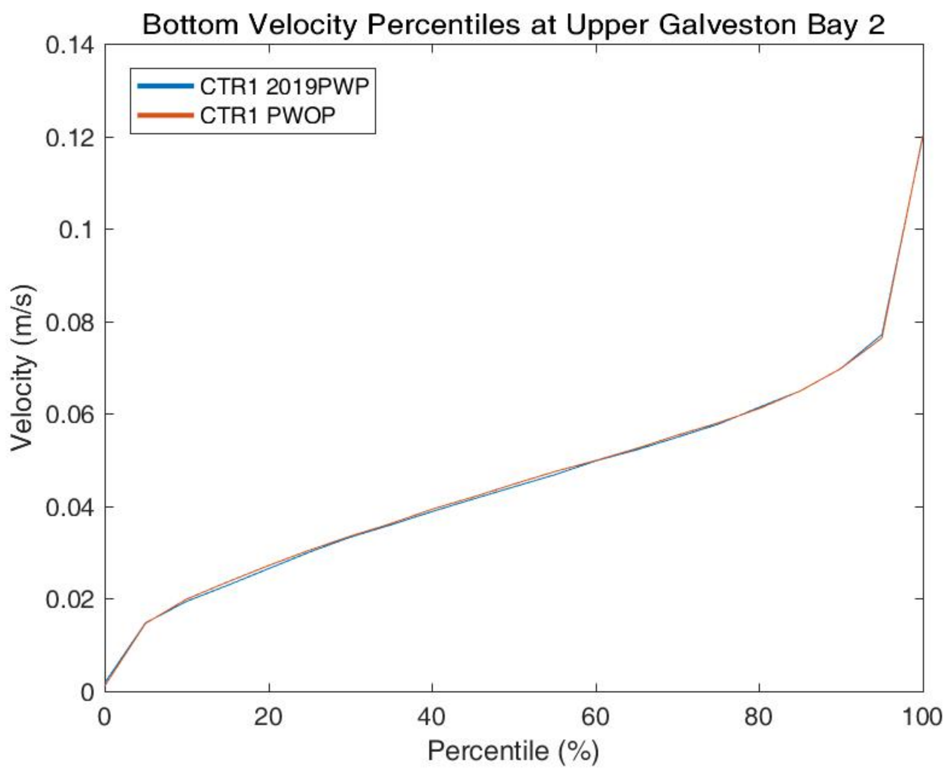

Surface Velocity at HSC at Gulf
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.5
1
1.5
Max
Mean
Min

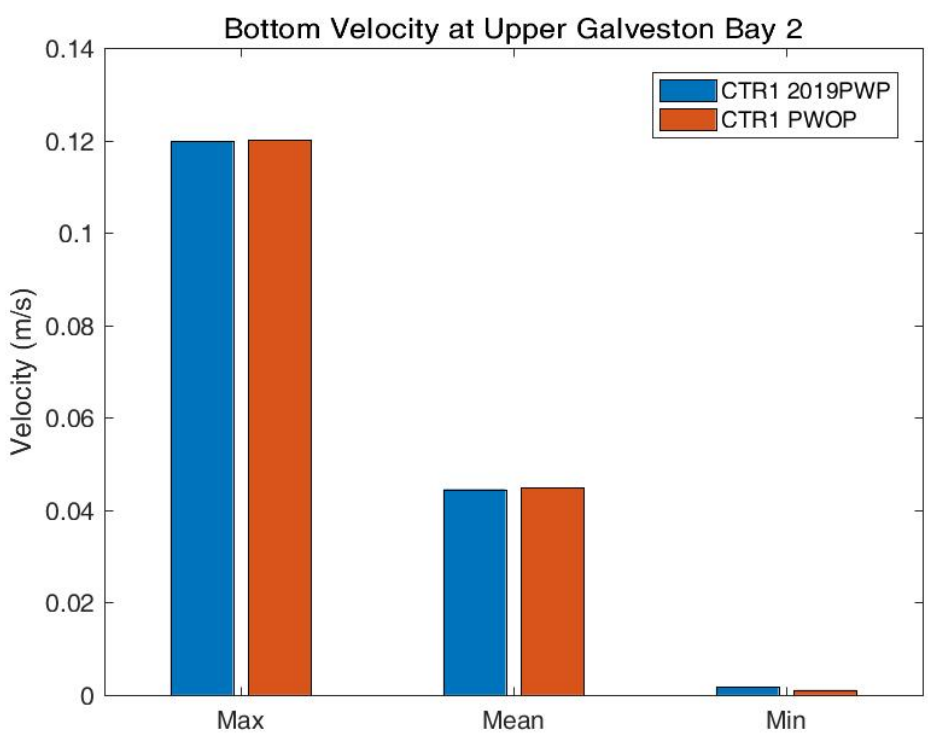

Bottom Velocity Percentiles at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
Percentile (%)

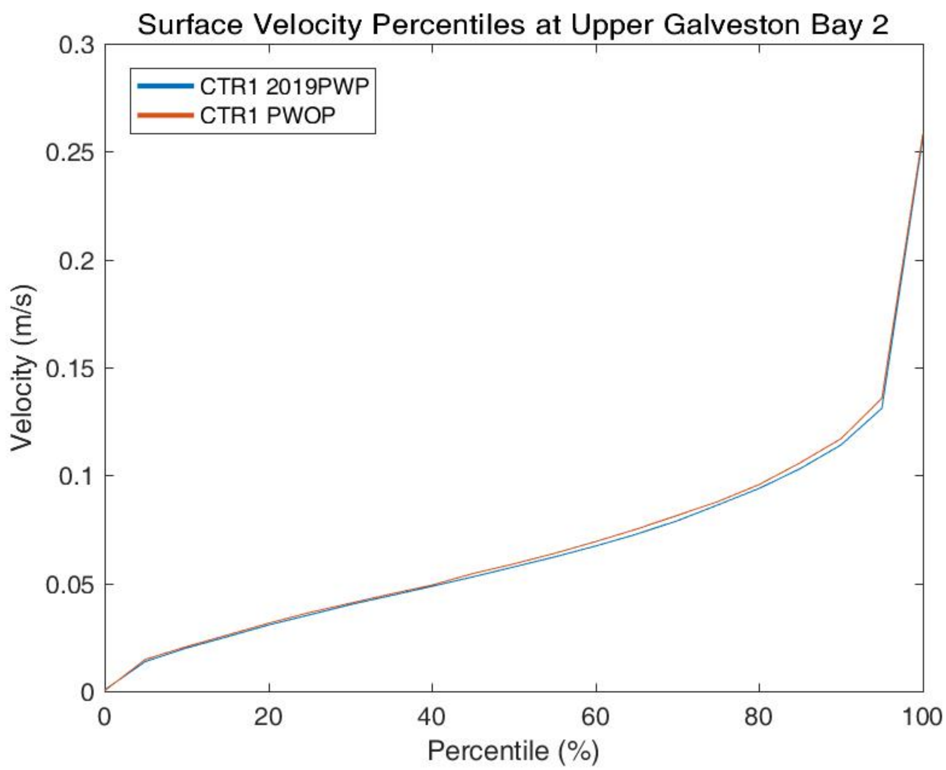

Bottom Velocity at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min

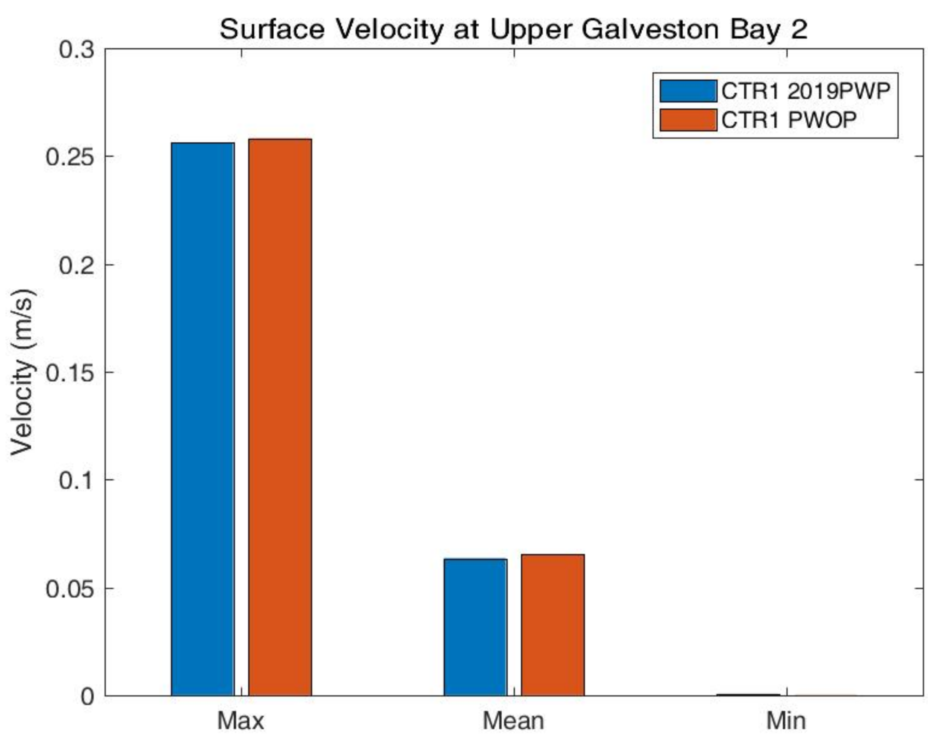

Surface Velocity Percentiles at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
Percentile (%)

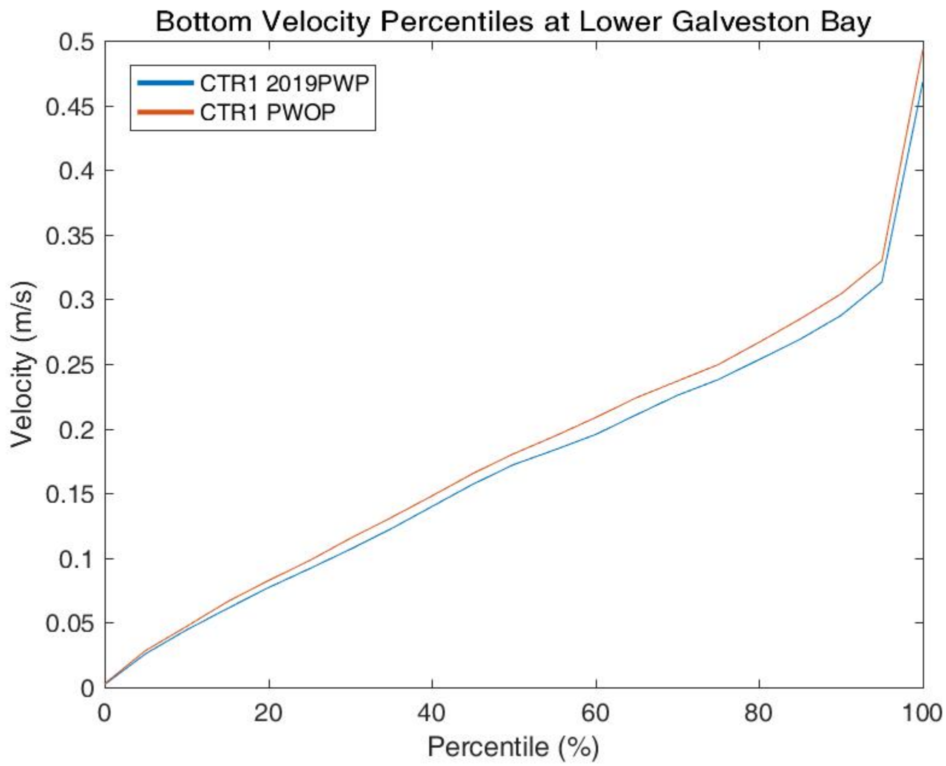

Surface Velocity at Upper Galveston Bay 1
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

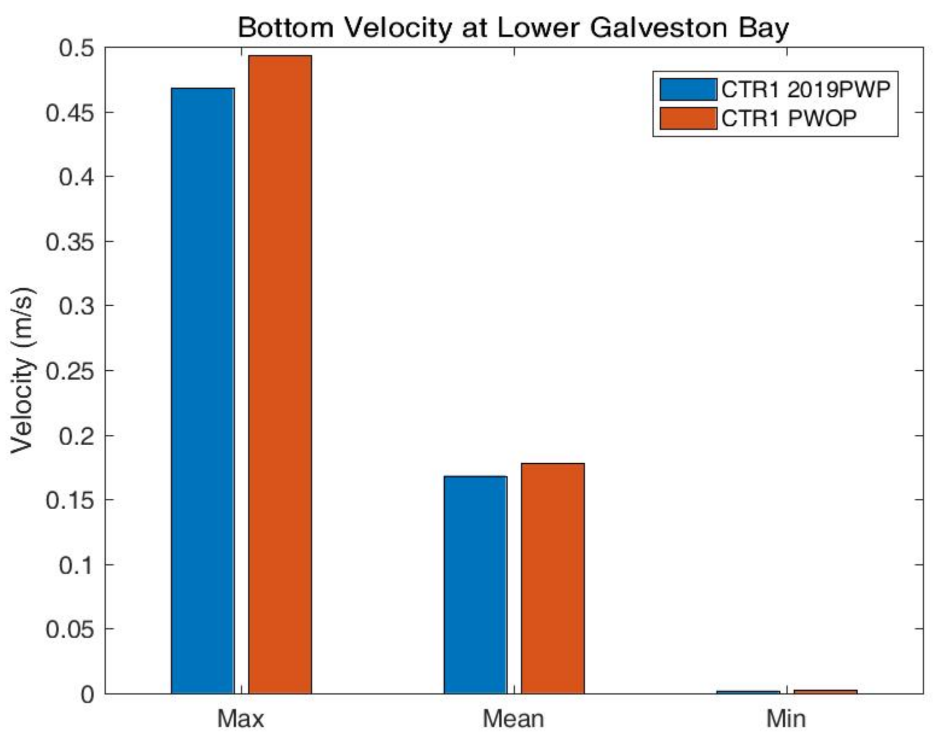

Bottom Velocity Percentiles at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
20
40
60
80
100
Percentile (%)

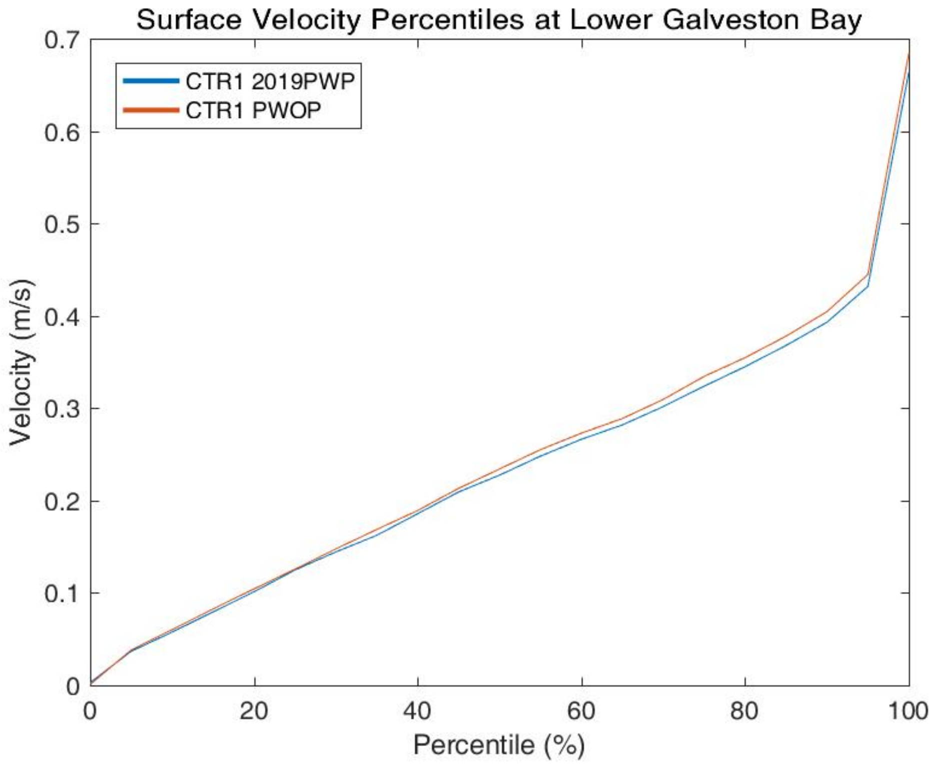

Bottom Velocity at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min

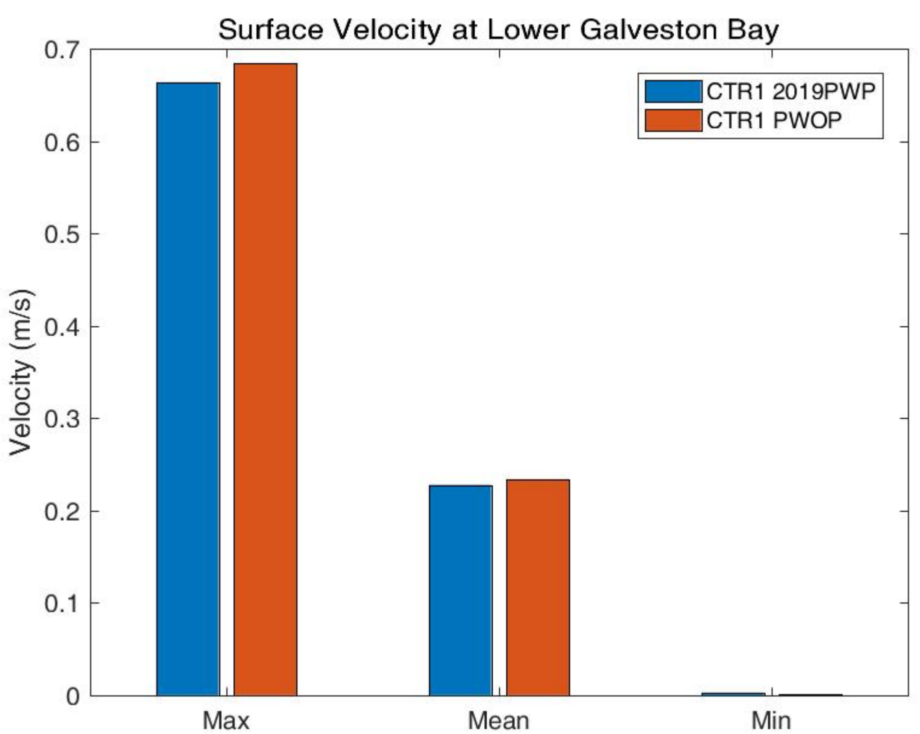

Surface Velocity Percentiles at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
20
40
60
80
100

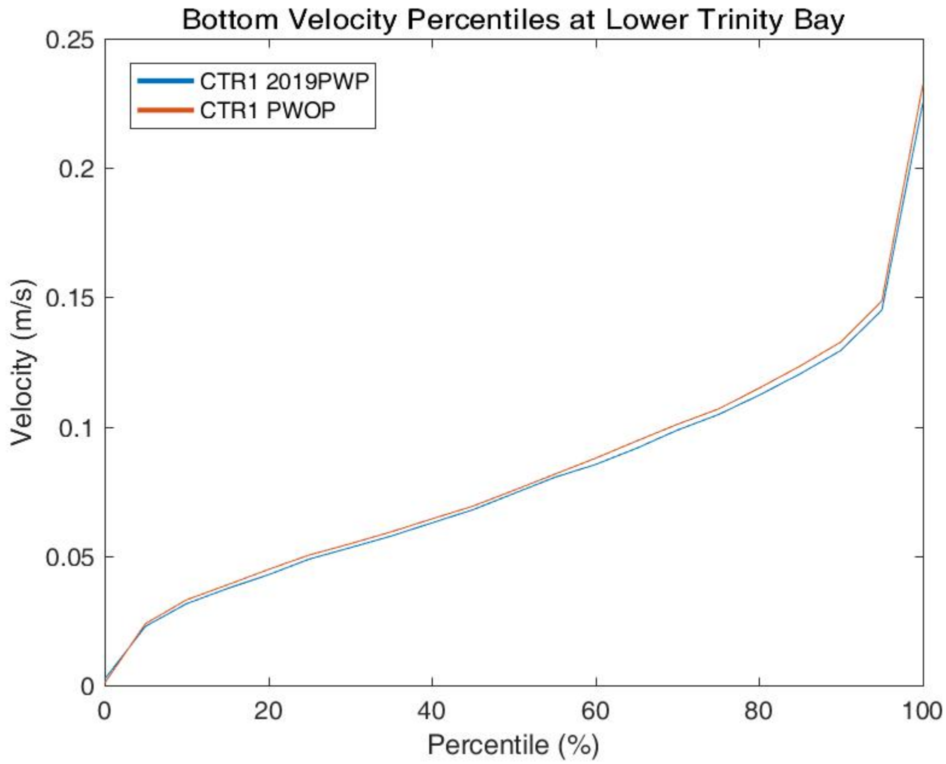

Surface Velocity at Upper Galveston Bay 2
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
Max
Mean
Min

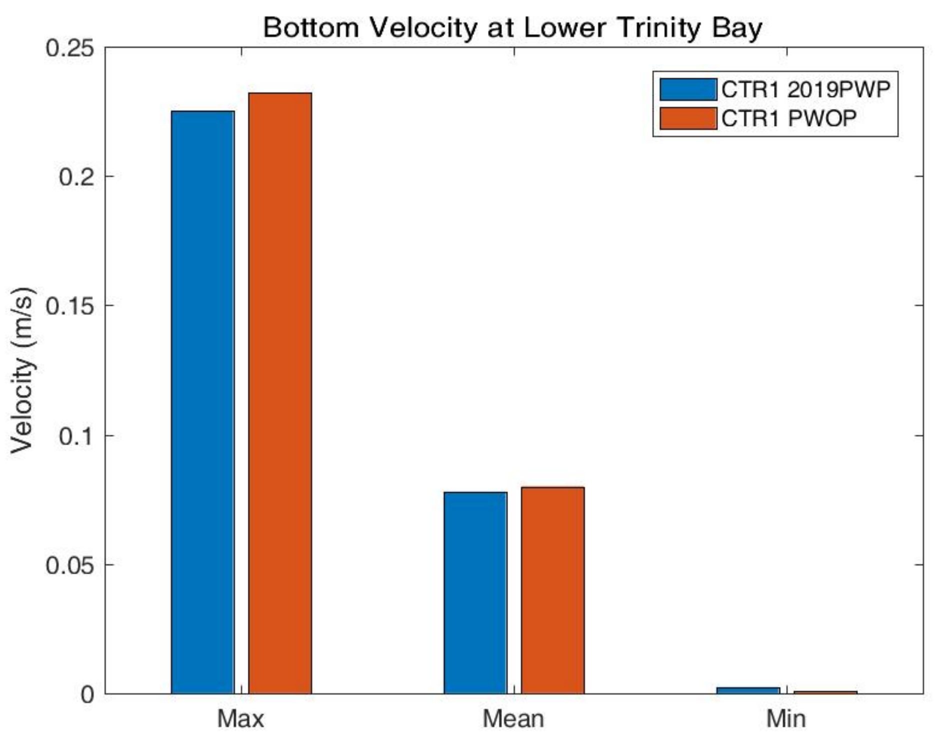

Bottom Velocity Percentiles at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

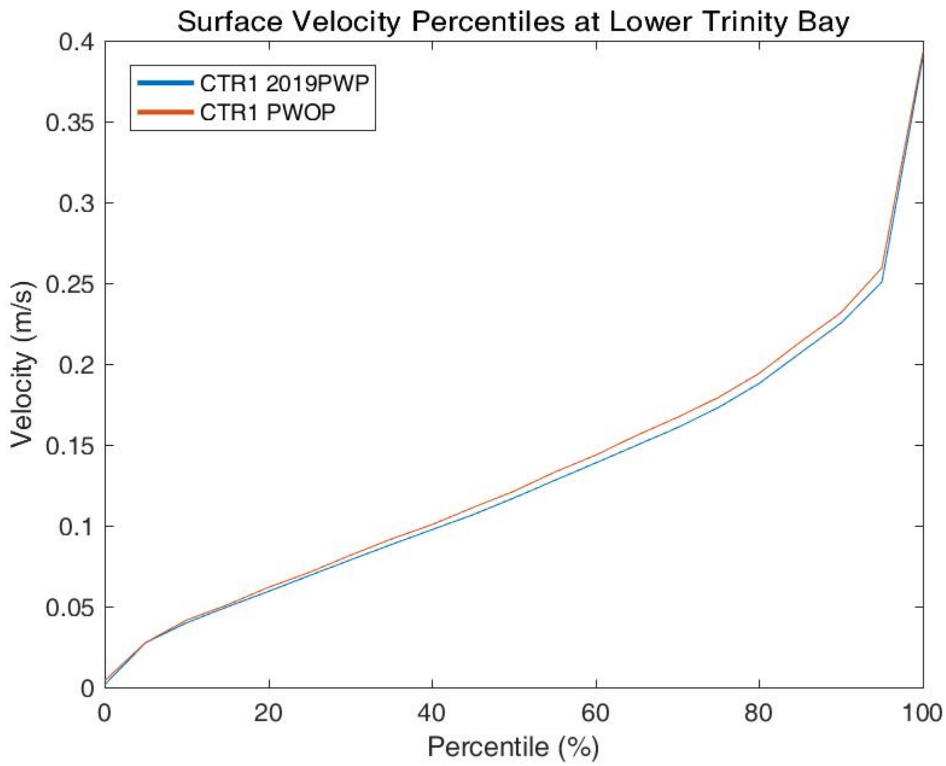

Bottom Velocity at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

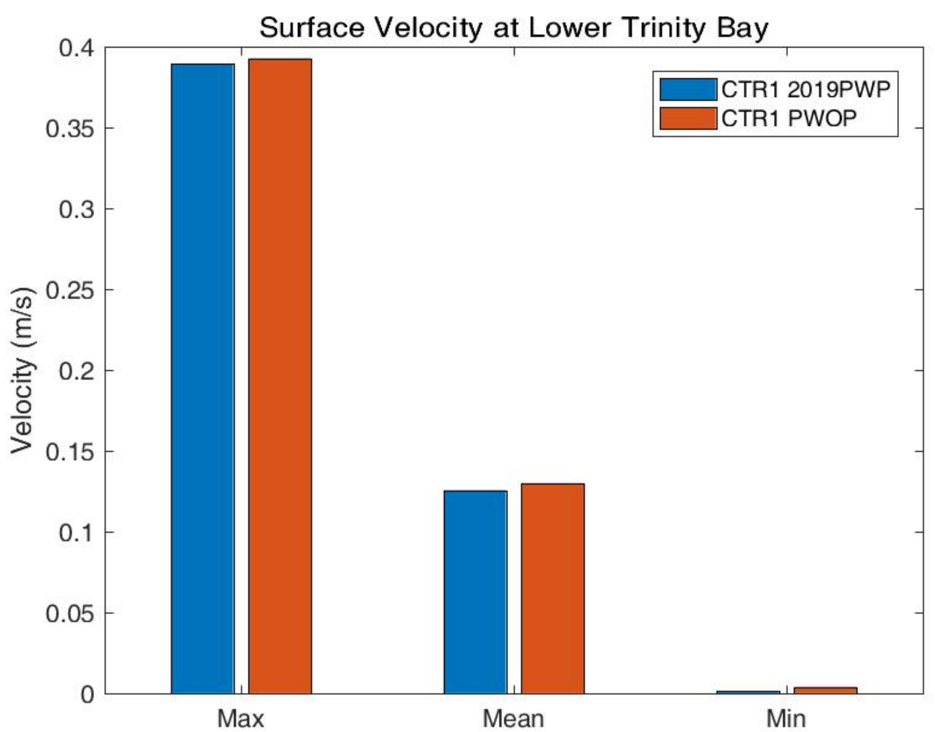

Surface Velocity Percentiles at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
20
40
60
80
100

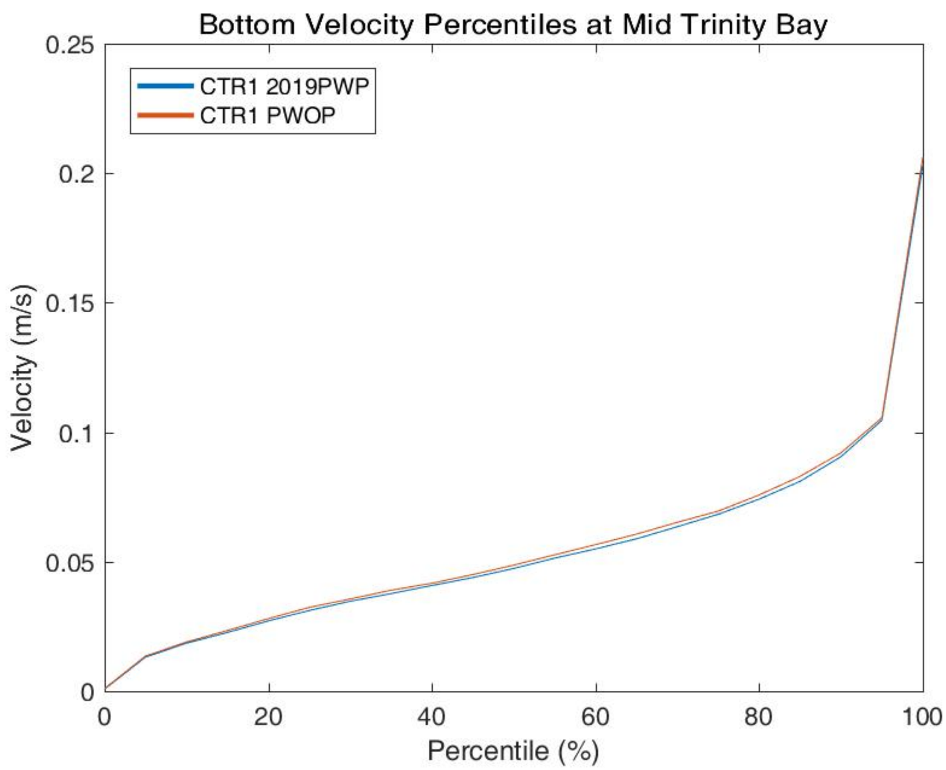

Surface Velocity at Lower Galveston Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Max
Mean
Min

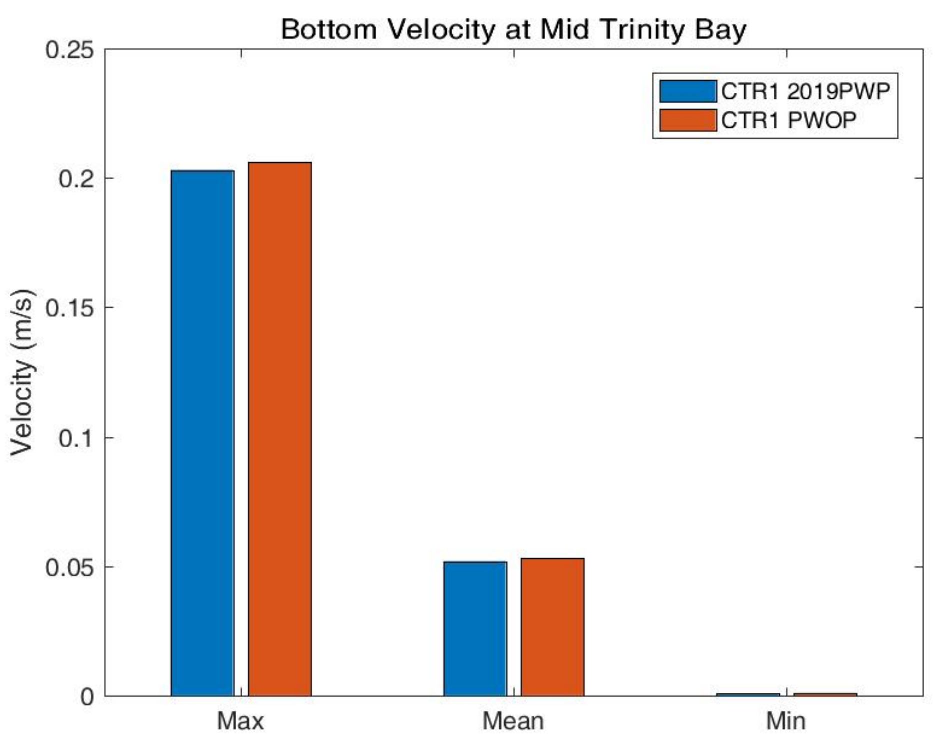

Bottom Velocity Percentiles at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0
20
40
60
80
100
Percentile (%)

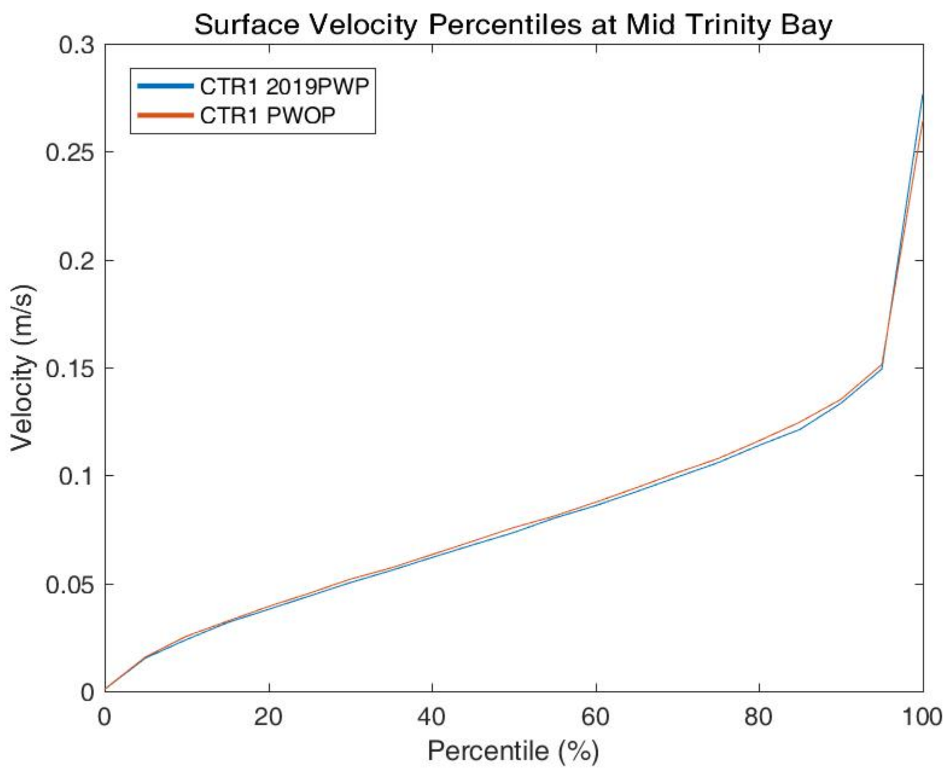

Bottom Velocity at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
Max
Mean
Min

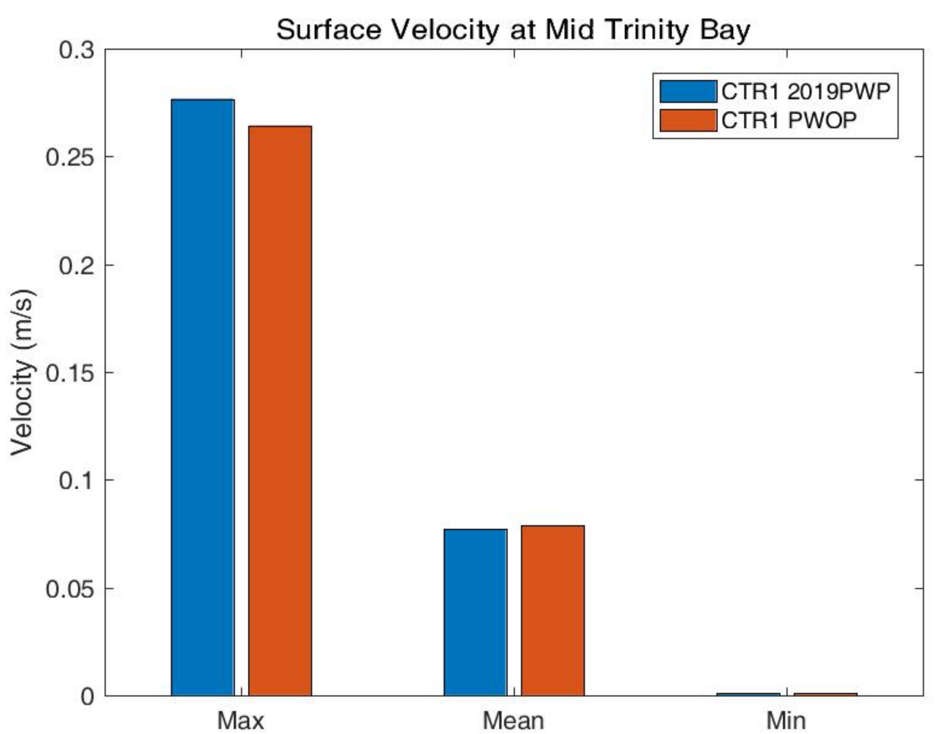

Surface Velocity Percentiles at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
20
40
60
80
100

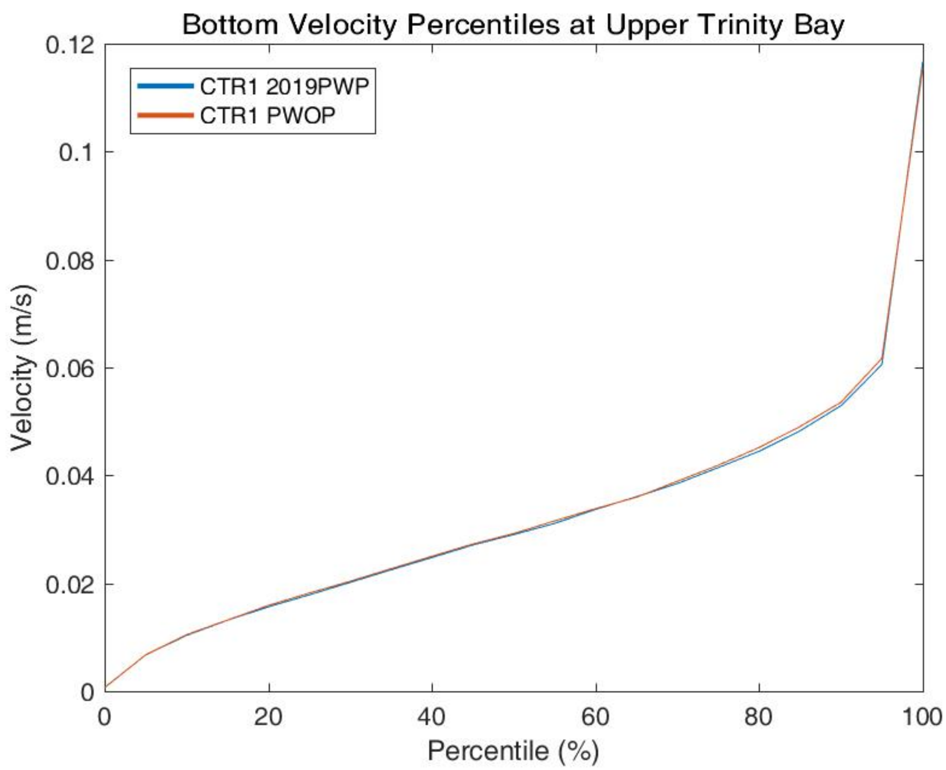

Surface Velocity at Lower Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Max
Mean
Min

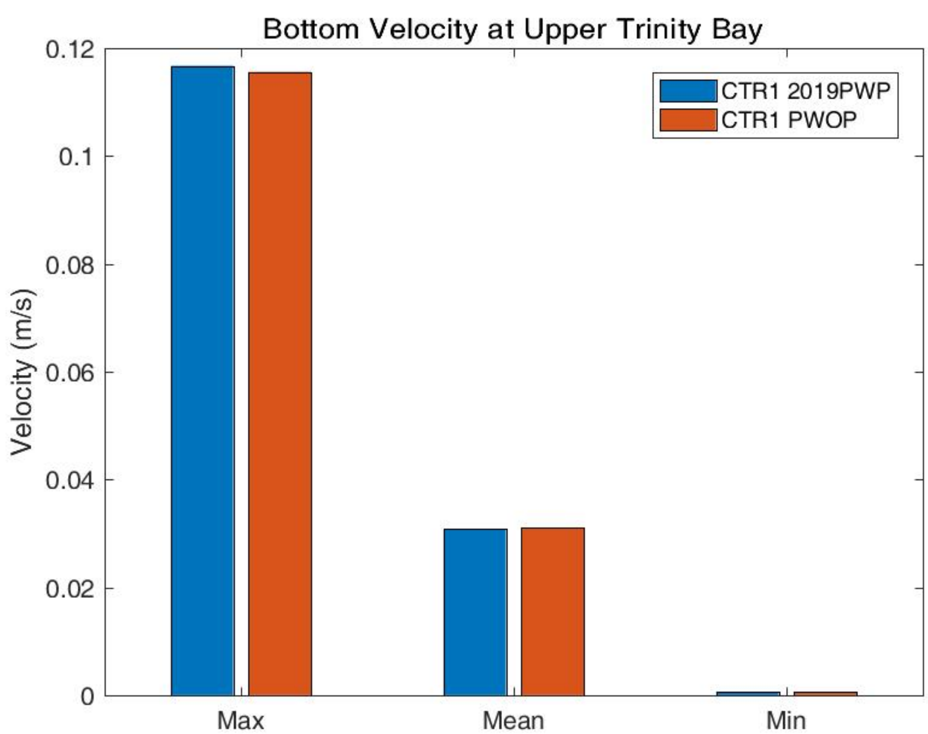

Bottom Velocity Percentiles at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

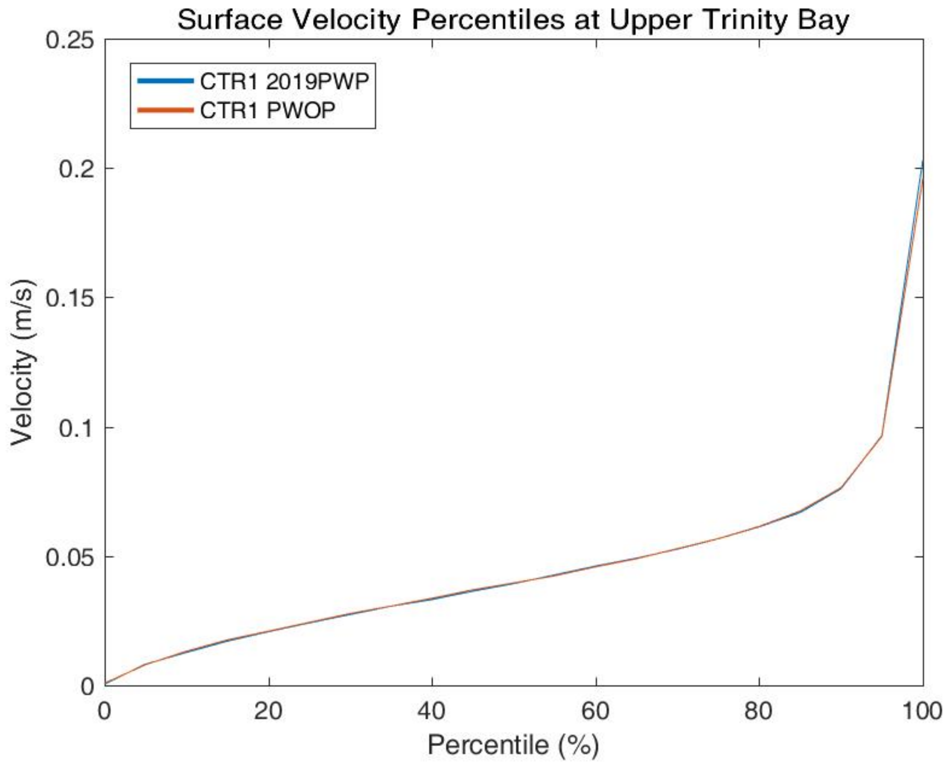

Bottom Velocity at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

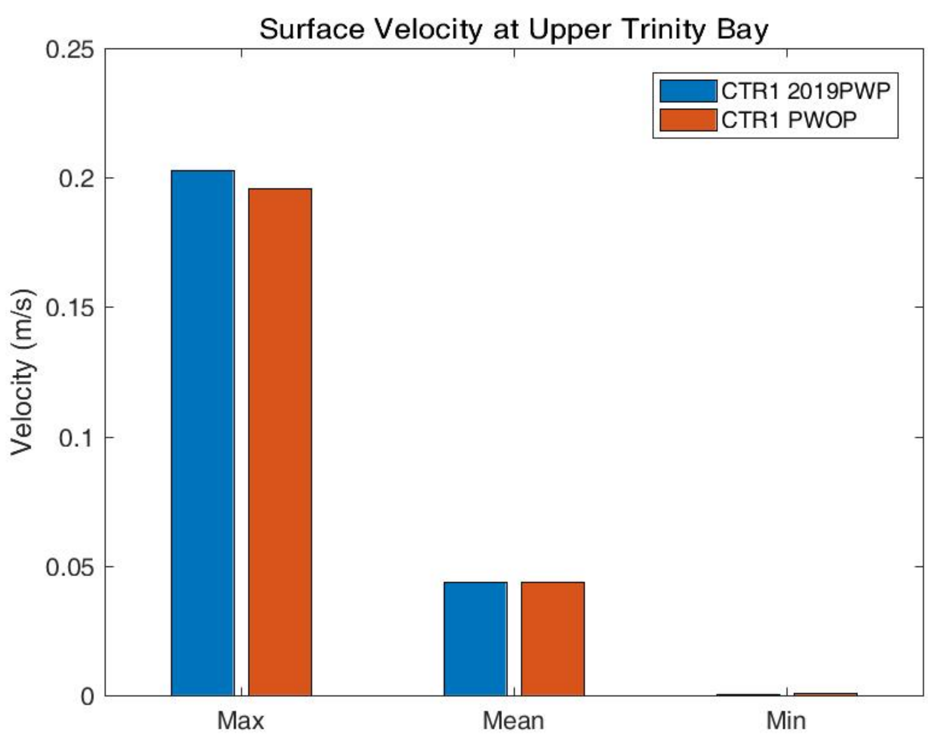

Surface Velocity Percentiles at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
20
40
60
80
100

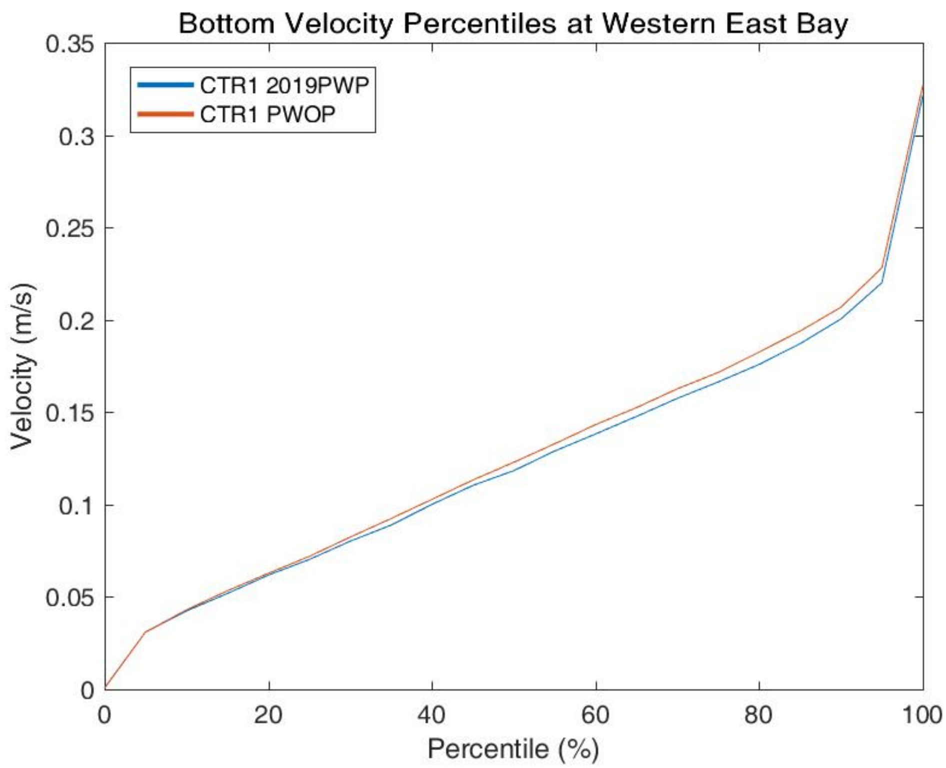

Surface Velocity at Mid Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
Max
Mean
Min

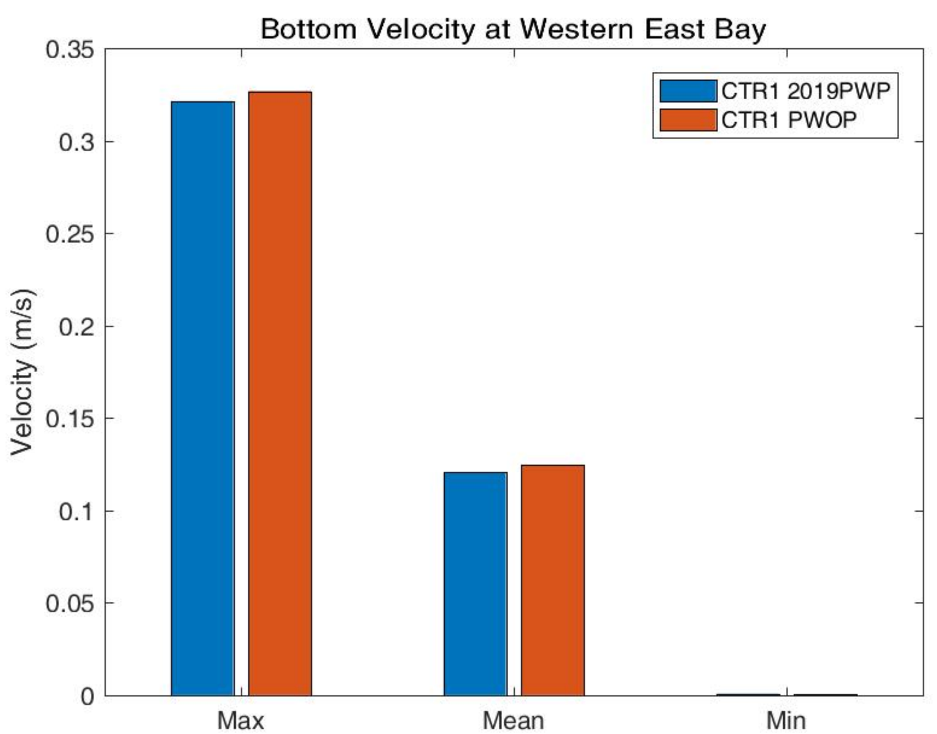

Bottom Velocity Percentiles at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100

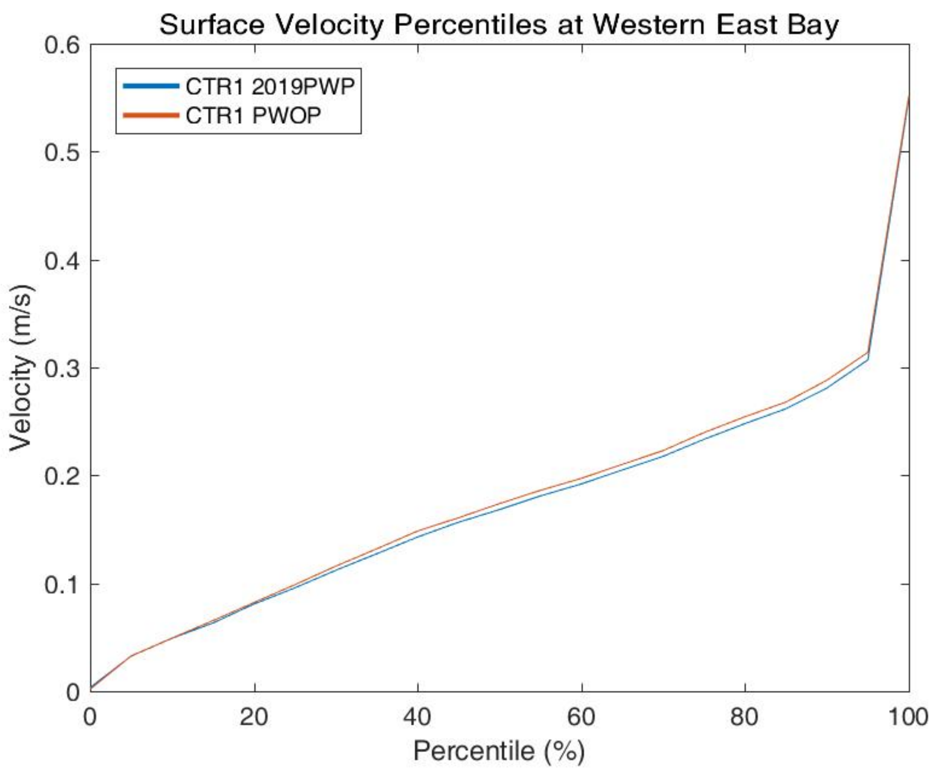

Bottom Velocity at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min

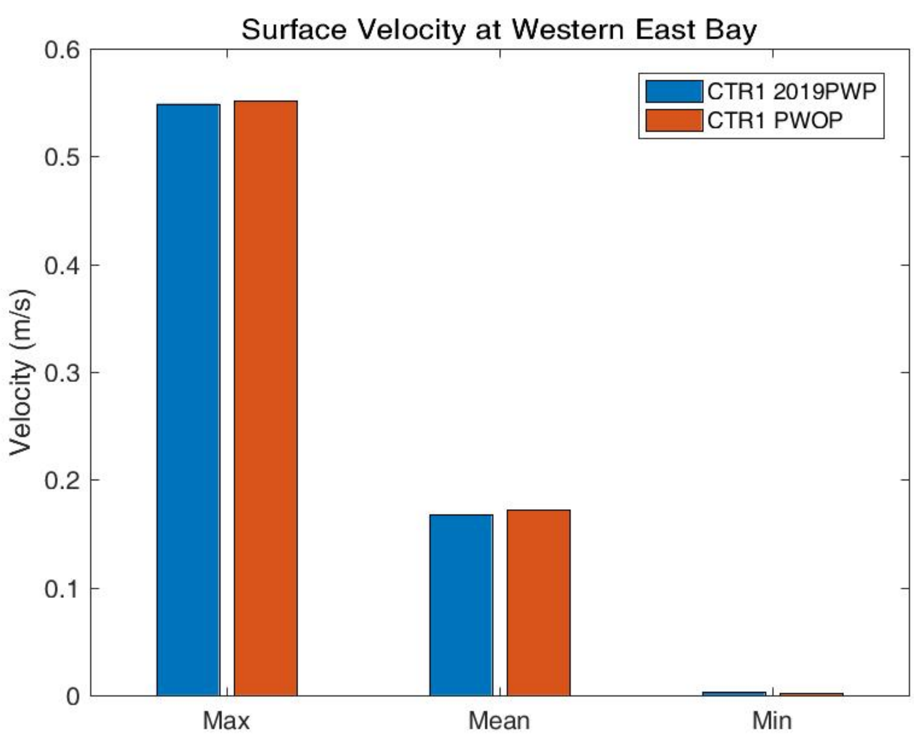

Surface Velocity Percentiles at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
Percentile (%)

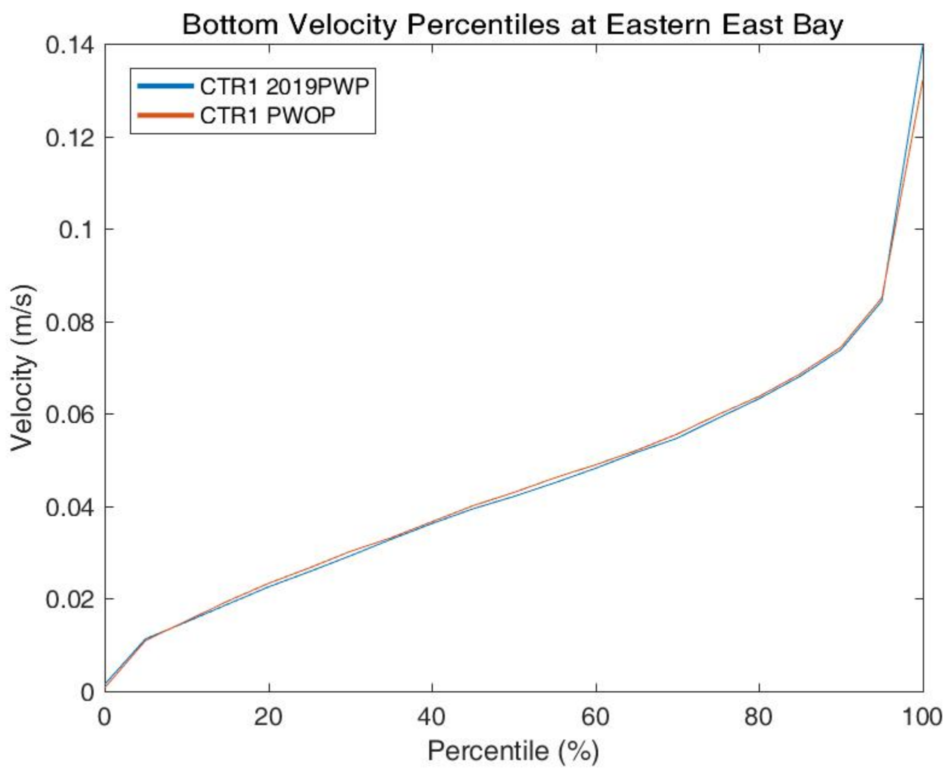

Surface Velocity at Upper Trinity Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

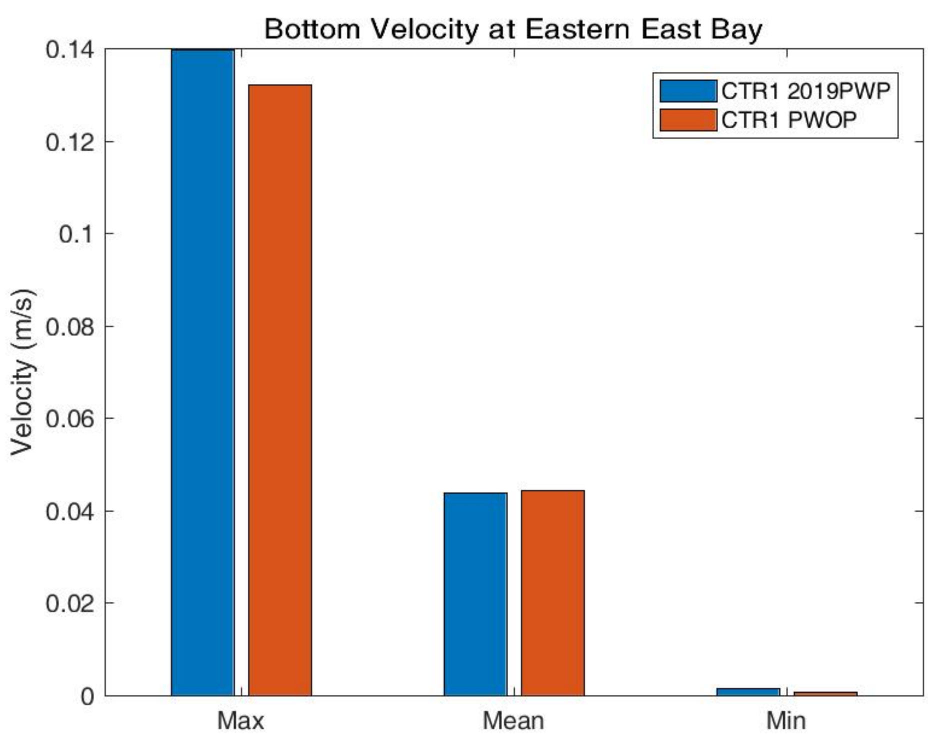

Bottom Velocity Percentiles at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

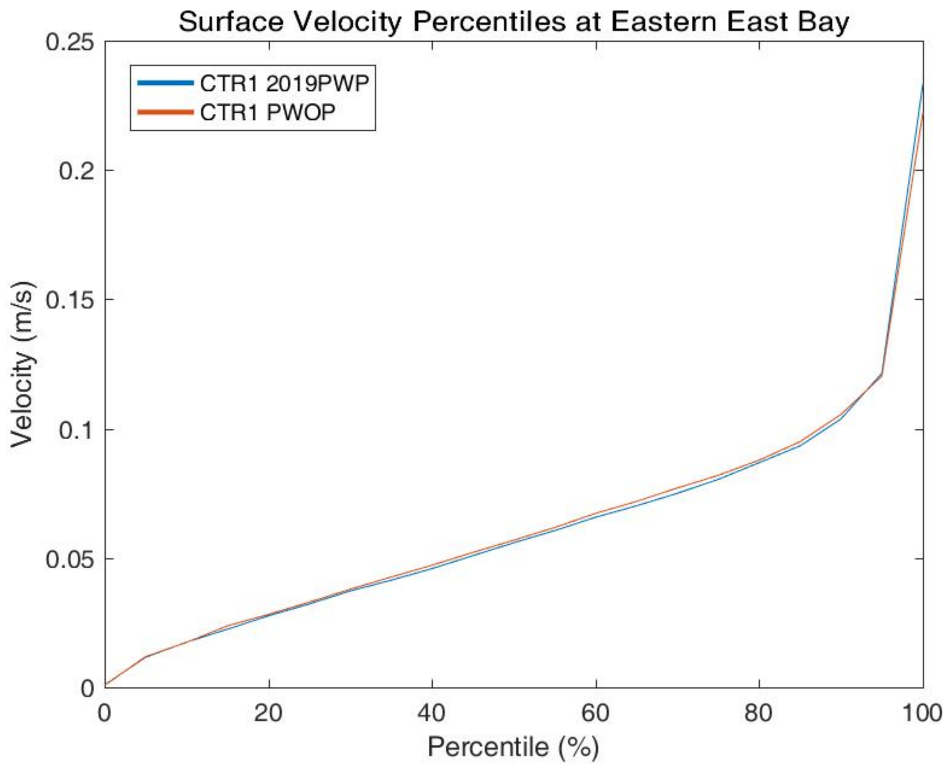

Bottom Velocity at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

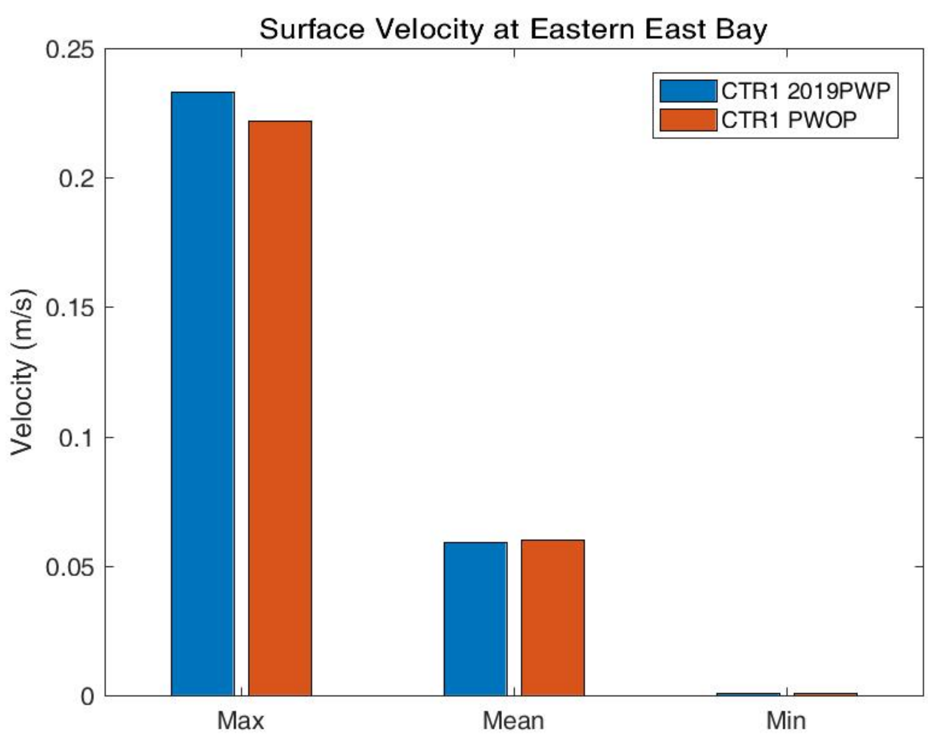

Surface Velocity Percentiles at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100

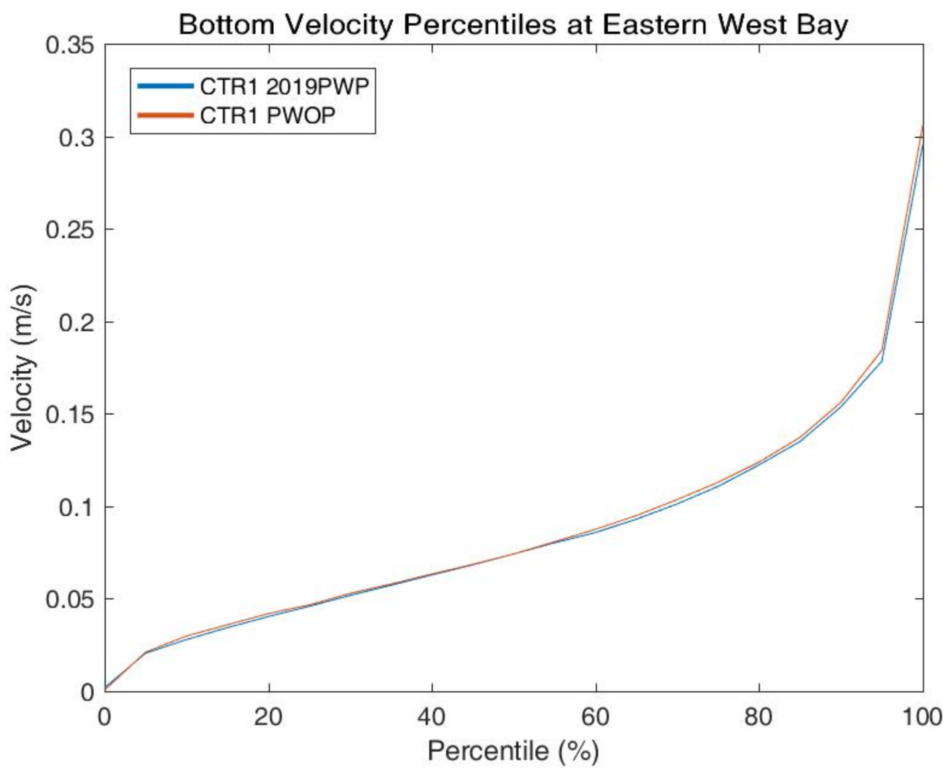

Surface Velocity at Western East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
Max
Mean
Min

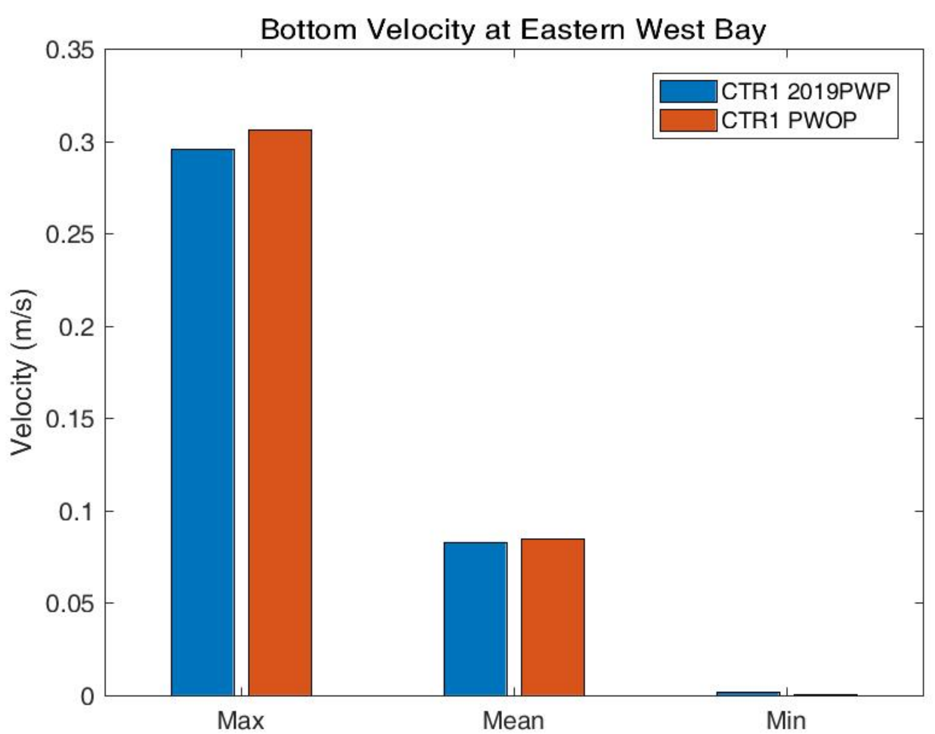

Bottom Velocity Percentiles at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100

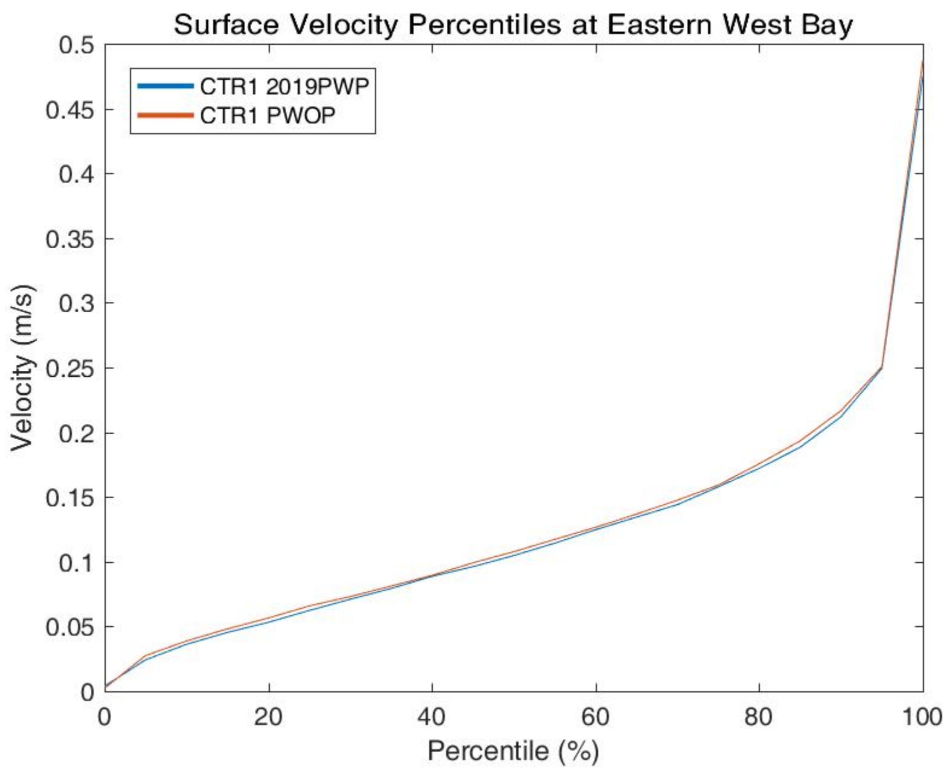

Bottom Velocity at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min

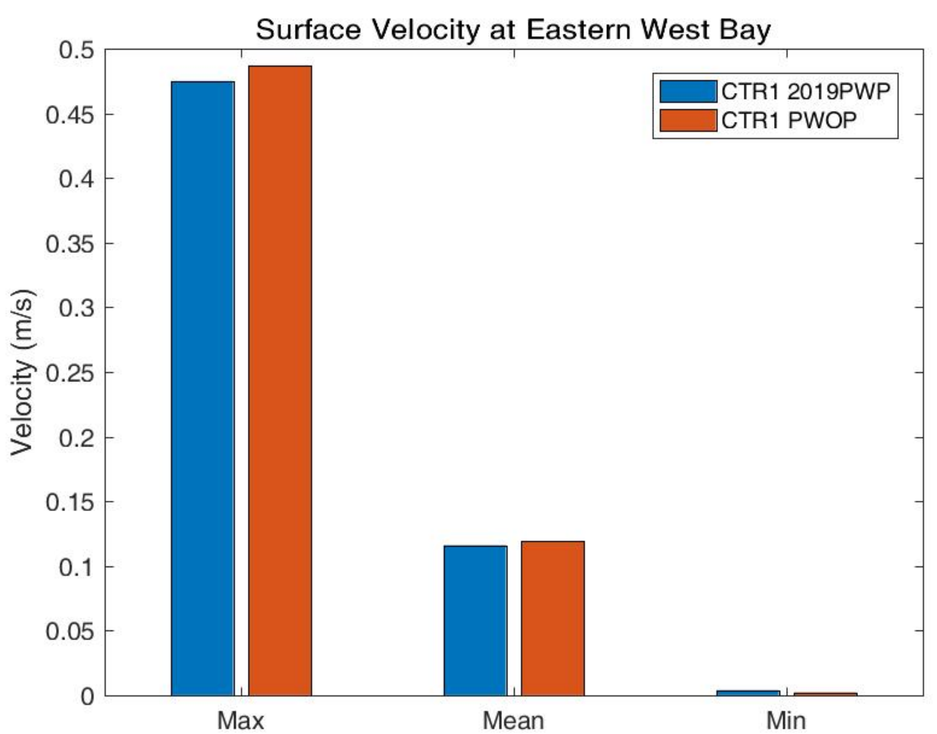

Surface Velocity Percentiles at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0
20
40
60
80
100

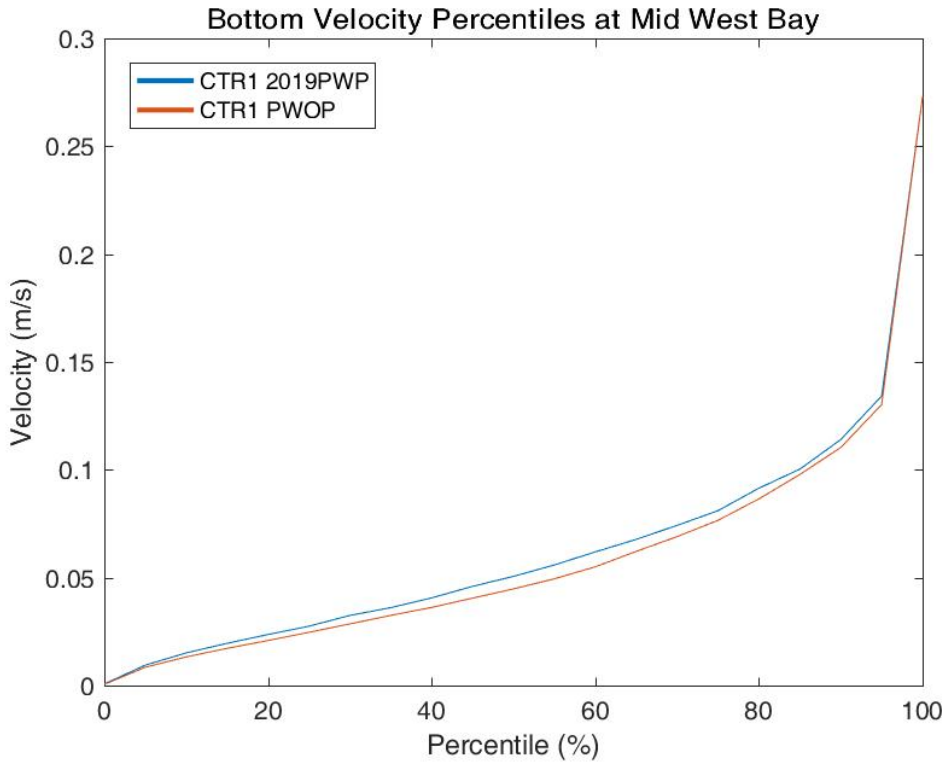

Surface Velocity at Eastern East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
Max
Mean
Min

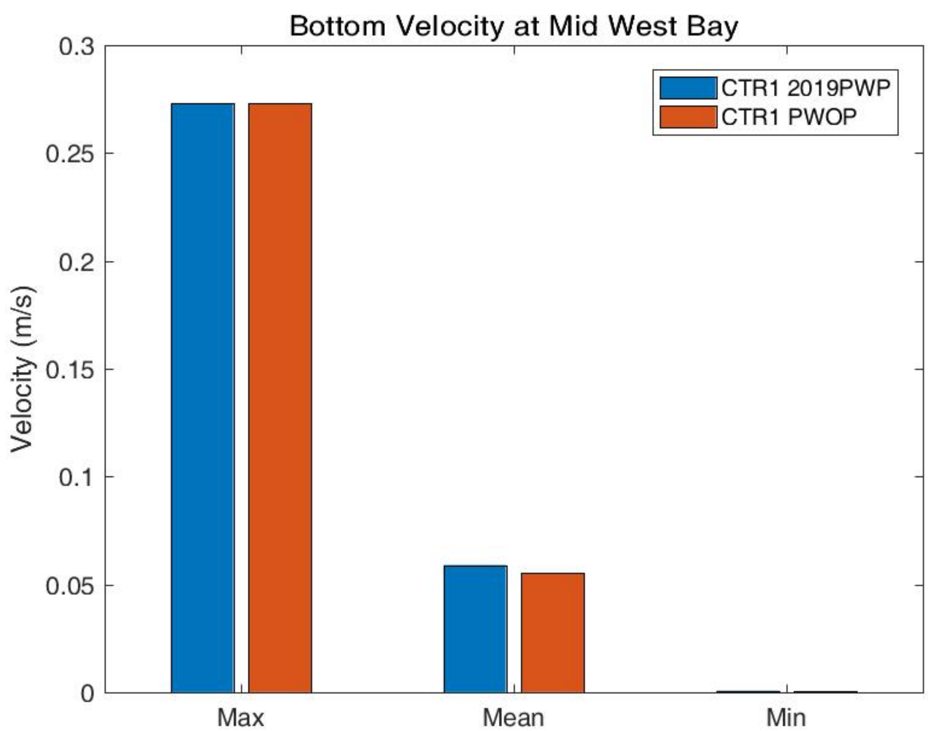

Bottom Velocity Percentiles at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

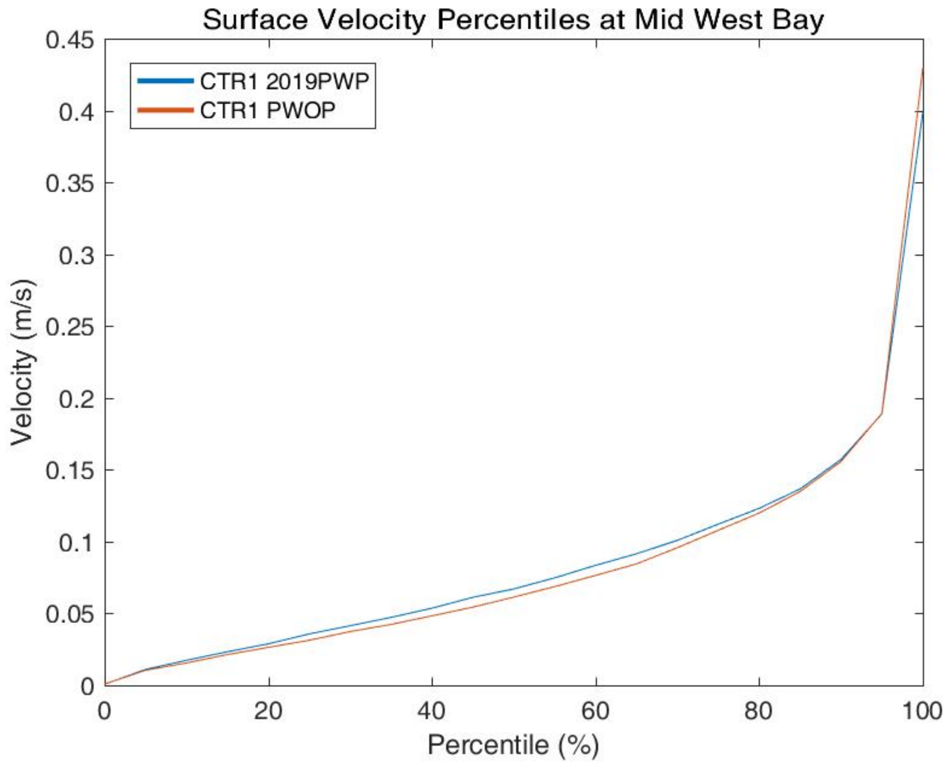

Bottom Velocity at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

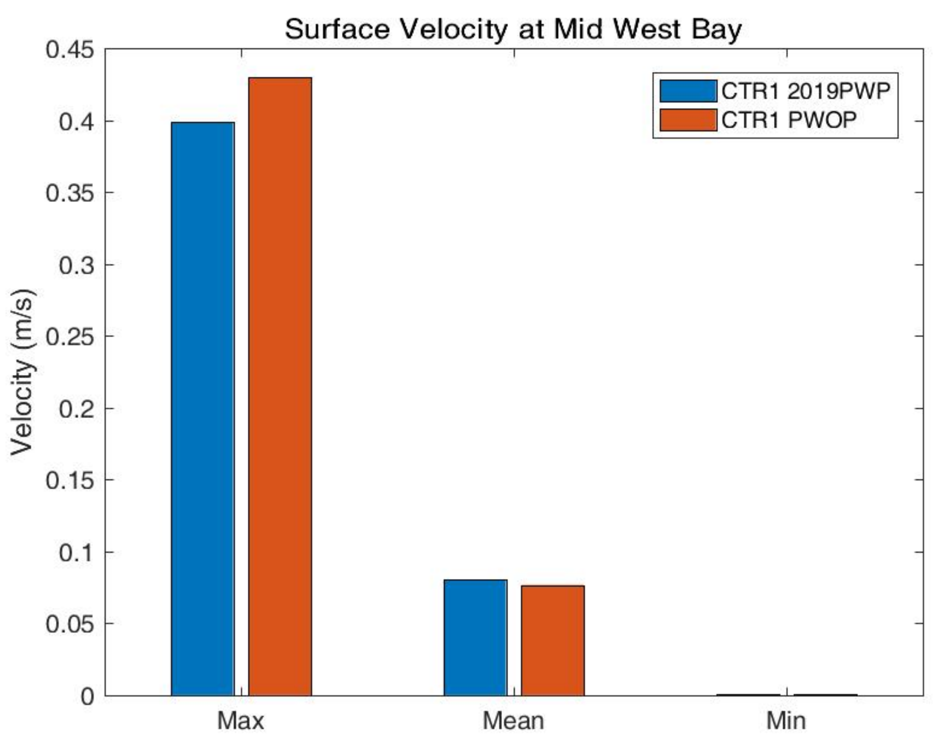

Surface Velocity Percentiles at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

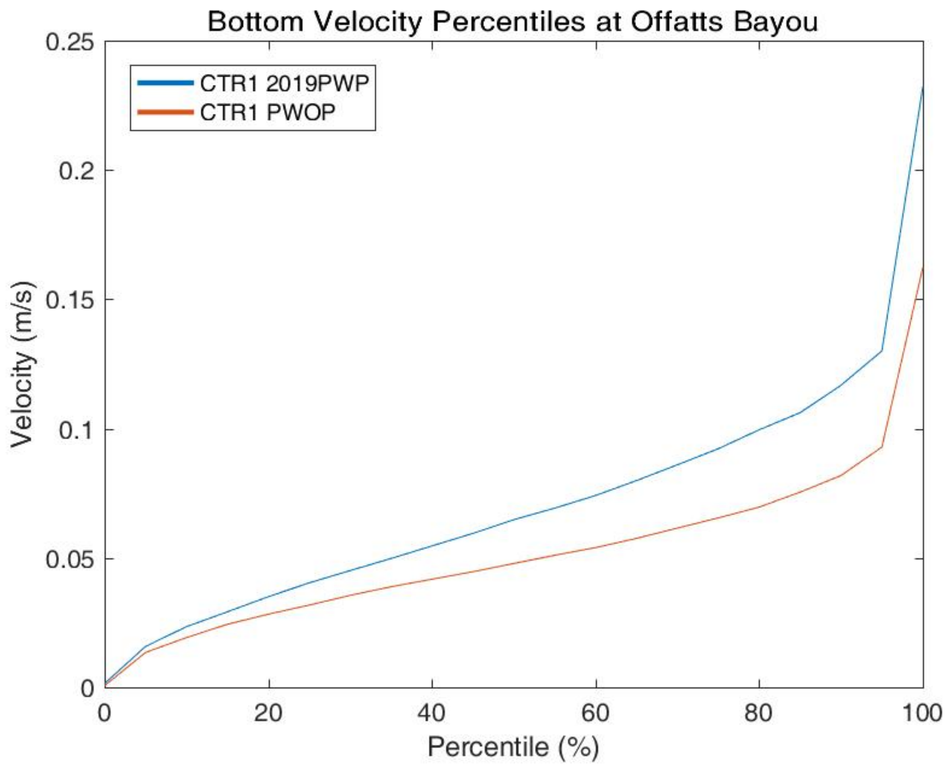

Surface Velocity at Eastern West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

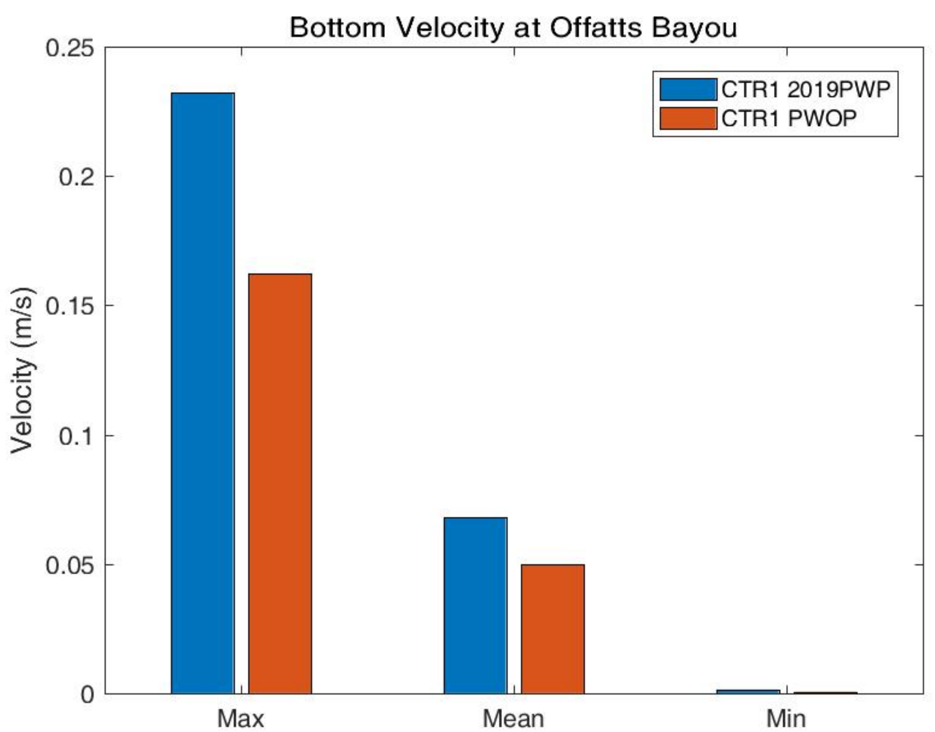

Bottom Velocity Percentiles at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
20
40
60
80
100

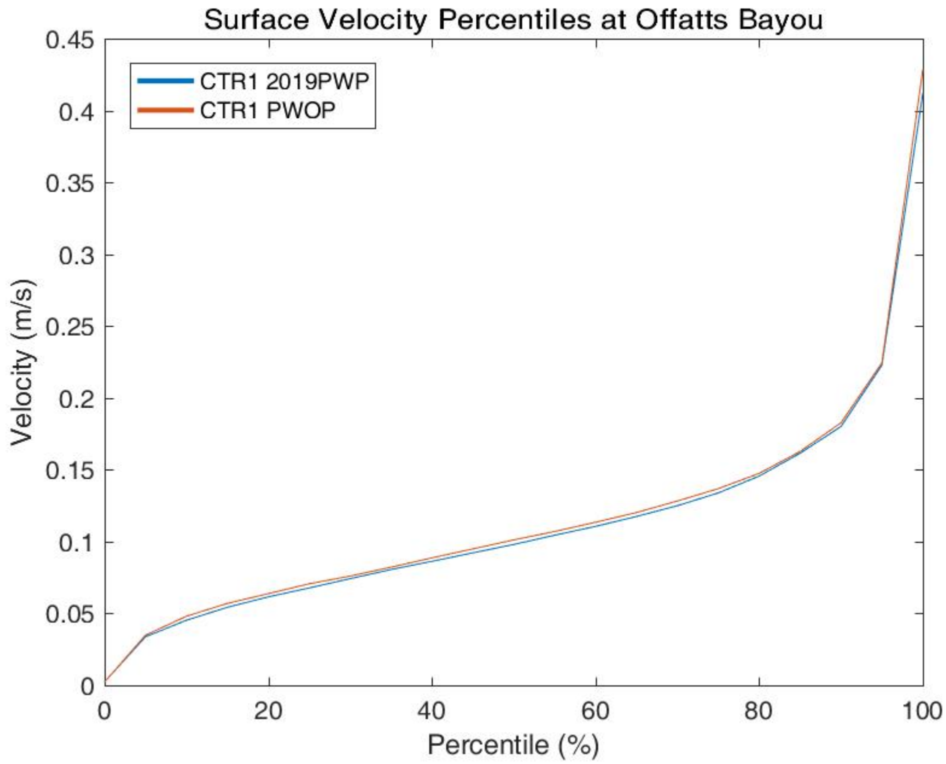

Bottom Velocity at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
Max
Mean
Min

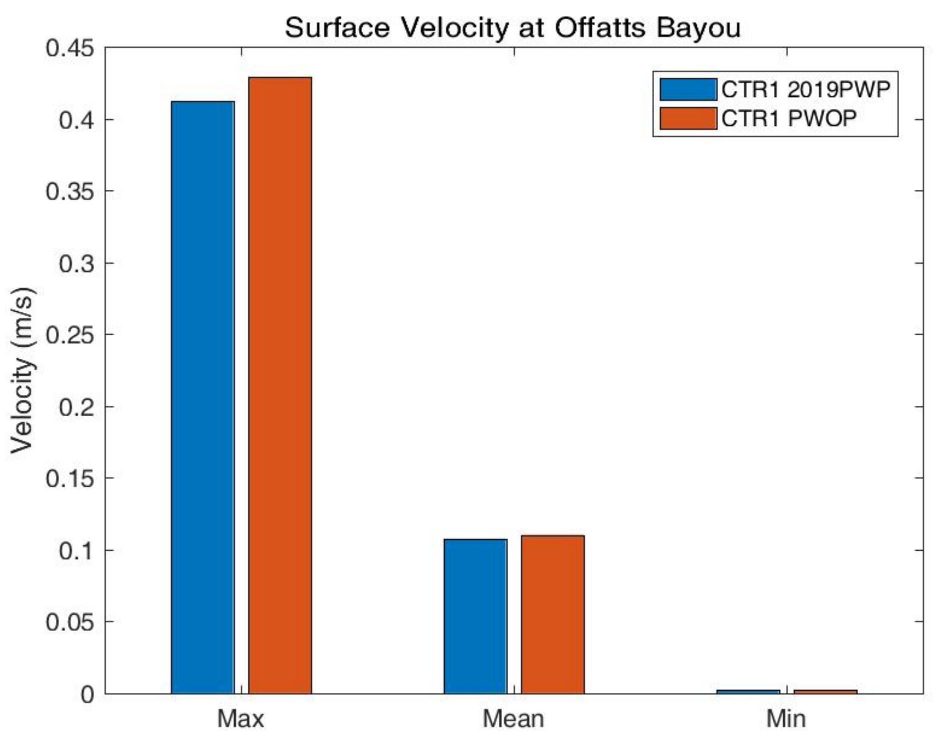

Surface Velocity Percentiles at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
20
40
60
80
100

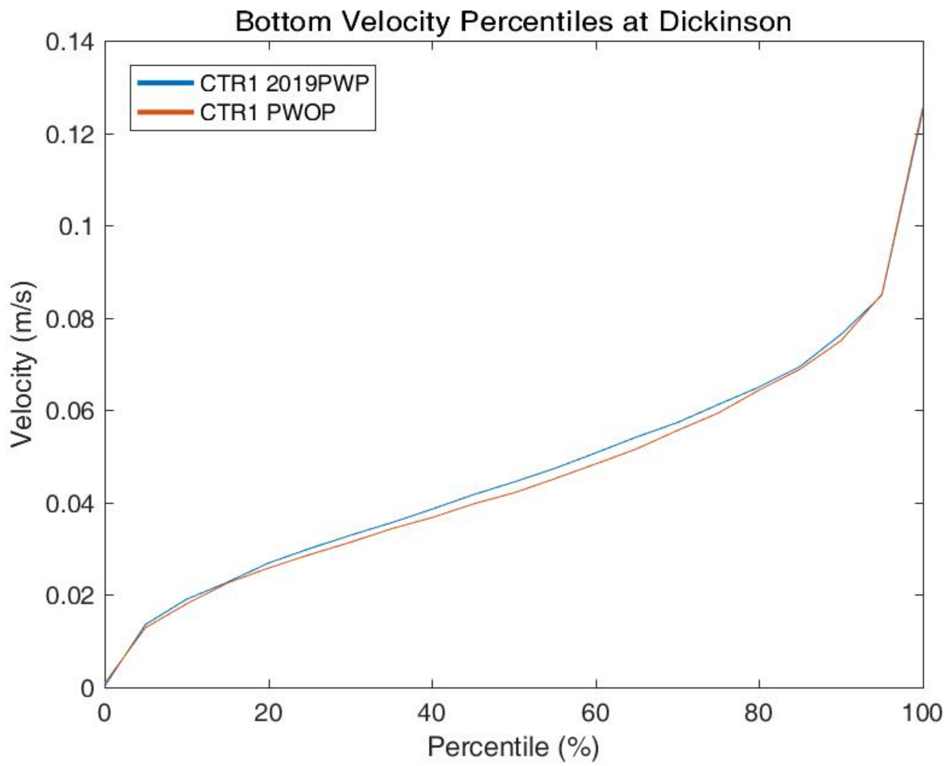

Surface Velocity at Mid West Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Max
Mean
Min

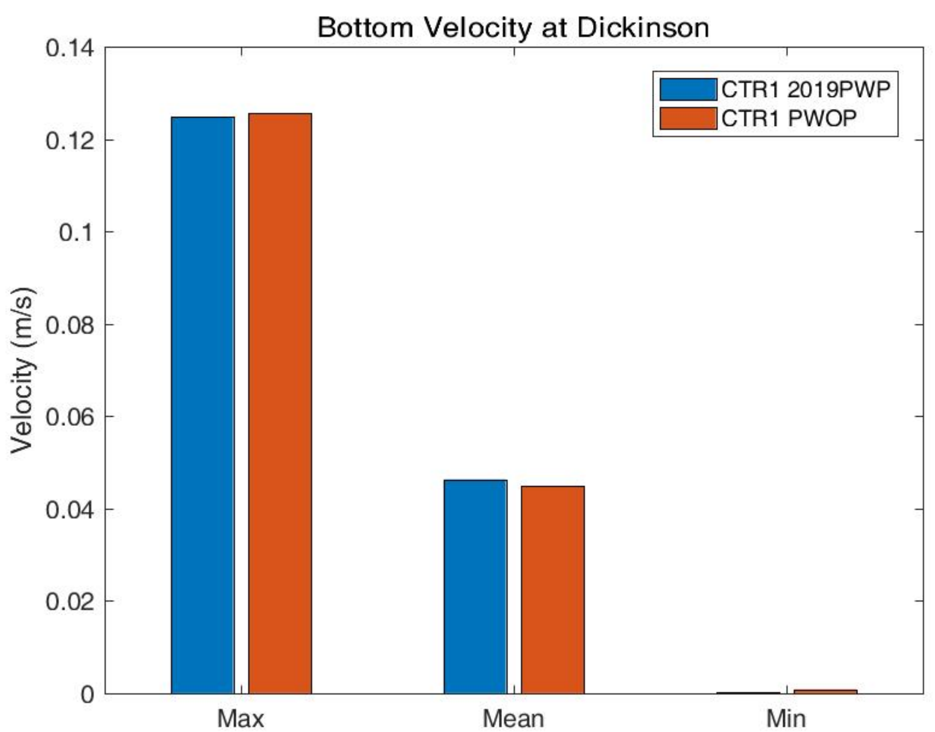

Bottom Velocity Percentiles at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

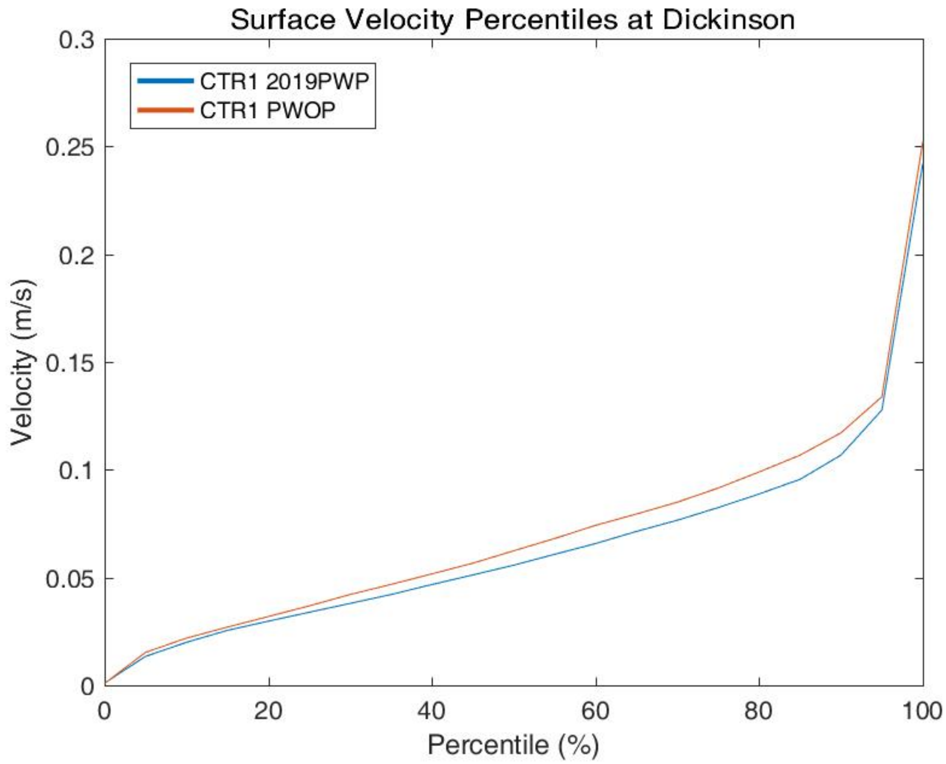

Bottom Velocity at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

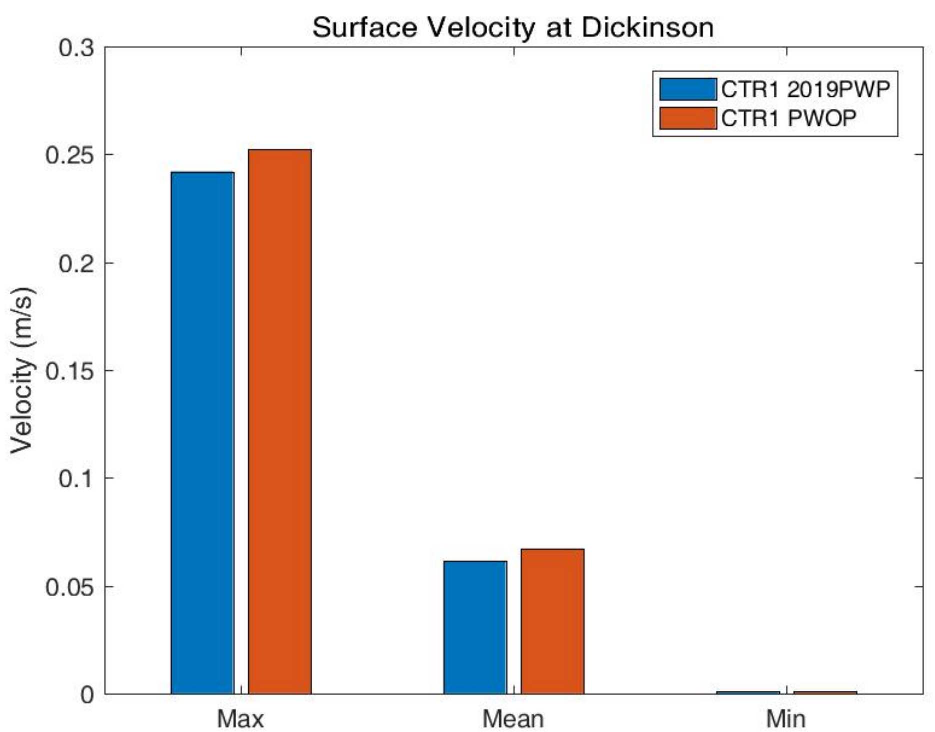

Surface Velocity Percentiles at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
Percentile (%)

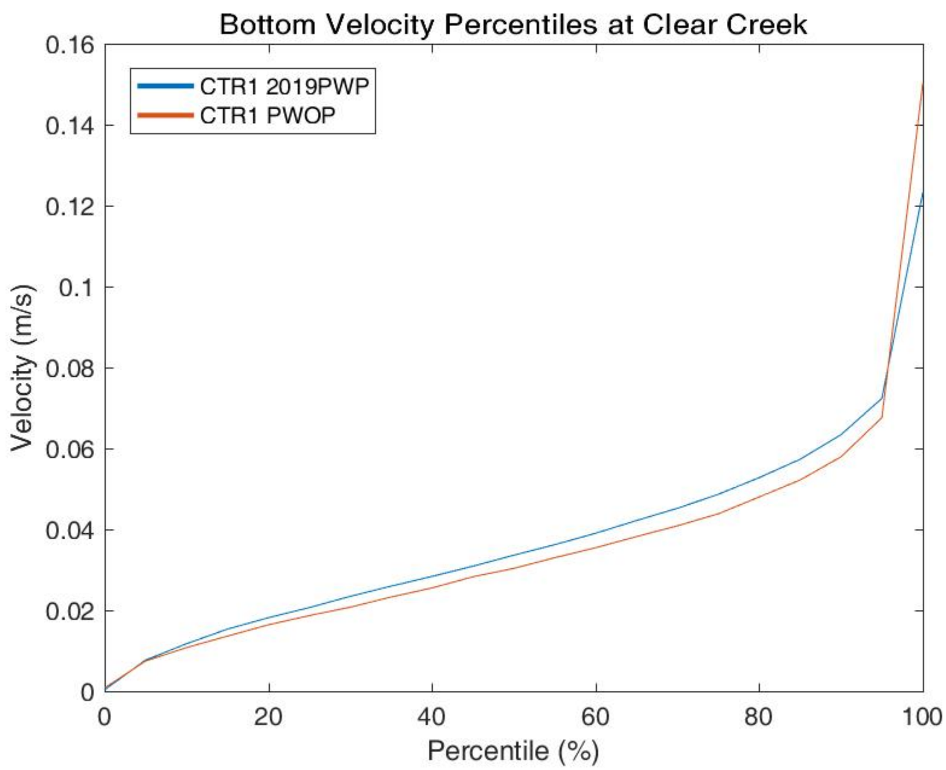

Surface Velocity at Offatts Bayou
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

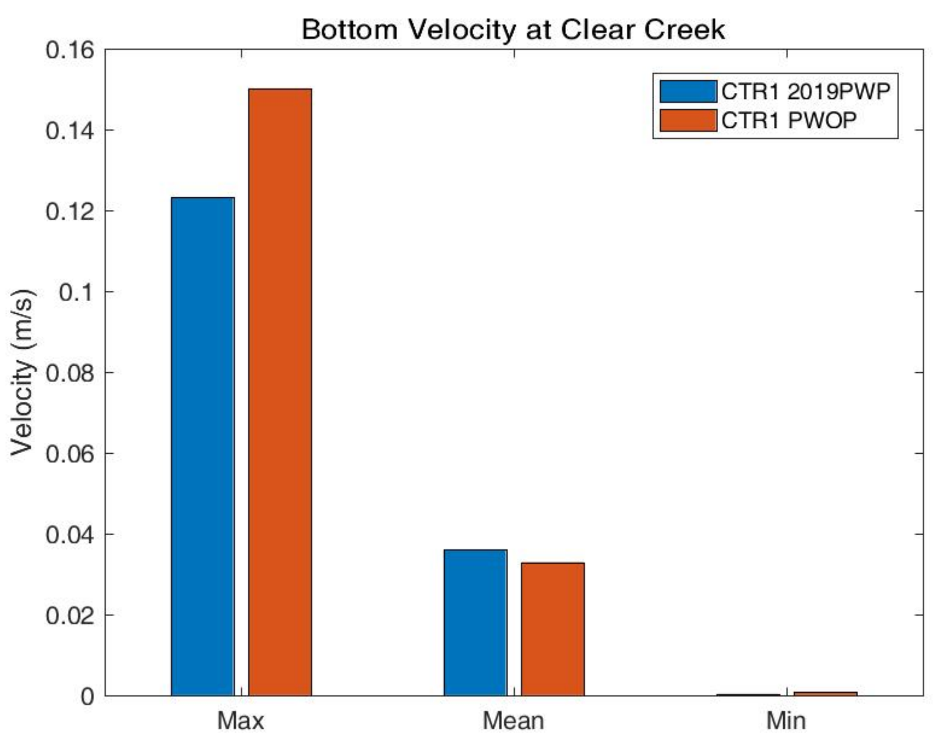

Bottom Velocity Percentiles at Dickinson
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
Percentile (%)

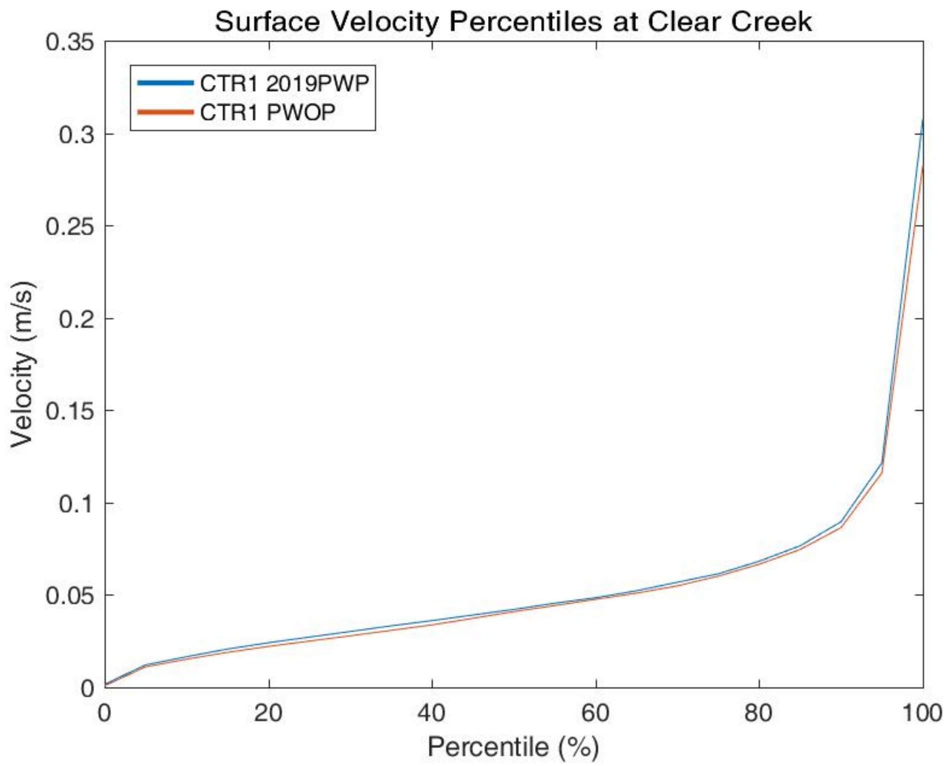

Bottom Velocity at Dickinson
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min

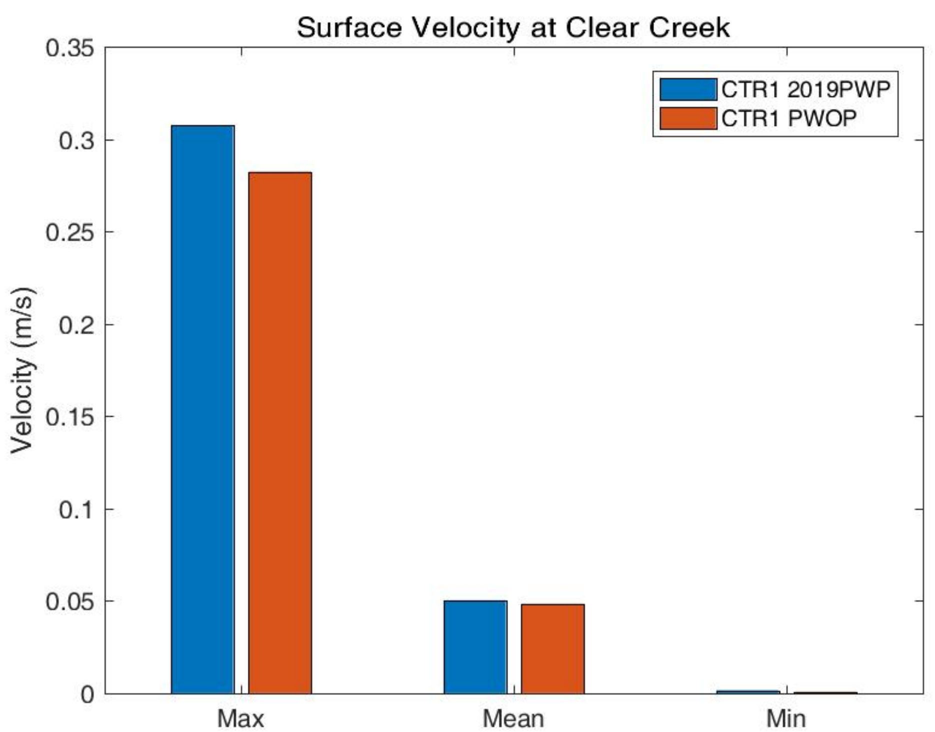

Surface Velocity Percentiles at Dickinson
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
20
40
60
80
100

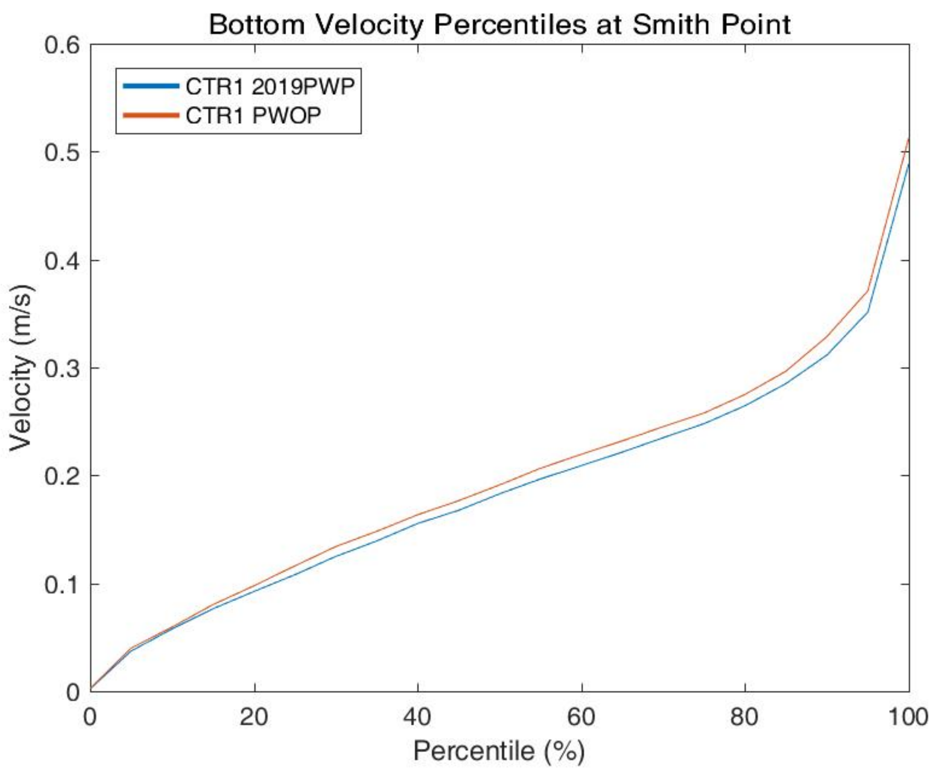

Surface Velocity at Dickinson
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
Max
Mean
Min

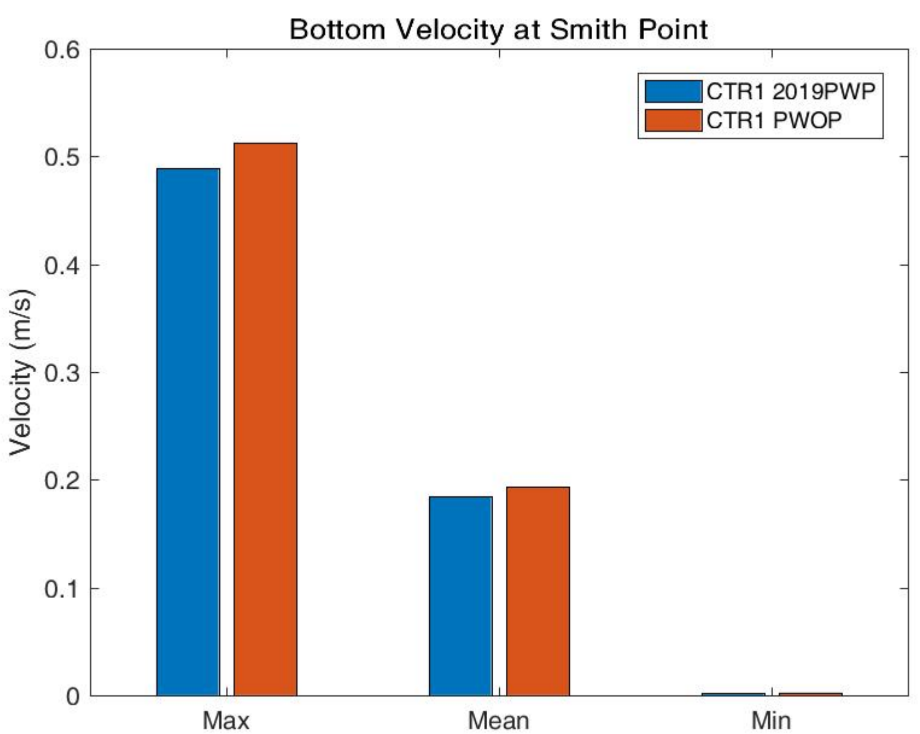

Bottom Velocity Percentiles at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0
20
40
60
80
100

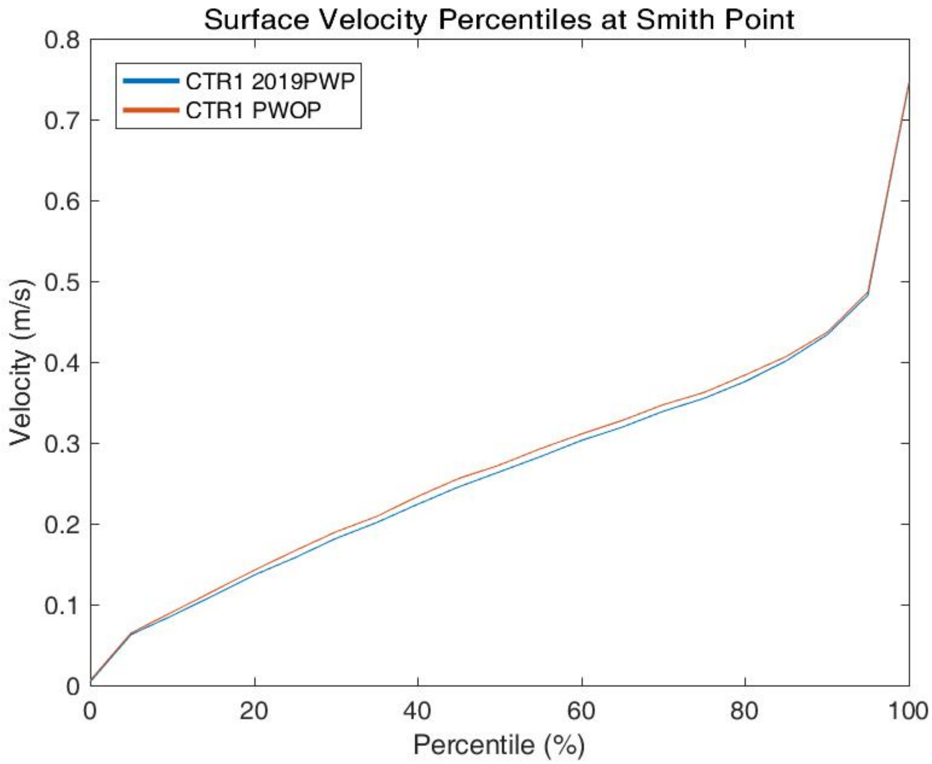

Bottom Velocity at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Max
Mean
Min

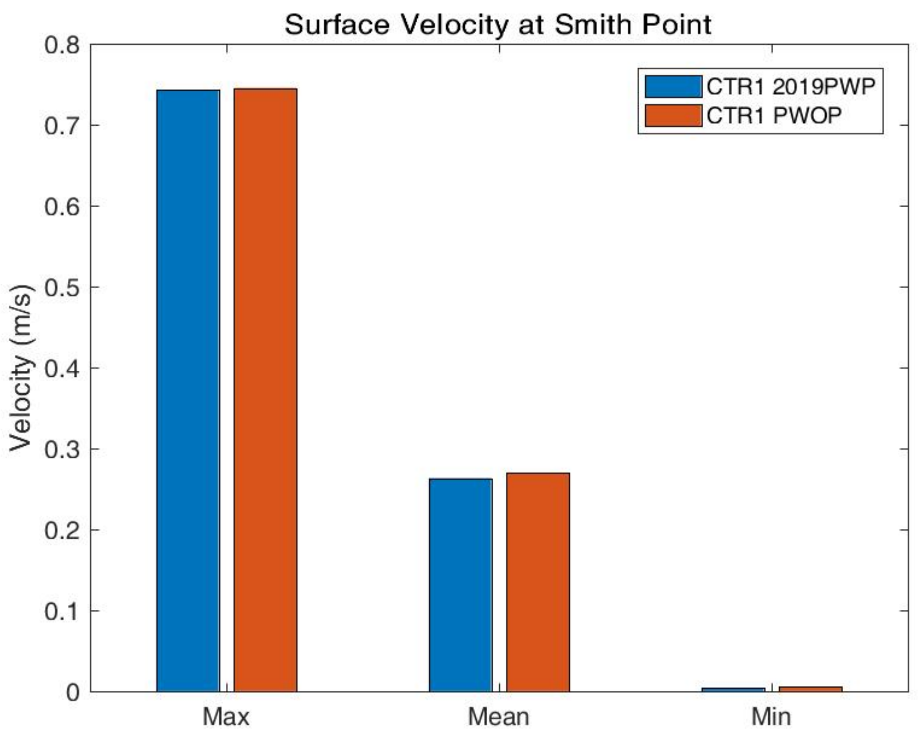

Surface Velocity Percentiles at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100

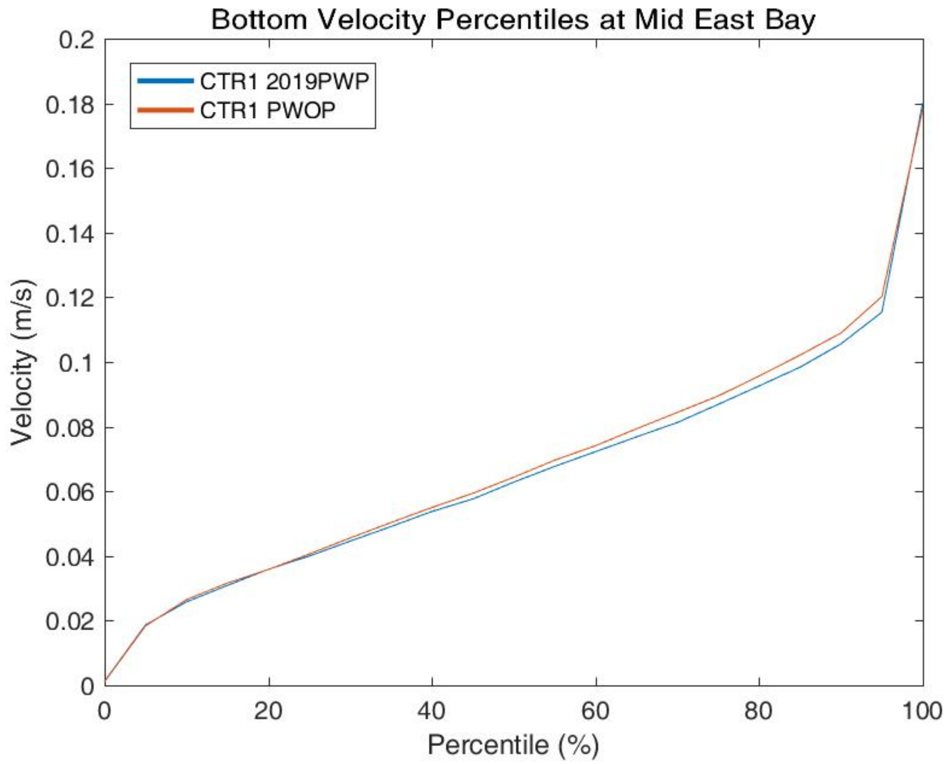

Surface Velocity at Clear Creek
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min

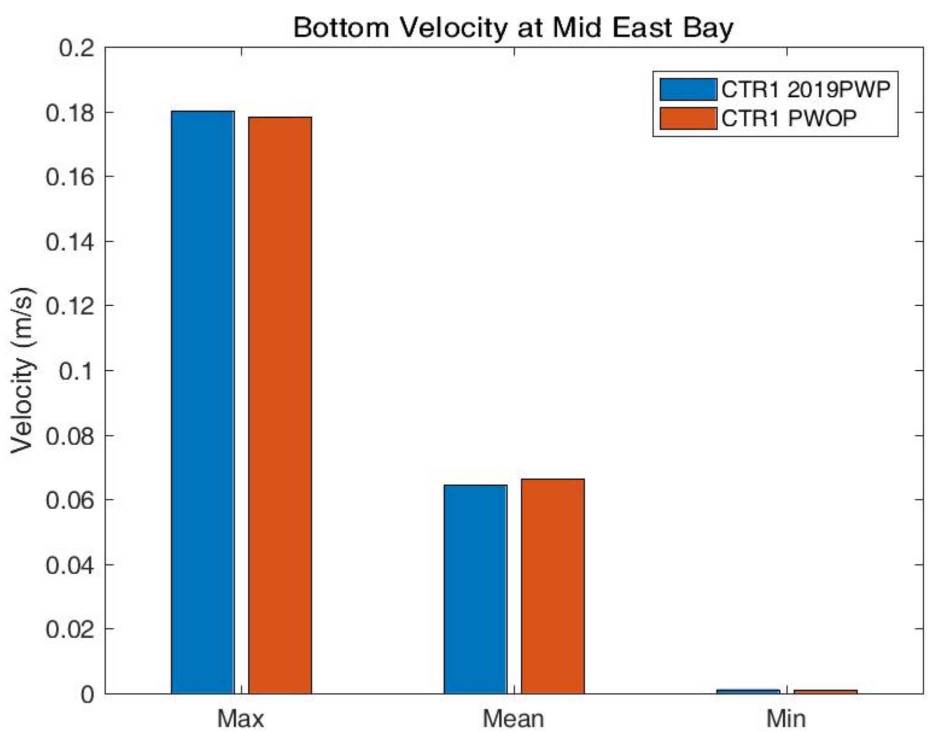

Bottom Velocity Percentiles at Smith Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100
Percentile (%)

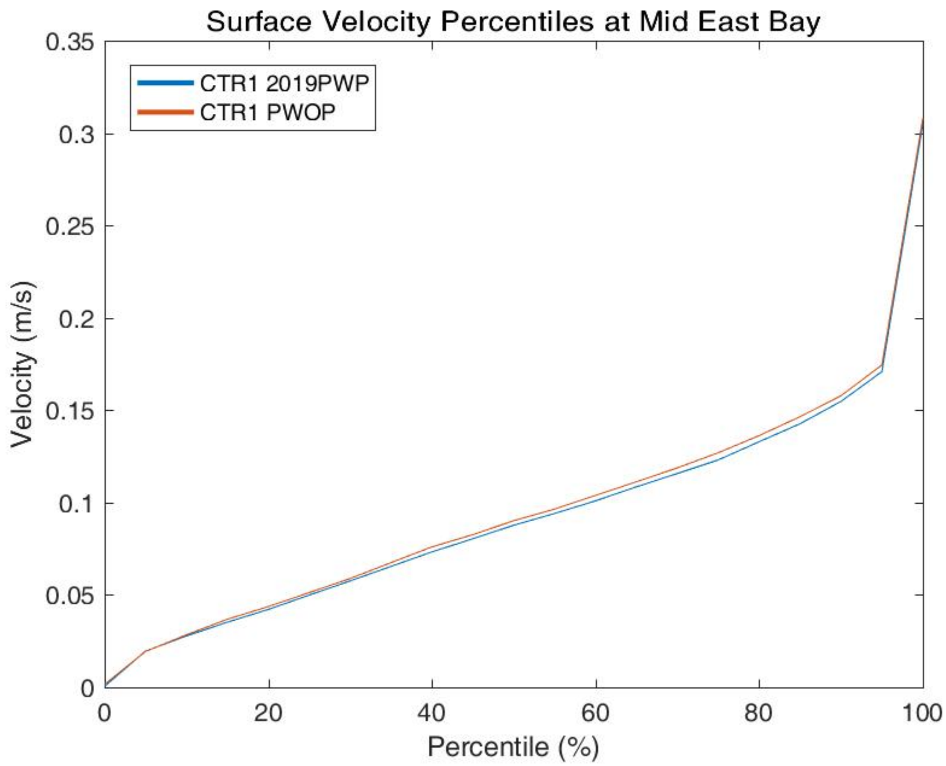

Bottom Velocity at Smith Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
Max
Mean
Min

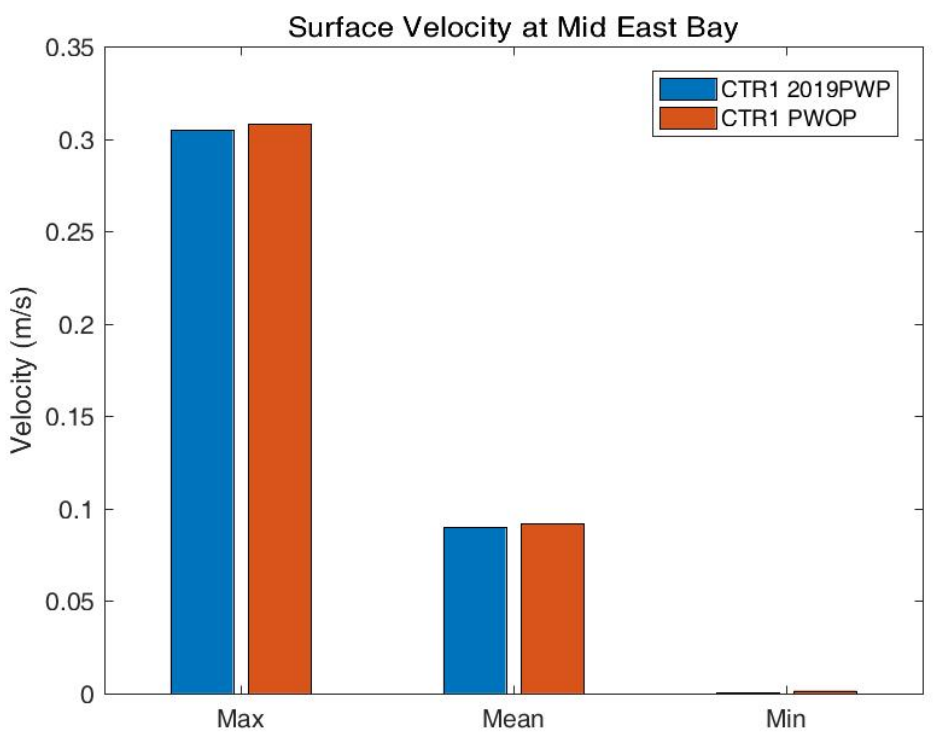

Surface Velocity Percentiles at Smith Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
Percentile (%)


Surface Velocity at Smith Point
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Max
Mean
Min


Bottom Velocity Percentiles at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
Percentile (%)


Bottom Velocity at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Max
Mean
Min


Surface Velocity Percentiles at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
Percentile (%)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100


Surface Velocity at Mid East Bay
CTR1 2019PWP
CTR1 PWOP
Velocity (m/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Max
Mean
Min