Simulation of Total Phosphorus in Biscayne Bay, USA

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Abstract. This research presents a preliminary water quality model for Biscayne Bay (Florida, USA). During the month of December 2018, water quality monitoring stations located in central Biscayne Bay reported total phosphorous concentration (TP) peaks ranging from 0.03 to 0.052 mg/L. Median TP concentrations range between 0.003 to 0.004 mg/L. The water quality simulations presented in this research show that the observed TP peaks were most probably caused by a surge in TP in the Atlantic Ocean waters close to the ocean boundary of Biscayne Bay. Analysis of observed chlorophyll-a concentrations showed that high TP concentrations during December 2018 were not related to algae or phytoplankton bloom. Computational experiments showed that the observed TP peaks are not likely caused by the transport of a sudden release of a high-concentration TP pulse at the coast. Dilution of TP concentration by ocean water limits the spatial reach of coastal contaminant plumes. In testing the TP ocean-surge-origin hypothesis, pulses of 0.044 and 0.024 mg/L were applied to the ocean boundary. The latter pulse generated TP concentrations of around 0.03 mg/L in most of central Biscayne Bay. This estimated concentration is very similar to the TP peaks observed in December 2018. Therefore, those concentration peaks could have originated by a TP pulse of magnitude similar to 0.024 mg/L that occurred in the Atlantic Ocean waters close to the ocean boundary of Biscayne Bay.

Keywords: Water quality modeling · Biscayne Bay · total phosphorus · boundary conditions

1 Introduction

Biscayne Bay is an estuary located on Florida's Atlantic coast. Rapid urban growth in the last decades and human activities (agriculture, etc.) have increased runoff and nutrient transport from inland watersheds to the Bay. Recent studies have identified

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increased chlorophyll-a and phosphate concentrations within the bay, which is more evident throughout the northern area and in nearshore areas of central Biscayne Bay, suggesting an urgent need for land use and land cover management to reduce local nutrient wash-off from the watershed to the Bay [1–3]. Santos et al. [4] established that freshwater discharges into nearshore areas (contaminated by anthropogenic disturbances) have resulted in the fragmentation of the spatial patterning of submerged aquatic vegetation, which is thought to influence the distribution, community composition, and behavior of marine fauna. Man-made canals and waterways carry excess run-off and contaminants, from inland watersheds to Biscayne Bay.

Biscayne Bay has experienced considerable environmental changes due to a century of extensive regional population growth that accelerated coastal and watershed development. Documented changes include periods of hypersalinity, algal blooms, seagrass die-offs, loss of some fish species, localized pollution problems, among others [5]. These changes have been attributed to extensive urbanization agricultural activities and changes in water management practices.

During the month of December 2018, water quality monitoring stations located in central Biscayne Bay reported total phosphorous concentration (TP) peaks ranging from 0.03 to 0.052 mg/L. These high concentrations are fourteen times the observed TP median concentration at an offshore water quality station (BB 37), and nine times the observed TP median concentration at a coastal station (BISC 101) (Fig. 1).

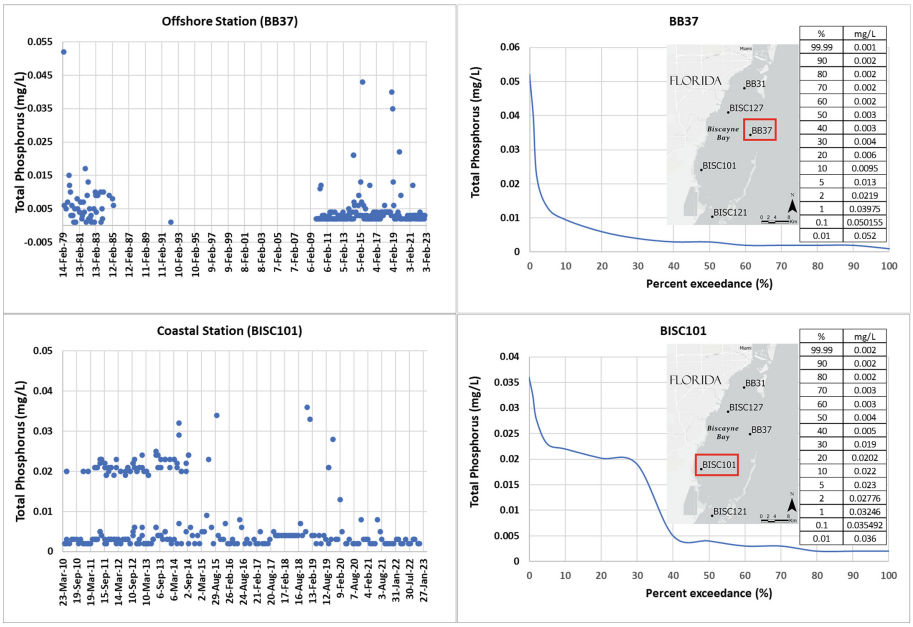


Fig. 1. Total phosphorous (TP) historical data for two water quality monitoring stations located in central Biscayne. Data for offshore station BB 37 corresponds to February 1979 through February 2023, and for coastal station BISC 101 to March 2010–January 2023. Probability of exceedance curves for total phosphorous concentrations are also shown.

Preliminary analysis of historical TP data (Fig. 1) shows that at the offshore station (BB 37) concentrations greater than 0.03 mg/L have a probability of exceedance of only 1.5%. TP concentrations greater than 0.04 mg/L have a probability of exceedance smaller than 0.8%. At the coastal station (BISC 101), with 12-year TP data records, concentrations greater than 0.03 mg/L have a probability of exceedance of only 2%. Interestingly, TP concentrations greater than 0.04 mg/L have a probability of exceedance smaller than 0.01%, at station BISC 101.

Figure 1 shows that TP concentrations at the coastal station (BISC 101) are greater than at the offshore station (BB37), since 80% of TP concentrations observed at the BISC 101 are smaller than 0.02 mg/L while 95% of TP concentrations observed at BB37 (offshore station) are smaller than 0.02 mg/L. Contaminants coming from inland watersheds are most probably degrading consistently the water quality of coastal waters. However, the greatest TP concentrations were observed at the offshore station (BB37): 0.052 mg/L on 19-March-1979, 0.043 mg/L on 3-June-2015, and 0.04 mg/L on 5-Dec-18.

The latter December-2018 TP concentration peak was observed at all stations in Biscayne Bay. The TP source is uncertain and for water quality modeling purposes it is important to ascertain where TP originated: inland watersheds or the ocean. As will be shown in next sections of this paper, meteorology does not play a role since observed precipitation was very low compared to rainfall observed in the wet season.

In this research, three hypotheses explaining these peaks are tested: 1) TP peaks come from algae or phytoplankton blooms, 2) TP peaks come from a sudden release of a high concentration TP pulse at the coast that is transported to most of the Bay, and 3) TP peaks come from the nearby ocean through the Biscayne Bay's ocean boundary. TP peaks could also be explained by data acquisition or instrument calibration issues, but the multiple days observed, and the standardization of the NOAA protocols for data collection suggest that this hypothesis is not valid. The computational experiments designed to test the hypotheses were performed via a 3-D water quality model developed in this research. The period of analysis was 2012–2022.

2 Methods

2.1 Study Area

Biscayne Bay (Fig. 2) is located on the southern Florida Atlantic coast, USA. It is a shallow estuary (average depth is around 3 m) characterized by having diurnal tides (average tidal range 0.48 m), short flushing rate (residence time less than one week), and well-mixed waters [6]. It receives freshwater inputs from several man/made canals and natural creeks and streams. The watersheds that drain to the bay are mostly covered by agricultural land in southern sectors and urban land cover in central and north Biscayne Bay.

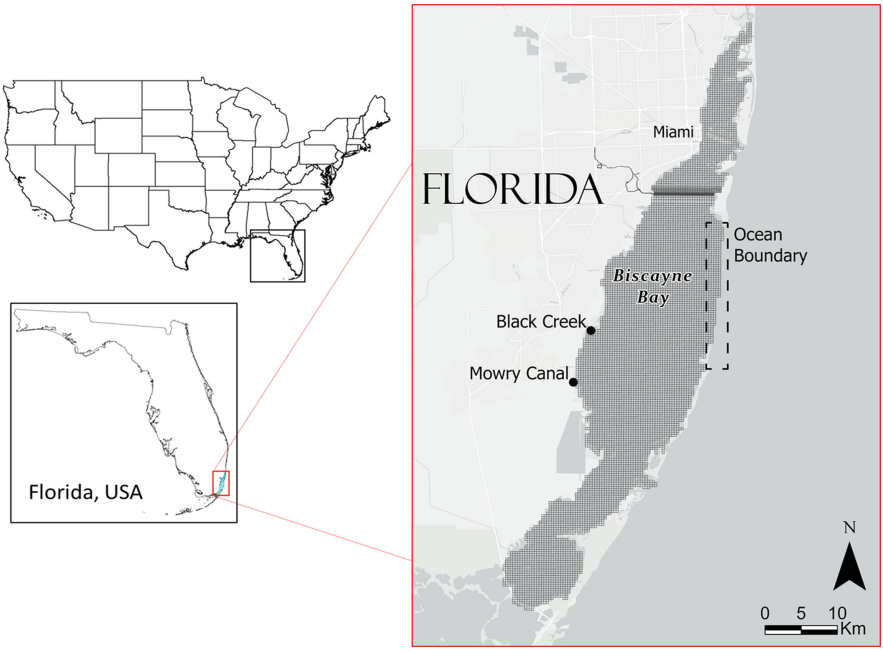


Fig. 2. Biscayne Bay. Computational grid, ocean boundary, Black Creek and Mowry Canal.

2.2 Water Quality Modeling

The estimation of water quality constituents in Biscayne Bay (total phosphorus, TP, and total nitrogen, TN) was performed by extending an existing hydrodynamic and salinity model of Biscayne Bay [7, 8]. The existing hydrodynamic model (Fig. 2) consists of 9,434 grid cells, two vertical layers, nine freshwater input cells (main streams draining to Biscayne Bay), and three open-ocean boundaries that represent the connection of the Bay with the Atlantic Ocean. The computational model was developed using the EFDC+ software [9]. To implement water quality, TP and TN boundary conditions were set up at the ocean water entrance to the estuary (Fig. 2). Three-dimensional salinity transport was calculated using the water quality module available in EFDC+.

2.3 Water Quality Data

This research used public domain water quality data from the following databases: South Florida Water Management District's environmental database DBHYDRO [10], and Miami Dade County Groundwater and Surface Water Quality Viewer, available through the Division of Environmental Resource Management [11]. Preprocessing and postprocessing of the observed water quality data available through these portals was performed using standard statistical software.

2.4 Data Analysis and Simulation Scenarios

Hypothesis 1 was tested through analysis of historical data for monitoring stations BB37 (an offshore station located close to the ocean boundary), and BISC101 (a station located near the central Biscayne Bay shoreline).

Hypotheses 2 and 3 were tested using the water quality model presented in this research. Since the TP peaks observed in December 2018 were preceded and followed by low TP concentrations, it was assumed (hypothesis 2) that they were caused by sudden TP peaks at the outfall of Black Creek or Mowry Canal. The Black Creek outfall is located close to a wastewater treatment plant; therefore, it is feasible that a 1.0 mg/L peak could have occurred during a short period of time. Mowry Canal is one of the main freshwater contributors to Central Biscayne Bay and the occurrence of a 0.084 mg/L TP peak is also possible since its watershed catchment covers urban areas which main wastewater management disposal treatment are septic tanks. To test hypothesis 3, pulses of 0.044 mg/L and 0.024 pulse mg/L were applied to the ocean boundary.

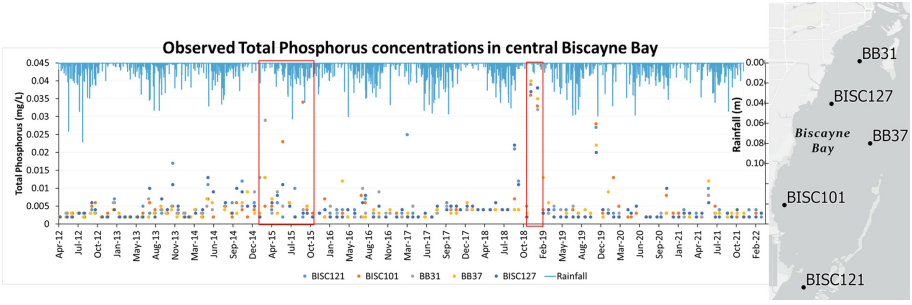


Fig. 3. Observed Total Phosphorus (TP) concentrations at water quality monitoring stations in central Biscayne Bay.

3 Results

3.1 High Concentrations of TP Originate from Algal or Phytoplankton Blooms

Figure 3 shows observed Total Phosphorus (TP) concentrations at water quality monitoring stations in central Biscayne Bay. The figure also shows precipitation at the top of the figure.

As shown in Fig. 3, most of observed TP concentrations are below 0.02 mg/L. There are some peak concentrations in the 2012/2022 period but the most noticeably peak occurs in December 2018, in which all monitoring stations show TP concentrations above 0.03 mg/L, reaching up to 0.04 mg/L. For water quality modeling purposes, it is important to understand the source of this TP peak. Observed precipitation was very low compared to rainfall observed in the rainy season.

One of the main causes of TP in estuaries and lakes is algal blooms. Algal growth causes a drastic change in aquatic conditions over a diel cycle, which may induce sensitive

feedback systems in sediments, causing P release [12]. Release of TP from dead algae is an important nutrient source that will support continuous algal blooms in lakes and estuaries [13]. However, if algal blooms are the source of the reported 2018 TP peaks, chlorophyll-a (an indicator of algal biomass) during or before their occurrence should also be observed. Moreover, if algal blooms were present, light attenuation in the estuary should be more efficient than when water is clear. As increased suspended matter (algae, suspended solids, etc.) occurs in the water column, light attenuation increases as well. When turbidity is high in the water column, light attenuation is also increased, and the absolute value of the attenuation coefficient K is also high.

Figure 4 shows charts corresponding to observed chlorophyll-a concentrations and light attenuation (represented by the attenuation coefficient K) for monitoring stations BISC101 and BB37. These stations were chosen because they are representative of the coastal region and the offshore locations that are close to the ocean boundary.

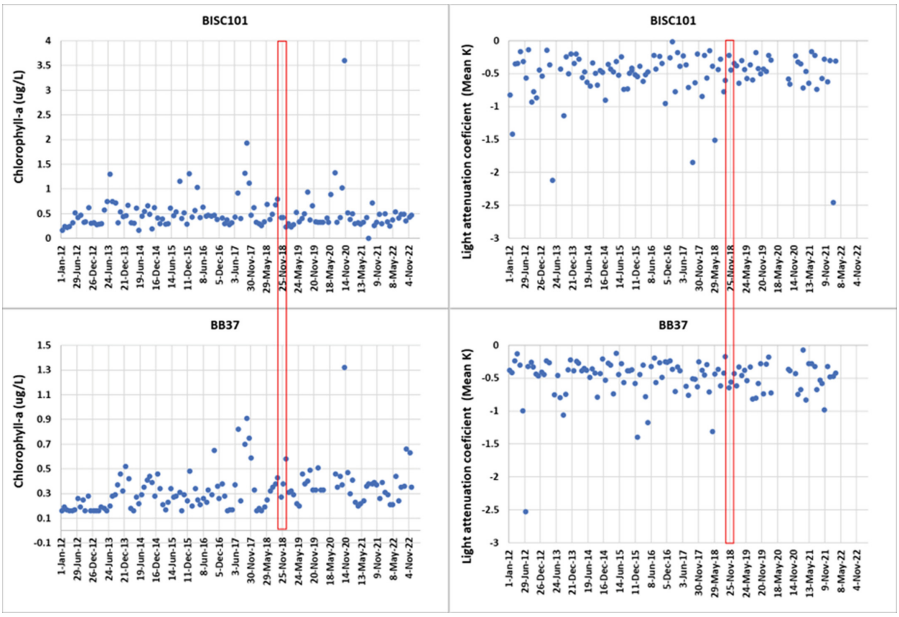


Fig. 4. Observed chlorophyll-a concentrations and light attenuation coefficient K for monitoring stations BISC101 and BB37. As the water gets more turbid, light attenuation is more effective and the absolute value of the light attenuation coefficient K is higher.

As shown in Fig. 4, observed chlorophyll-a concentrations from November 2018 to January 2019 were below 0.7 μg/L which indicates that algal presence was not particularly high during those months. Similarly, observed light attenuation coefficient values for the same months ranged between 0 and −0.7, showing that ocean water at those locations was within normal turbidity range. This leads to the conclusion that high TP concentrations during December 2018 are not directly connected to algae or phytoplankton bloom.

3.2 High Concentrations of TP Come from High TP Pulses Occurring at the Outfall of Streams that Feed Biscayne Bay

In order to test the second hypothesis, a computational experiment was performed using the hydrodynamic model of Biscayne Bay. Two phosphate pulses (Fig. 5) were implemented at two coastal locations (Mowry Canal, Black Creek) to see if those pulses would produce a TP response in Biscayne Bay similar to what was observed in December 2018. The principal dissolved phosphorus species in natural waters is the inorganic phosphate anion, orthophosphate. Orthophosphate is the form of phosphorus preferred by algae and free-living micro-organisms, including the phytoplankton.

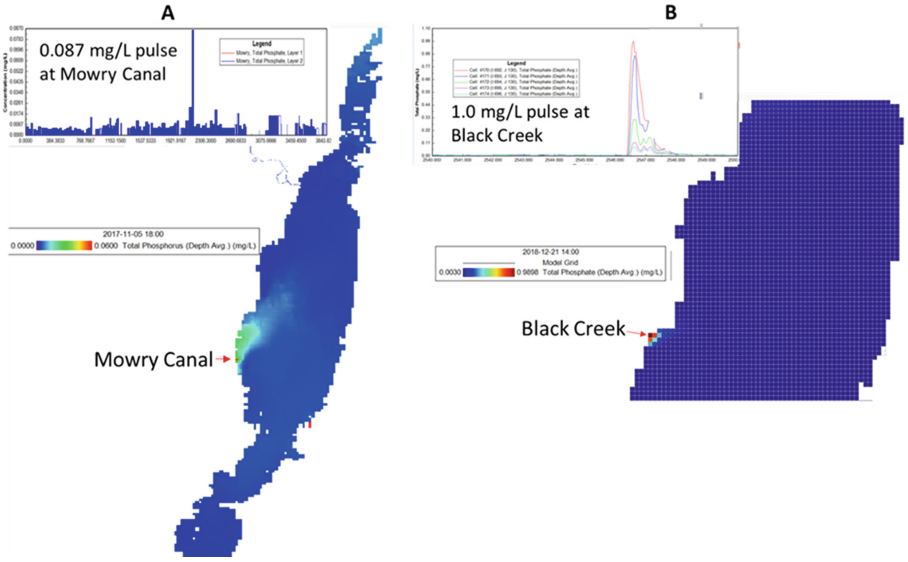


Fig. 5. Application of a pulse of 0.087 mg/L at Mowry canal (A), and 1.0 mg/L pulse at Black Creek (B). Mowry canal is one of the most important freshwater contributors to central Biscayne Bay. Black Creek is a stream located near a wastewater treatment plant.

Figure 5A shows the results of applying a sustained pulse of 0.087 mg/L of phosphate at Mowry canal. Mowry canal is one of the most important freshwater contributors to central Biscayne Bay. Notice that this concentration is twice the TP concentration that was observed during December 2018 throughout the Bay.

As shown in Fig. 5A, at its maximum spatial coverage the spatial distribution of TP concentration is shown to rapidly decrease for offshore locations. The dilution of the high pulse concentration by ocean water is shown to be very effective. The simulation shows that a pulse of these characteristics would not produce the 0.03–0.04 mg/L concentrations observed during December 2018.

Figure 5B shows the effect of implementing a 1.0 mg/L pulse at Black Creek. Since this stream contributes lower flowrate than Mowry Canal, a much higher concentration pulse was applied. Similar to what was simulated for Mowry Canal, even this

high concentration pulse has limited spatial reach within Biscayne Bay. Figure 5B also shows TP time-series plots corresponding to consecutive 300-m grid cells going from Black Creek towards the ocean boundary, horizontally. In 1500 m, the 1.0 mg/L pulse is damped to concentrations smaller than 0.05 mg/L. At 2500 m from Black Creek outfall, concentrations reduce to 0.003 mg/L.

Although it is unlikely that a high contaminant pulse would occur at two locations at the same time, Fig. 6 shows the effects of a simultaneous 0.5 mg/L phosphate pulse at Black Creek and Mowry Canal. As shown, the spatial extent of the contaminant plume is also limited.

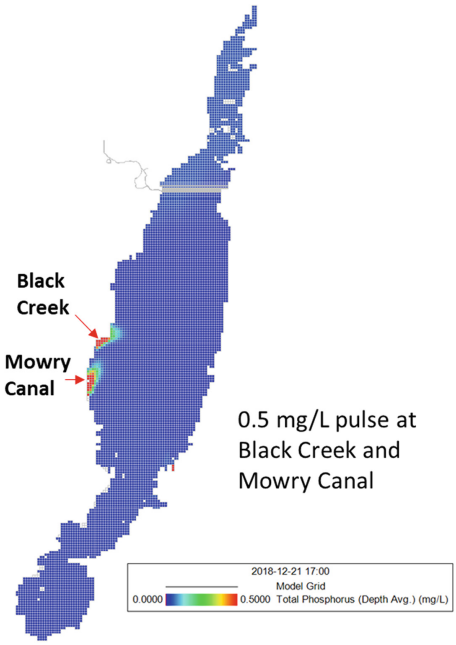


Fig. 6. Application of a simultaneous 0.5 mg/L phosphate pulse at Black Creek and Mowry Canal. The spatial extent of the contaminant plume at both locations is not large.

The computational experiments (summarized in Figs. 5 and 6) show that the observed December 2018 TP peaks are not caused by hydrodynamic transport of a high-concentration TP pulse applied at coastal streams. Dilution of TP concentrations by ocean water limits the spatial reach of the contaminant plume and the pulse cannot reach all water quality station's locations as observed in December 2018.

3.3 High Concentrations of TP Originate in the Ocean

In testing of the third hypothesis, a pulse of 0.044 mg/L pulse (twentieth of the pulse applied to Mowry Canal) was applied to the ocean boundary (Fig. 7A). As shown in the figure, such a pulse would raise TP concentrations to 0.04 mg/L in regions close

to the ocean boundary, 0.03 mg/L in mid-bay, and 0.01 mg/L at central Biscayne Bay shoreline. Figures 7B and 7C show simulation results for a 0.024 mg/L pulse applied on 12-18-2012 that is decreased to 0.022 a week later (12-25-2018). By the end of the day on 12-18-2018, 0.03 mg/L concentrations are estimated in regions close to the ocean boundary, 0.025 mg/L in mid-bay, and 0.012 mg/L at central Biscayne Bay shoreline (Fig. 7B). Twenty-five days later (on 01-19-2019, Fig. 7C) the simulation shows that concentrations in most of central Biscayne Bay are around 0.03 mg/L. This estimated concentration is very similar to what was observed in December 2018 Fig. 3.

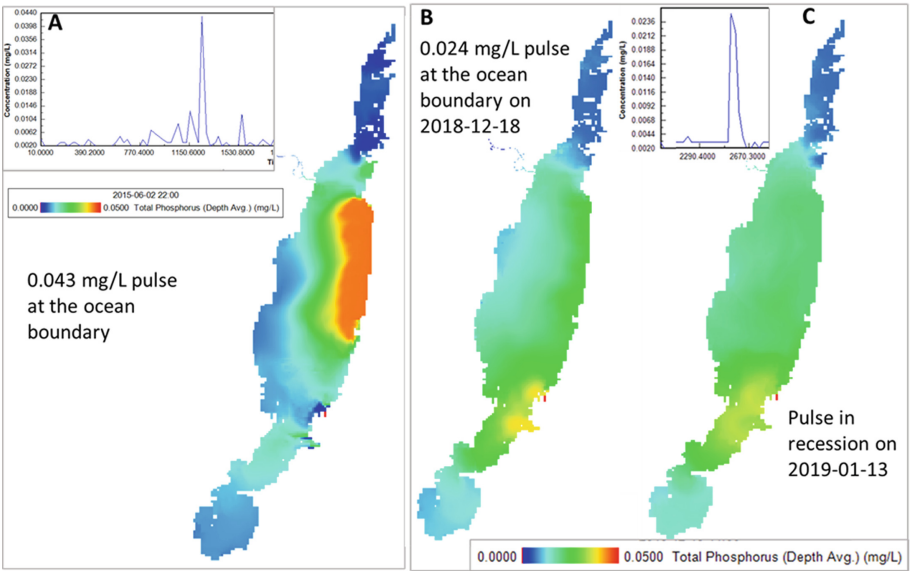


Fig. 7. TP concentration pulses at the ocean boundary. A) Simulation results for a pulse of 0.044 mg/L applied to the ocean boundary. B) Simulation results for a 0.024 mg/L pulse applied on 12-18-2012, decreased to 0.022 a week later. C) Simulation results after 25 days from the pulse application.

The rapid hydrodynamic dispersion of TP observed in Figs. 7B and C is a consequence of the efficient circulation of ocean water in the Bay. Figure 8 shows velocity vectors for 12-18-2018, at 8 AM (ebb tide), and 4 PM (flood tide). During ebb tide (Fig. 8A), water exits Biscayne Bay through the ocean boundary. Velocity vectors have higher magnitudes at the ocean boundary (up to 0.5 m/s approximately) than at the shoreline. Throughout the bay water moves towards the ocean boundary: southeast wards from northern sectors and northeast wards from southern zones. During flood tide (Fig. 8B), water vectors reach up to 0.7 m/s at the ocean boundary, and consequently water velocities towards the shoreline are greater than during ebb tide. Therefore, ocean water quality constituents will be hydrodynamically transported more efficiently towards the shoreline during flood tide, than contaminated freshwater will travel towards the ocean during ebb tide.

The velocity vectors shown in Fig. 8 show that water circulation imposed by the ocean boundary dominates water and water quality constituents transport in central Biscayne Bay. This is consistent with other research that explored the effects of ocean boundaries in enclosed estuaries [14, 15].

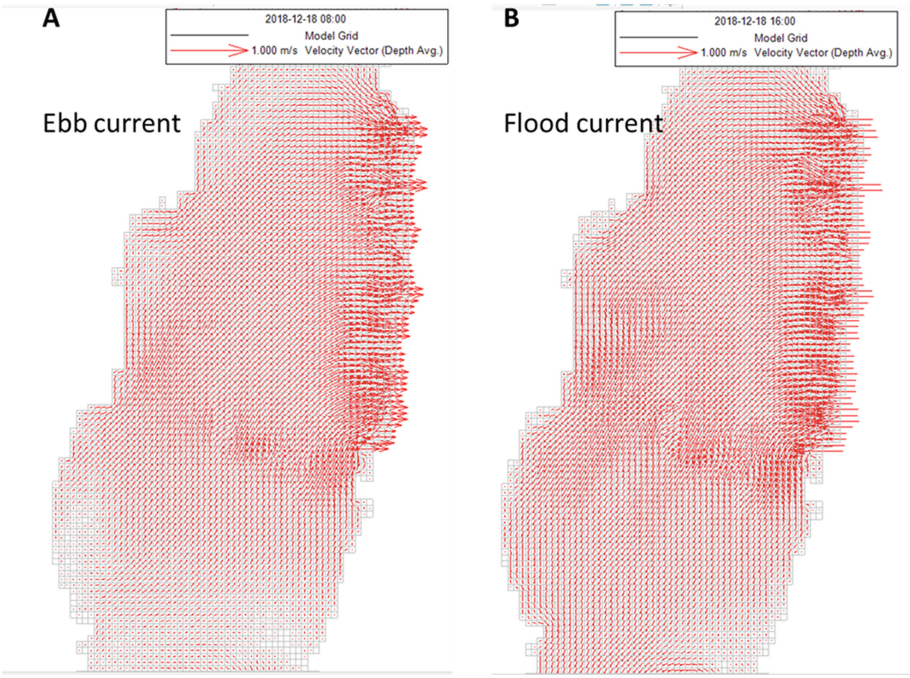


Fig. 8. Velocity vectors during ebb and flood current for December 18, 2018. A) Ebb current at 8 AM. B) Flood current at 4 PM. Vectors show that ocean water quality constituents would be hydrodynamically transported towards the shoreline more efficiently during flood tide, than contaminated freshwater would travel towards the ocean during ebb tide.

4 Conclusions

The water quality simulations generated in this research show that the observed total phosphorus (TP) peaks observed throughout Biscayne Bay during December 2018 were most probably caused by a surge in TP in the Atlantic Ocean waters close to the ocean boundary of Biscayne Bay. Analysis of observed chlorophyll-a concentrations from November 2018 to January 2019 showed that algal presence was not particularly high during those months (<0.7 μg/). Similarly, observed light attenuation coefficient values for the same months ranged between 0 and -0.7, showing that ocean water at those locations was within normal turbidity range. This leads to the conclusion that high TP concentrations during December 2018 were not directly connected to algae or phytoplankton blooms.

Computational experiments showed that the observed December 2018 TP peaks are not likely caused by the transport of a sudden release of a high-concentration TP pulse at the coast. Pulses of several magnitudes (0.088, 0.5, and 1.0 mg/L) were implemented at Black Creek and Mowry Canal (independent and concurrent pulses). Dilution of TP concentration by ocean water limits the spatial reach of the contaminant plume and the pulses did reach all monitoring stations as observed in December 2018.

In testing the TP ocean-surge-origin hypothesis, a pulse of 0.044 mg/L pulse was applied to the ocean boundary. This pulse raised TP concentrations to 0.04 mg/L in regions close to the ocean boundary, 0.03 mg/L in mid-bay, and 0.01 mg/L at central Biscayne Bay shoreline. Similarly, a 1-week duration 0.024 mg/L pulse applied to the ocean boundary generated TP concentrations of around 0.03 mg/L in most of central Biscayne Bay. This estimated concentration is very similar to the TP peaks observed in December 2018. Therefore, those peaks were most probably caused by a surge in TP in Atlantic Ocean waters close to the ocean boundary of Biscayne Bay.

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References

1. Millette, N.C., Kelble, C., Linhoss, A., Ashby, S., Visser, L.: Using spatial variability in the rate of change of chlorophyll a to improve water quality management in a subtropical oligotrophic estuary. Estuaries Coasts **42**(7), 1792–1803 (2019). https://doi.org/10.1007/s12237-019-00610-5
2. Swart, P.K., Anderson, W.T., Altabet, M.A., Drayer, C., Bellmund, S.: Sources of dissolved inorganic nitrogen in a coastal lagoon adjacent to a major metropolitan area, Miami Florida (USA). Appl. Geochem. **38**, 134–146 (2013)
3. Caccia, V.G., Boyer, J.N.: A nutrient loading budget for Biscayne Bay, Florida. Mar. Pollut. Bull. **54**(7), 994–1008 (2007). Epub 2007 Apr 5, PMID: 17418240. https://doi.org/10.1016/j.marpolbul.2007.02.009
4. Santos, R.O., Lirman, D., Pittman, S.J., Serafy, J.E.: Spatial patterns of seagrasses and salinity regimes interact to structure marine faunal assemblages in a subtropical bay. Mar. Ecol. Progr. Ser. **594**, 21–38 (2018). https://doi.org/10.3354/meps12499
5. SFWMD, South Florida Water Management District: South Florida Environmental Report (2021). https://www.sfwmd.gov/sites/default/files/documents/2021_sfer_highlights_hr.pdf
6. Wang, J.D., Luo, J., Ault, J.S.: Flows, salinity, and some implications for larval transport in South Biscayne Bay. Florida. Bull. Mar. Sci. **72**(3), 695–723 (2003)
7. Alarcon, V.J., et al.: Coastal inundation under concurrent mean and extreme sea-level rise in Coral Gables. Nat. Hazards **2022**, 1 (2022). https://doi.org/10.1007/s11069-021-05163-0
8. Alarcon, V.J., Linhoss, A.C., Mickle, P.F., Kelble, C.R., Fine, A.: Estimation of groundwater and salinity for the Central Biscayne Bay Coast, Florida, USA. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) ICCSA 2022. LNCS, vol. 13379, 594–606. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10545-6_40
9. DSI: The Environmental Fluid Dynamics Code: Theoretical & Computational Aspects of EFDC+, Dynamic Solutions - International, LLC, Edmonds, WA, USA (2017)

10. SFWMD, South Florida Water Management District: DBHYDRO (Environmental Data) (2020). https://www.sfwmd.gov/science-data/dbhydro
11. DERM, Division of Environmental Resource Management: Miami Dade County Groundwater and Surface Water Quality Viewer (2023). https://mdc.maps.arcgis.com/apps/webappviewer/index.html?id=3fd24515ee614f5db63924d7323a4ea7
12. Chen, M., et al.: Mechanisms driving phosphorus release during algal blooms based on hourly changes in iron and phosphorus concentrations in sediments. Water Res. **133**, 153–164 (2018). https://doi.org/10.1016/j.watres.2018.01.040
13. Feng, W., Li, C., Zhang, C., et al.: Characterization of phosphorus in algae from a eutrophic lake by solution 31P nuclear magnetic resonance spectroscopy. Limnology **20**, 163–171 (2019). https://doi.org/10.1007/s10201-018-0562-2
14. Alarcon, V.J.: Using gridded multi-mission sea surface height data to estimate tidal heights at Columbia River Estuary. In: Misra, S., et al. (eds.) ICCSA 2019. LNCS, vol. 11621, pp. 602–611. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-24302-9_43
15. Alarcon, V.J.: The role of boundary conditions in water quality modeling. In: Murgante, B., et al. (eds.) ICCSA 2014. LNCS, vol. 8581, pp. 721–733. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-09150-1_53