Biological Sciences

An evaluation of the relationships between the duration of red tide (*Karenia brevis*) blooms and watershed nitrogen loads in southwest Florida (USA)

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Abstract Harmful blooms of the marine dinoflagellate *Karenia brevis* form over the West Florida Shelf in the Gulf of Mexico and can be transported toward the coast of southwest Florida by currents and winds nearly annually. Once on the coast, blooms can be intensified by multiple factors including anthropogenic land-based nitrogen loads. This study investigates the relationship between two management endpoints: land-based nitrogen loads and the duration of red tide events. For the purposes of this effort, a red tide event was defined as a period exhibiting maximum daily *K. brevis* cell counts $>$100,000 cells/L or $>$10,000 cells/L for at least 30 days within the study area—between Estero Bay and Sarasota Bay—and considered total nitrogen (TN) loads from the Myakka, Peace (inclusive of Horse Creek and Joshua Creek), and Caloosahatchee Rivers occurring within $\pm$30 days of the onset of red tide events. TN loads from the Caloosahatchee River exhibited statistically significant correlations with red tide event duration (under both definitions of a red tide event) whereas TN loads from the Peace and Myakka Rivers did not exhibit such correlations. The results suggest that policy and management efforts to reduce nitrogen loading may substantially reduce the duration of red tide events in southwest Florida.

Keywords Caloosahatchee River, Lake Okeechobee, nitrogen, eutrophication, harmful algal blooms (HABs)

Introduction

Harmful *Karenia brevis* blooms, known colloquially as red tides, occur nearly annually along the southwest Florida coastline (Liu et al. 2016, Medina et al. 2022). The organism, a marine dinoflagellate, produces a neurotoxin (brevetoxin) that negatively affects ecological systems via bioaccumulation, wildlife mortality, and hypoxia (Anderson et al. 2021, Milbrandt et al. 2021). In addition, blooms can result in hospitalizations following consumption of contaminated shellfish (and other seafood species) or inhalation of aerosolized brevetoxin, which can be transported up to several kilometers inland (Kirkpatrick et al. 2004, Fleming et al. 2005, Watkins et al. 2008). These ecological and public health impacts translate into substantial economic losses in the regional

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economy, including the tourism, recreation, fishing, and real estate sectors (Bechard, 2021, Court et al. 2021).

Earlier studies indicate that coastal *K. brevis* blooms are driven by a complex combination of naturogenic and anthropogenic processes (Steidinger, 2009, Heil et al. 2014, Medina et al. 2022), as with other harmful algal blooms (HABs) throughout the world (Anderson et al. 2012, Foulon et al. 2019, Anderson et al. 2021). *K. brevis* blooms initiate offshore over the West Florida Shelf (Gulf of Mexico) and are transported toward the coast under suitable atmospheric, biological, and physical oceanic conditions (Steidinger, 2009, Heil et al. 2014, Weisberg et al. 2019). If a bloom arrives near the coast, a variety of nutrient sources may contribute to its maintenance and intensification, including re-mineralized nutrients liberated by the mortality of fish and other fauna (due to brevetoxin), fluxes of benthic nutrients, and anthropogenic riverine inputs from developed watersheds (Walsh et al. 2006, Heil et al. 2014, Medina et al. 2020, 2022).

The influence of land-based nutrient loads on *K. brevis* blooms is particularly relevant to mitigation efforts, because nutrient management is one of only a few levers of control available, and earlier studies have linked anthropogenic nutrient loading to *K. brevis* bloom development along Florida's southwest coast. An analysis of sediment cores estimated that nitrogen inputs to Charlotte Harbor increased threefold between 1800 and 2000, due to population growth and associated land use intensification (Turner et al. 2006). Brand and Compton (2007) observed that *K. brevis* abundance and bloom duration increased between 1954 and 2002 and hypothesized that the increase is partially attributable to land-based nutrient loads, particularly from the Caloosahatchee River. Indeed, subsequent studies have estimated that anthropogenic nutrient loads can contribute substantially to the nutrient requirements of coastal *K. brevis* blooms (Vargo, 2009, Heil et al. 2014) and found that nitrogen loading from the Caloosahatchee River plays a consistent role in their intensification (Medina et al. 2020, 2022).

Successfully mitigating anthropogenic nutrient loading as a driver of *K. brevis* bloom maintenance and intensification will require quantification of this link. This study frames the question of anthropogenic influence in practical terms by investigating the relationship between two management endpoints: the duration of *K. brevis* blooms and land-based nitrogen loads from gaged river basins. Specifically, it was hypothesized that bloom duration would exhibit a detectable correlation with nitrogen loads delivered from the gaged basins of the Caloosahatchee, Peace, and Myakka Rivers (Figure 1).

Materials and Methods

Study area. The study area comprises the southwest Florida (USA) coast from Estero Bay north to Sarasota Bay, including Charlotte Harbor. Gaged basins that drain to this section of the coast include the Peace River (and its tributaries Joshua Creek and Horse Creek), Myakka River, and Caloosahatchee River (Figure 1). Discharges from the Peace and Myakka Rivers are unregulated, whereas discharges from the Caloosahatchee River are regulated at the S-79 flow control structure. Discharges from S-79, operated by the U.S. Army Corps of Engineers, include runoff from the non-tidal Caloosahatchee River basin as well as discharges from Lake Okeechobee and its upstream Kissimmee River basin (Rumbold and Doering, 2020, Montefiore et al. 2024). Discharges from Lake Okeechobee are also released east to the Atlantic coast via the St. Lucie River.

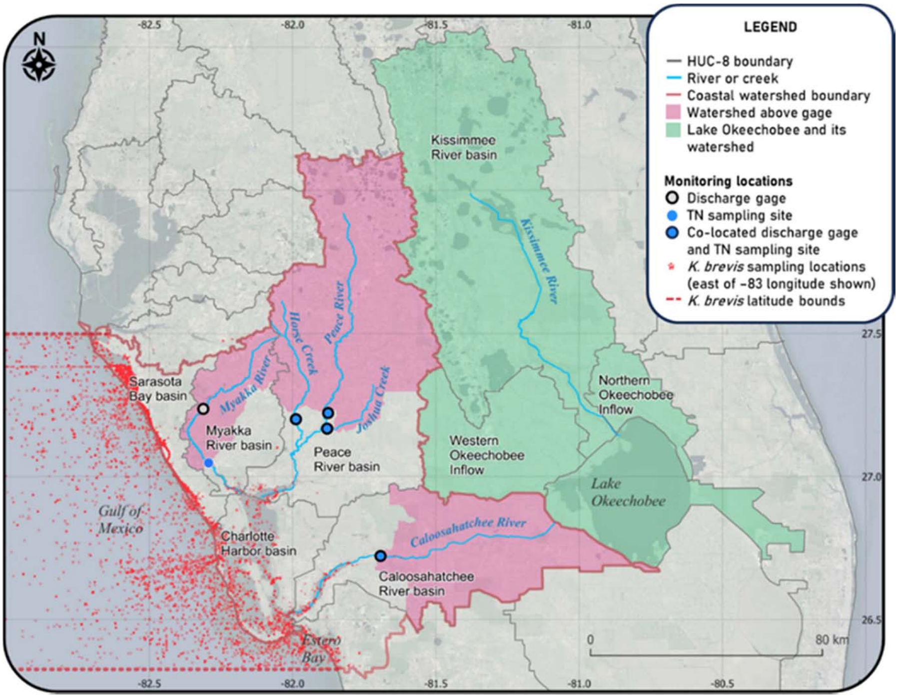

Figure 1. The Southwest Florida coast and gaged watersheds included in the study. Stream gages and water quality sampling sites are shown as circles. Gaged watershed areas are shown in pink. Lake Okeechobee and the Kissimmee River watershed are shown in green. *K. brevis* cell count data (red dots) used in this study were restricted to locations between latitudes 26.33° north and 27.50° north (red dashed lines).

Identification of red tide events. *K. brevis* cell count data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Harmful Algal Bloom Observing System (HABSOS) for the eastern Gulf of Mexico within latitude bounds 26°19′36″ N (Estero Bay) and 27°29′53″ N (Sarasota Bay) between 2007 and 2023 (Figures 2 and 3). The *K. brevis* sampling design includes both routine and event-based sampling. Samples are typically collected on weekdays, with multiple samples collected throughout the study area per day, and less frequently on weekends.

Although cell counts of 5000 cells/L trigger closures of shellfish harvesting and may cause respiratory irritation (Stumpf et al. 2022), the start and end of a "red tide event" is not well defined. We therefore analyzed the load-duration relationship under two definitions of an event (henceforth referred to as "Thresholds") to test the robustness of the results to the definition:

Thresholds 1. Maximum daily cell count >100,000 cells/L for 30 or more days.
Thresholds 2. Maximum daily cell count >10,000 cells/L for 30 or more days.

For each Threshold, a one-week buffer period was allowed to avoid the problem of artificially separating a single event into multiple events due to a short intervening period of lower recorded cell counts or a short-term lapse of sampling effort. For instance, under Threshold 1, if maximum daily cell counts exceeded 100,000 cells/L for 20 days, then fell below the threshold for five days (or if samples were not collected for five days) before exceeding 100,000 cells/L for another 20 days, this would be considered a single 45-day event, rather than two 20-day events separated by five days.

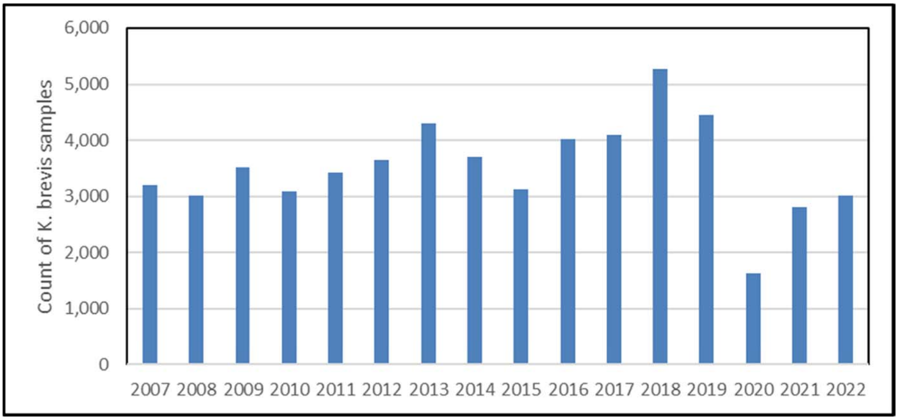

Figure 2. Number of *K. brevis* samples available within the study area per calendar year (NOAA-HABSOS).

Estimation of hydraulic and total nitrogen loads. Monthly hydraulic loads at each stream gage were determined by summing the daily discharge values at the Peace River, Horse Creek, Joshua Creek, Myakka River, and Caloosahatchee River gages (Table 1). Discharge data were obtained from the U.S. Geological Survey National Water Information System (see gage locations in Figure 1). For the Myakka River, the discharges were prorated to a larger contributing area further downstream (to coincide with the water quality sampling site) and discounted with a 10% reduction to account for the diversion of runoff to Roberts Bay and the Venice Inlet via the Blackburn Canal (Hammett, 1990).

Monthly total nitrogen (TN) loads were estimated as the product of monthly hydraulic loads and monthly averaged TN concentrations at corresponding monitoring sites. TN concentration data, typically available on a monthly timestep, were obtained from the Southwest Florida Water Management District, Sarasota County, Lee County, and the Florida Department of Environmental Protection (Table 1). TN sampling sites are co-located with USGS gages on the Peace River, Horse Creek, Joshua Creek, and

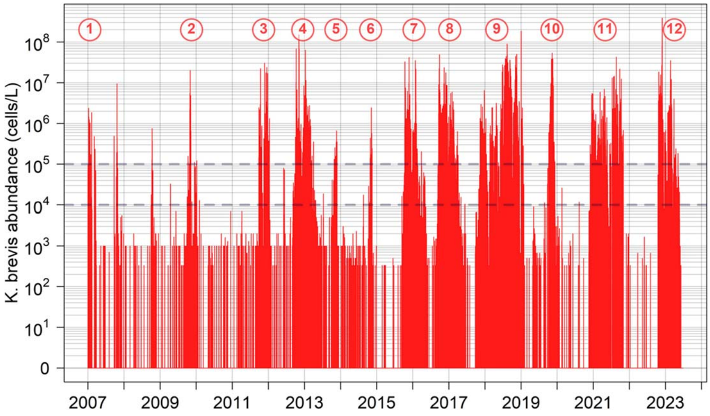

Figure 3. Maximum daily *K. brevis* cell counts. The dashed lines indicate the two cell count Thresholds used to define red tide events (10,000 cells/L and 100,000 cells/L). Event numbering (red) is consistent with Table 2.

Table 1. Sources of discharge and TN concentration data.

Basin	USGS Stream Gage	Stream Gage Period of Record	TN Station(s)	TN Period of Record
Myakka River	02298830	09/01/1936 - 12/31/2022	SC MY4	02/24/1998 - 10/10/2007
			SC MY-E	11/25/2007 - 11/13/2021
Peace River	02296750	4/1/1931 - 12/31/2022	FDEP 3556	10/8/1998 - 09/12/2022
Horse Creek	02297310	5/1/1950 - 12/31/2022	SWFWMD 24029	08/05/1997 - 11/03/2021
Joshua Creek	02297100	5/1/1950 - 12/31/2022	SWFWMD 24431	07/07/1998 - 11/03/2021
Caloosahatchee River	02292900	03/30/1953 - 12/31/2022	CES01SUR	04/08/1999 - 12/07/2022
			FDEP 3568	04/29/1999 - 11/2/2022

Caloosahatchee River (Figure 1). The Horse Creek and Joshua Creek sites provided only bimonthly data after 2011 and no data in 2015. In these cases, the missing monthly TN values were replaced with the average TN concentration values for the corresponding month from the period of record.

Relationships between total nitrogen loads and red tide event duration. TN loads associated with each red tide event were based upon the monthly TN load estimates 30 days before until 30 days after the initiation of each event. For both Thresholds, three linear regression models were developed to estimate red tide event duration as a function of TN loading (1) for all five gages, (2) for the Caloosahatchee River gage only, and (3) for the four other gages (excluding the Caloosahatchee). While the duration of each red tide event varied, the period of the TN load estimate was held constant to avoid confounding the duration of the load estimates (explanatory variable) with the duration of red tide events (response variable). In addition, analogous regression models were developed for red tide event duration as a function of hydraulic loads. Results were interpreted using a significance level of 0.05. Statistical tests were conducted using the *mgcv* package in R version 4.3.1 (R Core Team, 2023, Wood, 2017).

Results

Red tide events. Depending on the Threshold, up to 12 red tide events were identified within the study area between 2007 and 2023 (Figure 3, Table 2). Under Threshold 1 (>100,000 cells/L), 11 events ranged in duration from 30 days (2013) to 437 days (2017–2019). Under Threshold 2 (>10,000 cells/L), 12 events ranged in duration from 31 days (2014) to 458 days (2017–2019). Days with no available data during events typically occurred on weekends and averaged 23% of days per event. For comparison, weekends represent 29% of all potential days.

Hydraulic and total nitrogen loads. Estimated monthly hydraulic loads and TN loads across the five gages exhibited expected seasonal patterns as well as inter-annual dynamics of a prolonged drought in 2007, very wet years such as 2013, and the influences of Hurricane Irma in 2017 and Hurricane Ian in 2022 (Figure 4a). As suggested by Figures 4a and 4b, hydraulic loads were directly proportional to TN loads. On average, the Caloosahatchee River accounted for approximately 54% of both the total hydraulic load and the total TN load from the five basins.

Red tide event duration and TN loads. Event duration was positively correlated with TN loads aggregated across the five discharge gages and with TN loads at the Caloosahatchee River gage, but duration was not significantly correlated with TN loads aggregated across the four other discharge gages (excluding the Caloosahatchee River). As such, TN loads at the Caloosahatchee gage exhibited the strongest relationship with

Table 2. Red tide event dates and durations, under Thresholds 1 and 2.

Event	Threshold (cells/L)	Start Date	End Date	Duration (days)
1	>10,000	01/02/07	02/09/07	39
	>100,000	01/08/07	02/08/07	32
2	>10,000	10/03/09	01/07/10	97
	>100,000	10/10/09	01/07/10	90
3	>10,000	09/26/11	01/12/12	109
	>100,000	09/26/11	01/12/12	109
4	>10,000	09/07/12	04/24/13	230
	>100,000	10/01/12	04/02/13	184
5	>10,000	10/22/13	11/26/13	36
	>100,000	10/28/13	11/26/13	30
6*	>10,000	10/17/14	11/16/14	31
	>100,000	10/27/14	11/16/14	21
7	>10,000	09/14/15	05/05/16	235
	>100,000	10/12/15	03/29/16	170
8	>10,000	09/09/16	05/03/17	237
	>100,000	09/19/16	04/05/17	199
9	>10,000	10/30/17	01/30/19	458
	>100,000	11/13/17	01/23/19	437
10	>10,000	09/17/19	12/10/19	85
	>100,000	10/09/19	12/10/19	63
11	>10,000	12/01/20	11/02/21	337
	>100,000	12/01/20	11/02/21	337
12	>10,000	10/18/22	05/23/23	218
	>100,000	10/21/22	05/08/23	200

* This event qualifies under Threshold 2 only (>10,000 cells/L).

red tide event duration (Figure 5, Table 3). These results were robust across Thresholds 1 and 2 (100,000 cells/L and 10,000 cells/L, respectively). Similar correlations were observed using hydraulic loads, rather than TN loads, as the explanatory variable (Figure 6, Table 3), suggesting that hydraulic loads may serve as a suitable surrogate for TN loads as a predictor of event duration.

Discussion

Earlier studies have demonstrated that offshore ocean physics plays a fundamental role in the development and shoreward transport of *K. brevis* blooms (e.g., Weisberg et al. 2019). Indeed, the Loop Current position is predictive of the incidence of red tide events (Liu et al. 2016, Weisberg et al. 2016). If blooms are transported to near-shore waters along the southwest coast of Florida, a variety of nutrient sources can contribute to their growth and maintenance, including but not limited to benthic flux, N_2 fixation, riverine inputs, and nutrient recycling (Vargo, 2009, Heil et al. 2014). Among these, nitrogen inputs from the Caloosahatchee River and Lake Okeechobee have exhibited a persistent influence on the temporal dynamics of coastal blooms (Medina et al. 2020, Medina et al. 2022, Phlips et al. 2023), with nitrogen inputs observed at S-79 exhibiting delayed effects on *K. brevis* abundance (Medina et al. 2022). Potential delay mechanisms include re-mineralization of

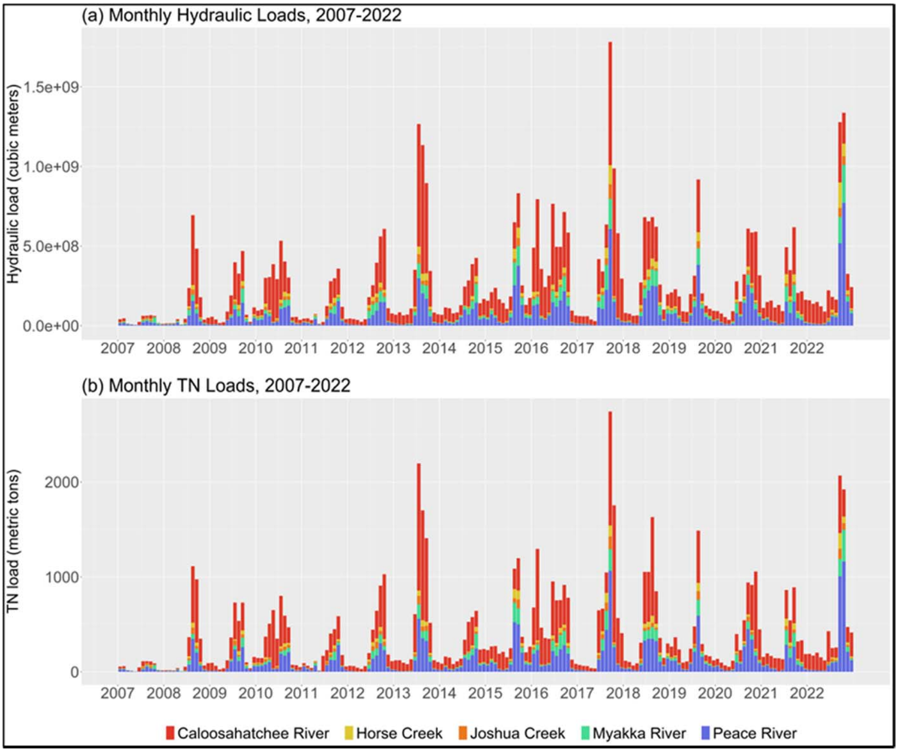

Figure 4. Monthly (a) hydraulic loads and (b) TN loads from the five gaged river basins, 2007–2022.

nitrogen from decomposing biomass, including wildlife mortality caused by brevetoxin (Bronk et al. 2014, Killberg-Thoreson et al. 2014), *K. brevis* grazing on picoplanktonic cyanobacteria (Glibert et al. 2009), N_2 fixation by other phytoplankton species of allochthonous or autochthonous origin (Vargo, 2009, Phlips et al. 2023), and N released by macroalgae, which has exhibited increasing abundance throughout the southwest Florida study area since 2017 (Vargo, 2009, Garcia et al. 2020).

Consistent with earlier work on anthropogenic forcing, the present analysis indicates that Caloosahatchee River (S-79) TN loads occurring within ±30 days of the onset of a red tide event are highly predictive of the event's duration (Figure 5). The straightforward correlation between two management endpoints—anthropogenic TN loading and red tide event duration—should be considered highly relevant to public policy and water resource management.

Between 2007 and 2023, TN loads at the S-79 structure (Caloosahatchee River) accounted for approximately one-half of the total load estimated for the five gaged basins considered in this study (Figure 4), and Lake Okeechobee discharges account for a variable but substantial portion of TN loads at S-79 (Rumbold & Doering, 2020, Montefiore et al. 2024). Indeed, annual TN loads at the S-79 structure exceeded loads from the other gaged basins by approximately a factor of two on an area-normalized basis, due in part to the artificial expansion of the Caloosahatchee watershed to include Lake

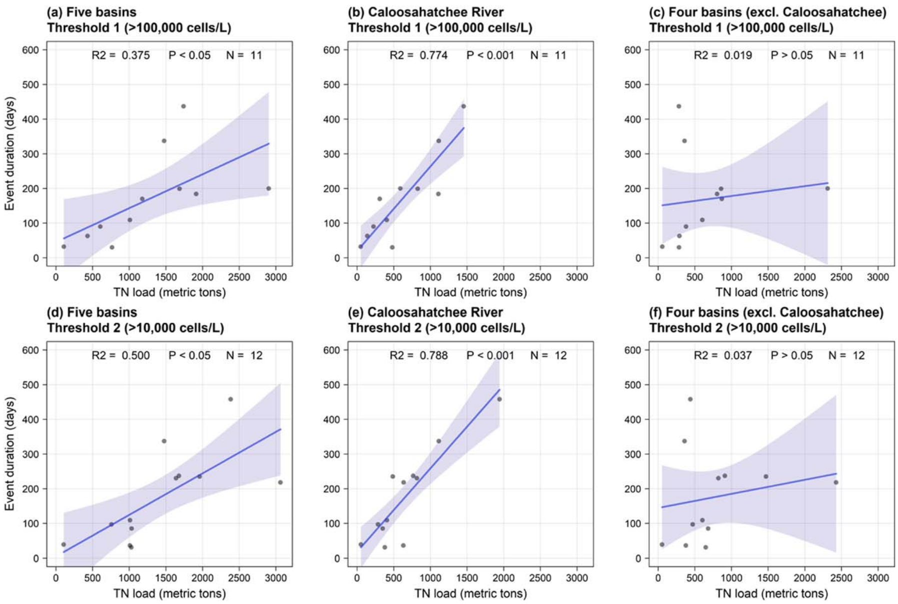

Figure 5. Red tide event duration as a function of TN loads occurring within ±30 days of bloom onset, under Threshold 1 (>100,000 cells/L; *a*, *b*, *c*) and Threshold 2 (>10,000 cells/L; *d*, *e*, *f*). Regressions pertain to loads aggregated across five gaged basins (*a*, *d*), loads at the Caloosahatchee gage (*b*, *e*), and loads aggregated across the four gaged basins excluding the Caloosahatchee (*c*, *f*).

Table 3. Results of regressions of event duration on TN loads and on hydraulic loads, under Threshold 1 (>100,000 cells/L) and Threshold 2 (>10,000 cells/L).

Basin	N	R^2	Slope ±SE	P
Event duration (days) ~ TN load (metric tons)				
Threshold 1 (>100,000 cells/L)				
Five basins	11	0.375	0.098 ± 0.042	P < 0.050
Caloosahatchee basin	11	0.774	0.244 ± 0.044	P < 0.001
Four basins (excl. Caloosahatchee)	11	0.019	0.028 ± 0.068	P > 0.050
Threshold 2 (>10,000 cells/L)				
Five basins	12	0.500	0.120 ± 0.038	P < 0.050
Caloosahatchee basin	12	0.788	0.240 ± 0.039	P < 0.001
Four basins (excl. Caloosahatchee)	12	0.037	0.041 ± 0.066	P > 0.050
Event duration (days) ~ Hydraulic load (km3)				
Threshold 1 (>100,000 cells/L)				
Five basins	11	0.390	146 ± 61	P < 0.050
Caloosahatchee basin	11	0.759	364 ± 68	P < 0.001
Four basins (excl. Caloosahatchee)	11	0.032	54 ± 99	P > 0.050
Threshold 2 (>10,000 cells/L)				
Five basins	12	0.477	171 ± 57	P < 0.050
Caloosahatchee basin	12	0.763	347 ± 61	P < 0.001
Four basins (excl. Caloosahatchee)	12	0.033	56 ± 96	P > 0.050

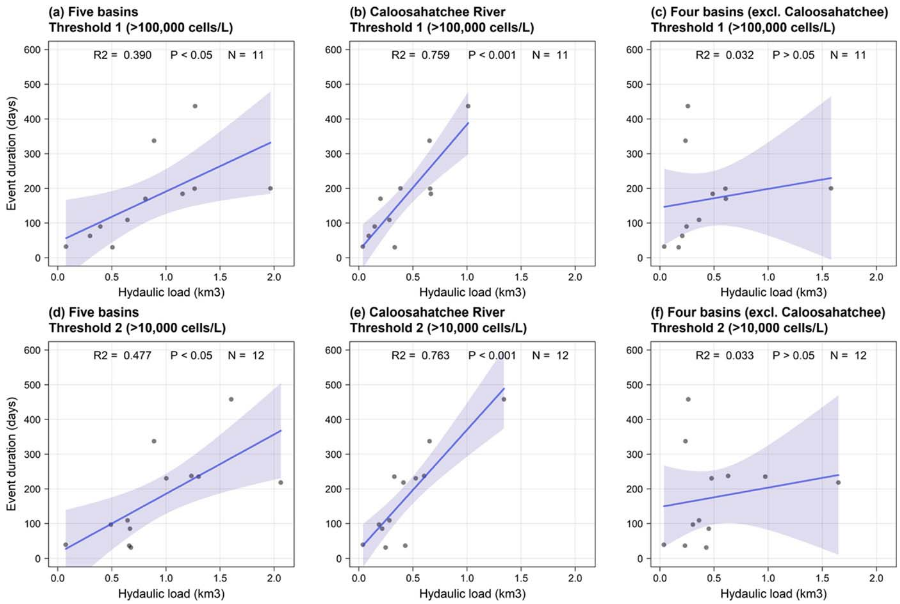

Figure 6. Red tide event duration as a function of hydraulic loads occurring within ±30 days of bloom onset, under Threshold 1 (>100,000 cells/L; *a*, *b*, *c*) and Threshold 2 (>10,000 cells/L; *d*, *e*, *f*). Regressions pertain to loads aggregated across five gaged basins (*a*, *d*), loads at the Caloosahatchee gage (*b*, *e*), and loads aggregated across the four gaged basins excluding the Caloosahatchee (*c*, *f*).

Okeechobee and its watershed (Table 4). In this context, our results suggest that reducing TN loads overall—and particularly those loads originating with the Caloosahatchee River and Lake Okeechobee—may significantly reduce the duration of *K. brevis* blooms along the southwest coast of Florida. Understanding the numerous and evolving management objectives associated with Lake Okeechobee water levels and discharges (USACE 1993, Montefiore et al. 2024), the results bolster arguments for policies that are more protective of Southwest Florida coastal waters and ecosystems as an additional objective (e.g., Phlips et al. 2023, Julian et al. 2024).

Management experience with other southwest Florida estuaries, such as Sarasota Bay and Tampa Bay, have demonstrated that past efforts to reduce anthropogenic nitrogen loads can successfully improve water quality and restore ecological function (Sherwood et al. 2017, Tomasko et al. 2018).

Table 4. Area-normalized TN loads (kg/ha/yr) between 2007 and 2022.

Gage	TN Unit Load (kg/ha/yr)
Myakka River at S.R. 72	5.4
Horse Creek	4.3
Peace River	4.3
Joshua Creek	6.2
Caloosahatchee River	10.7

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