A Marine Harmful Algal Bloom Monitoring Plan for the Coastal Bend of Texas

Final Report

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I. Preface

Harmful algal blooms (HABs) are caused by the proliferation of phytoplankton species that have harmful effects on marine life, ecosystems, human health and coastal economies. Marine waters in Texas have been affected by episodic blooms of *Karenia brevis* ("red tide") for many centuries, although bloom frequency appears to be increasing since the mid-1990's. In recent decades, novel blooms of other HAB species have been observed coincident with localized or, in some cases, large-scale changes in coastal watersheds that create conditions favorable for HAB growth. These changes include land use changes favoring urbanization or agricultural activities that facilitate increased non-point and point source nutrient loads to marine waters, or to the hydrology of estuarine systems because of drought and growing human freshwater demands.

In Texas, HAB sampling efforts by state agencies (Texas Parks & Wildlife Department, TPWD; Texas Department of State Health Services, TDSHS) center on *event response* to blooms, focusing on assessments of impacts on living resources (TPWD) and/or humans via shellfish (TDSHS). This event response-based sampling is by necessity of the mandates that each agency operate under. However, it is not capable of providing early warning of HAB events or of identifying environmental conditions leading to blooms. *Proactive* monitoring for early warning and forecasting purposes is accomplished by automated HAB detection sensors that are limited to three locations along the 367 miles of coastline, emphasizing the likelihood that HABs not in the immediate vicinity of these sensors will be missed. Estuaries are particularly under sampled, especially in the Texas Coastal Bend, where recurring blooms of HAB taxa and the presence of emerging HAB taxa have been documented. Yet estuaries also support waterborne activities (shellfish harvesting, recreational and commercial fishing, tourism) that contribute significantly to local economies. Given regional and local disparities in marine HAB monitoring, as well as concerning trends in potential environmental drivers of HABs, it is imperative that Texas expand monitoring activities, especially for estuarine-dependent taxa.

The goal for this plan is to provide a data-driven prioritization framework for expanded marine HAB monitoring in the Coastal Bend region of the Texas Coast. Once implemented, the monitoring efforts identified in the plan will improve early warning of HABs and facilitate greater understanding of HAB dynamics. The plan is built upon information gained from synthesis of historical marine HAB events and existing sampling efforts, stakeholder input on strengths and weaknesses of these efforts, an economic analysis of sectors most affected by HABs as well as a new analysis of water quality "hot spots" to identify high priority locations for improving HAB monitoring. In the near term, a key outcome of this effort will be ***enhanced mitigation*** of negative impacts from marine HABs on human, environmental and economic health by facilitating greater early warning and increased awareness of the presence of HABs. A longer-term outcome, facilitated by improved understanding of the spatial-temporal distribution of particular HABs and their relationships with environmental drivers, will be an increased likelihood for ***prevention*** of some HABs by reshaping the environment to no longer be conducive for them.

II. Background

a. *What is a harmful algal bloom, and why should we care?*

A harmful algal bloom (HAB) is broadly defined as the proliferation of a phytoplankton species that results in harmful effects on marine life, ecosystems and/or human health. At present, there are ≤ 100 marine HAB species, each of which has unique life histories and mechanism(s) for causing harmful impacts. Some HABs produce toxins that can: 1) cause mortality of fish and other marine life, 2) bioaccumulate in shellfish and cause negative health impacts in humans upon consumption, and/or 3) become aerosolized and cause negative human health impacts (in the case of the Gulf of Mexico "red tide" dinoflagellate, *Karenia brevis*). Not all HAB species are toxic however, as some cause marine life mortalities through depletion of oxygen in the water column, while others are simply a poor food source for fish and shellfish. Regardless of the mode of harmful action, marine HABs have been responsible for devastating negative impacts on local and regional economies, estimated at ~$83 million dollars annually in the United States (year 2000 dollar; ~$126 million in year 2020)(Hoagland et al. 2002).

Large die-off of recreationally- and commercially important fish, Baffin Bay, 2010. Photo credit: Scott Murray.

b. *Global trends in HABs*

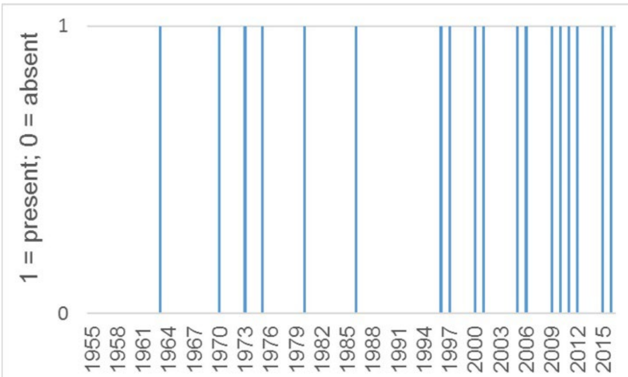
There has been a well-documented trend of increasing marine HAB frequency and/or severity over the past half century (Hallegraeff 1993; Anderson et al. 2012). A variety of factors have been implicated, with increasing nutrient inputs being a primary cause in many cases (Anderson et al. 2008; Heisler et al. 2008). Nutrients, such as nitrogen and phosphorus, are necessary for phytoplankton growth. In marine systems, nitrogen availability is often the main nutrient that limits phytoplankton growth, thus increased nitrogen loads can act to stimulate HAB events (Paerl 1997; Anderson et al. 2002). Human activity in coastal watersheds, including land use change favoring urbanized and/or agricultural land cover, is a major driver of the increased nutrient loadings (Hopkinson and Vallino 1995; Bowen and Valiela 2001; Kaushal et al. 2008). Climate change and associated changes in temperature and precipitation patterns have also been implicated as an emerging driver of HAB formation (Hallegraeff 2010; Najjar et al. 2010; Wells et al. 2015).

c. *HABs in Texas marine waters*

HABs affecting Texas' marine waters can be classified in three categories based on frequency of occurrence: 1) recurring with some degree of frequency, 2) episodic, and 3) emerging but not yet reaching bloom proportion. A brief description of HAB species falling into each category can be found below.

Recurring:
1. Karenia brevis – K. brevis is a dinoflagellate that blooms primarily during late summer-fall. Blooms are believed to begin offshore and are advected into nearshore and estuarine waters

(Hetland and Campbell 2007; Thyng et al. 2013; Henrichs et al. 2015). *K. brevis* produces brevetoxin that causes significant fish kills, shellfisheries closures, marine mammal and seabird mortality, and respiratory and digestive distress in humans (Kirkpatrick et al. 2004; Brand et al. 2012). Magaña et al. (2003) reported that the frequency of *K. brevis* red tides on the Texas coast increased over the period of 1996-2000 compared to earlier years, and a new study by Tominack et al. (in press) suggests that bloom frequency has indeed increased sharply since the mid-1990's compared to an earlier period going back to the 1950's.



Presence or absence of K. brevis bloom in Corpus Christi, showing sharp increase in bloom frequency in recent decades. From Tominack et al. in press.

2. *Aureoumbra lagunensis* – *A. lagunensis*, also known as the Texas "brown tide", is a pelagophyte species that first bloomed in Baffin Bay and the Upper Laguna Madre in late 1989. The bloom subsequently lasted for 7 years (Buskey et al. 2001), and since then, several additional long-lasting blooms have occurred in these systems (unpubl. Texas Parks & Wildlife reports; Wetz et al. 2017). *A. lagunensis* does not produce a toxin, but nonetheless blooms have harmful effects on the ecosystem. For example, during blooms the water turns a brownish color and light penetration is greatly reduced, resulting in seagrass die-off (Onuf 1996; Onuf 2000). Drivers of these blooms are complex, resulting from the combined effects of long residence times, high salinity, and excessive nutrient availability in Baffin Bay and Upper Laguna Madre (Buskey et al. 1997; Wetz et al. 2017; Cira and Wetz 2020).

Aerial view of a "brown tide" bloom in Baffin Bay. Photo source: https://tpwd.texas.gov/landwater/water/environconcerns/hab/brown_tide/

3. *Dinophysis cf. ovum* – In late winter 2008, a bloom of the toxic dinoflagellate *D. cf. ovum* was observed in estuaries of the Texas Coastal Bend for the first time ever (Campbell et al. 2010; Swanson et al. 2010). This organism produces okadaic acid, which can cause diarrhoetic shellfish poisoning in humans upon consumption of contaminated shellfish. Okadaic acid was detected in relatively high concentrations in the tissue of important shellfish species during the bloom, leading to the temporary closure of shellfish beds from Corpus Christi Bay to Matagorda Bay (Deeds et al. 2010). Coincidentally, an "unusual" mortality event involving bottlenose dolphins was also noted during the bloom, and okadaic acid was detected in the gastrointestinal system of the dolphins. Although the specific environmental conditions supporting blooms are unknown, an offshore origin is suggested (Campbell et al. 2010). Since 2008, there have been several additional blooms that have led to shellfish closures.

Episodic:
1. *Pyrodinium bahamense – P. bahamense* is a ubiquitous dinoflagellate in many shallow tropical and subtropical marine ecosystems, including estuaries of the Coastal Bend (M.S. Wetz, unpubl. data). Although most strains are harmless, some strains have been known to produce saxitoxin that is harmful to humans when contaminated fish are ingested (Phlips et al. 2015). To date, there has been no evidence of *P. bahamense*-derived saxitoxin production in Texas. However, a large fish kill occurred in Baffin Bay in 2010 coincident with hypoxia as well as a *P. bahamense* bloom (unpubl. Texas Parks & Wildlife reports). *P. bahamense* has been implicated in low dissolved oxygen events that lead to fish kills elsewhere (e.g., Morrison and Greening 2011), and recent studies suggest that it is typically most competitive under relatively high nutrient conditions (Phlips et al. 2015) such as in Baffin Bay.

Emerging:
Over the past decade, investigator-led sampling efforts have observed previously undetected HAB species in estuaries of the Coastal Bend (Table 1). Fortunately bloom levels have not been observed but changing environmental conditions in these systems may create conditions more conducive to bloom formation in the future.

Table 1. Phytoplankton species of concern observed in estuaries of the Texas Coastal Bend.

Species	**Potential deleterious effects**	**Location(s) where observed**
Prorocentrum minimum	Toxin	Baffin Bay; Corpus Christi Bay; Oso Bay
Prorocentrum texanum	Toxin	Corpus Christi Bay
Akashiwo sanguinea	Toxin; hypoxia	Baffin Bay; Corpus Christi Bay; Oso Bay; San Antonio Bay
Margalefidinium polykrikoides	Toxin; hypoxia	Baffin Bay; Corpus Christi Bay; Oso Bay
Gonyaulax sp.	Some species toxic	Corpus Christi Bay; Oso Bay
Karenia mikimotoi	Toxin	Corpus Christi Bay; Oso Bay
Karlodinium veneficum	Toxin	Corpus Christi Bay; Oso Bay
Kryptoperidinium foliaceum	Toxin; hypoxia	Baffin Bay; Oso Bay
Alexandrium monilatum	Toxin	Baffin Bay; Corpus Christi Bay
Chattonella subsalsa	Toxin; hypoxia	Baffin Bay; Corpus Christi Bay; Oso Bay; San Antonio Bay
Fibrocapsa japonica	Toxin	Corpus Christi Bay
Chloromorum toxicum	Toxin	Baffin Bay; Oso Bay
Pseudonitzschia sp.	Toxin	Baffin Bay; Corpus Christi Bay; Oso Bay; San Antonio Bay

III. Overview of marine HAB sampling efforts in Texas

Marine HAB sampling efforts in Texas are undertaken by three entities: 1) Texas Parks & Wildlife Department (TPWD), 2) Texas Department of State Health Services (TDSHS) and 3) individual university researchers. A brief description of each can be found below. In addition, early warning of *K. brevis* blooms is provided by NOAA's National Ocean Service through a weekly bulletin to stakeholders. Detection is based on satellite observations of water column pigments with optical characteristics of pigments specific to *K. brevis*.

TPWD: The TPWD Kills & Spills Team initiates sampling under three scenarios. First, reports of discolored water will lead to a TPWD investigation. If investigators determine that the discolored water is not related to a pollution source, a sample is then collected to verify a bloom. Secondly, TPWD will investigate upon receiving reports of a fish kill. If investigators suspect that a HAB is the cause, a sample is collected to verify a bloom. In both scenarios (discolored water, fish kill), if a HAB is identified, TPWD notifies state partners. The final scenario that may lead to initiation of sampling by TPWD arises when the agency receives reports of a bloom event via Imaging FlowCytobots (IFCB), NOAA bulletins, or other sources. Sampling may occur prior to fish kills to verify extent of the bloom. Once a fish kill begins, efforts are shifted to fish kill assessment. Bloom sampling is not uniform across the state and is generally based on regional preference, skillset, and partnerships.

TDSHS: The following information is synthesized from TDSHS's 2019 Contingency Plan for the Control of Marine Biotoxins, which primarily focuses on two HAB species, *K. brevis* and *D. cf. ovum*. The TDSHS initiates sampling based on reports from the public, partner agencies, individual researchers, or IFCB detection of a HAB. If a HAB is confirmed, TDSHS will coordinate with TPWD on sampling. TPWD will conduct flyovers to assess the extent and movement of the bloom and to survey fish or other species affected, while TDSHS plots the movement of the bloom from the water and collects water samples to confirm cell count densities. The number of water samples and frequency of collection will be based upon the size of the affected area. If water samples indicate that cell concentrations of either *K. brevis* or *D. cf. ovum* exceed 5000/liter, all adjacent shellfish growing areas will be closed to harvesting. TPWD, regional and local health officials, harvesters and the general public are immediately notified of closures. After an area has been closed, collection of water to monitor cell densities will continue at a number and frequency that is reflective of the size of the affected areas. When water samples show cells less than 5000/liter, both water samples and shellfish tissue samples are collected. If a second round of water samples confirms that no cells are present, the shellfish tissue samples are prepared for mouse bioassay testing. Procedures for shellfish toxin bioassays are outlined in Recommended Procedures for the Examination of Seawater and Shellfish, 4th Edition, (APHA, 1970). If the second round of water samples contain cells, collection of water samples will continue, and the tissue samples discarded. Water sampling and tissue analysis will then continue until no cells are present. When samples from all key locations meet defined criteria, the area is reopened to harvesting.

It is important to note that both sampling programs center on *event response* to blooms. This event response-based sampling is, by necessity of the mandates that each agency operate under, focused on assessment and protection of immediate threats to environmental and/or human health. However, it is not capable of providing early warning of HAB events or of identifying environmental conditions leading to blooms. Only s*ustained, proactive* monitoring can do this.

Individual researchers: In Texas, *sustained, proactive* HAB monitoring is accomplished by real time or quasi-real time automated sampling and by discrete sampling programs run by individual investigators. The automated sampling relies on four IFCBs, operated by Texas A&M University researchers and deployed at or near ocean inlets on the north (Surfside Beach, Galveston Bay) and central (Port Aransas) Texas coast, with the Port Aransas site being the only one in the Coastal Bend. The IFCBs detect and quantify phytoplankton/HABs in real time and facilitate early warning notifications to the aforementioned agencies and interested stakeholders. Examples of their utility comes through warnings of impending blooms of *K. brevis* and *D. cf. ovum* (Campbell et al. 2010; Campbell et al. 2013). High costs to purchase and maintain these instruments have hindered their wider adoption, leaving Texas with just these four instruments to cover 367 miles of coastline. This approach misses large regions of the Texas coast, especially within estuaries. Hence, estuarine-dependent HABs such as *A. lagunensis* and nearly all of the emerging species noted above are not covered by the current monitoring. Aside from the limited spatial coverage, *A. lagunensis* and smaller HAB species would fall outside of the lower size range of detection of the IFCB, thus its deployment would not be appropriate in some locations where smaller HABs occur.

Sustained discrete monitoring by individual researchers occurs in Galveston Bay (Dr. A. Quigg, TAMU-Galveston), Copano Bay (Dr. E. Buskey, UT Marine Science Institute) and Baffin Bay (Dr. M. Wetz, TAMU-Corpus Christi). Each program varies in the frequency, spatial extent and water quality/phytoplankton variables of interest that are sampled for. When coupled with collection of data on relevant factors affecting growth of HABs, over time these programs have the ability to elucidate drivers of blooms. Nonetheless, as with IFCBs, there is an expense necessary to support ongoing sampling. Furthermore, sampling may not be frequent enough to capture some bloom events.

Given the regional and within-system disparities in HAB monitoring, as well as concerning trends in potential environmental drivers of HABs (see Chapter V), it is imperative that Texas expand monitoring activities, especially for estuarine-dependent taxa. ***The goal for this plan is to provide a data-driven framework for expanded HAB monitoring in the Coastal Bend region of the Texas Coast.***

IV. Plan development

Development of the Texas Coastal Bend HAB monitoring plan was guided by knowledge acquired from five sources: 1) assessment of literature and investigator-derived information on HABs in the region, 2) stakeholders that routinely deal with HAB-related issues , 3) assessment of historic coastal fish kills, 4) assessment of economic impacts from HABs in the Coastal Bend, and 5) analysis of water quality trends on the Texas coast. A description of the HABs of concern was included earlier (see section II.c), and a brief summary of the latter four approaches is provided below.

Stakeholder input – In 2019, stakeholders were posed a series of questions that addressed which impact(s) from HABs concerned them the most, strengths-weaknesses-opportunities-threats of/to current marine HAB monitoring efforts, and stakeholder perception of particular areas that need additional attention from a HAB monitoring standpoint. Results were collated and assessed for commonality of responses, as well as consistency with results from the other sources of information.

Coastal fish kill assessment – At the time that this plan was assembled, fish kill records were not readily accessible and required a FOIA request. Instead, results from a comprehensive study of 55 years of coastal fish kills (Thronson and Quigg 2008) were utilized. Those findings were more than adequate for determining regions displaying a propensity for fish kills, as well as potential drivers.

Economic impact assessment – The potential economic impact of red tides on the accommodations and food services sectors of the Coastal Bend was assessed empirically. Red tide occurrence in individual regions (Mission-Aransas Bay, Nueces-Corpus Christi Bay, coastal waters of Padre Island, Upper Laguna Madre) was compared with economic data from these sectors. Red tide events in those locations are expected to potentially affect their nearby communities. Linear regression models were applied to estimate the economic impact of red tide events. The monthly sales volume of the accommodation and food services sector were the dependent variable in all models.

Water quality trend analysis – Bugica et al. (2020) recently analyzed a multidecadal water quality dataset, obtained from the Texas Commission on Environmental Quality's (TCEQ's) Surface Water Quality Monitoring (SWQM) program. This program collects water samples on a quarterly basis from all estuaries on the Texas coast. Findings provided information on trends in an indicator of algal biomass (chlorophyll *a*) as well as potential environmental drivers of algal growth.

V. Findings from data sources supporting HAB plan development

a. *Stakeholder input*

Respondents pointed to two key <u>strengths</u> of marine HAB monitoring in Texas: 1) TPWD's ability to rapidly respond to HAB events anywhere on the Texas coast, and 2) the network of IFCB's that offer real-time detection. Multiple respondents pointed to a general lack of routine monitoring as the main <u>weakness</u>, along with the limited spatial coverage of the IFCB network. In particular, respondents felt stronger focus was needed on routine monitoring in estuaries, which hold substantial economic and ecological value as habitat for many important fish and shellfish species and which are often closest to population centers where exposure risk to HABs would be greatest. To close gaps in the spatial coverage of HAB monitoring, several respondents suggested exploring <u>opportunities</u> to partner with entities such as aquaculture facilities and/or ports to co-locate and integrate HAB detection equipment with their operations. Other respondents highlighted the rapidly advancing field of HAB sensor development as an <u>opportunity</u> to lower costs that would otherwise be associated with manpower/field time-intensive sampling. Finally, the most prominent <u>threat</u> to ongoing marine HAB monitoring efforts was a general lack of state funding for ongoing monitoring efforts, and no clear funding pathway for expansion of monitoring.

b. *Coastal fish kill observations*

Thronson and Quigg (2008) provide a thorough evaluation of historic fish kills from the period of 1970-2006. For the decade from 1995-2006, Matagorda Bay had the largest cumulative total of fish kills, with most of these due to low dissolved oxygen events. The Laguna Madre (Upper & Lower combined) had the second largest total of dead fish reported, which were attributed to a freeze and also low dissolved oxygen events. Other estuaries of the Coastal Bend had cumulative totals of dead fish that were an order of magnitude lower than the aforementioned systems, although ephemeral high impact fish kills were observed and were attributed to a variety of factors.

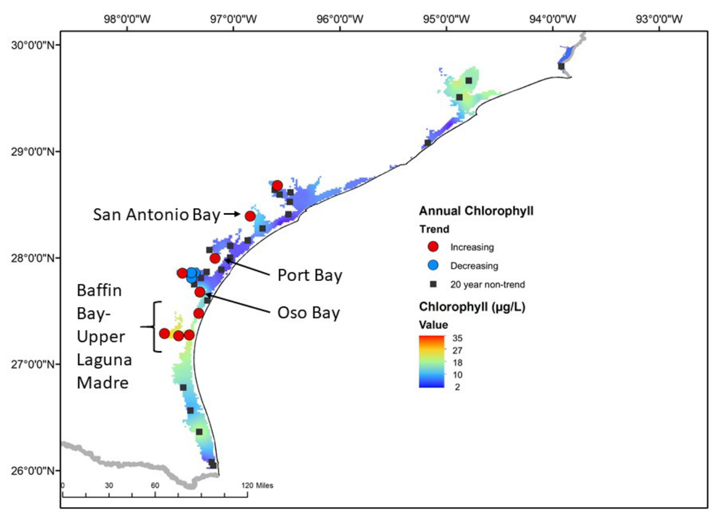
c. *Economic impact assessment*

Sales activity in accommodation and food services declined by 1-10% during a month in which red tide occurred, suggesting that tourism in general was negatively impacted. The greatest impact appeared to be on Port Aransas as compared to other regions of the Coastal Bend. These findings are consistent with a study conducted on a 2000 red tide bloom in Galveston (Evans and Jones 2001), which found that the tourism and commercial shellfishing sectors were most affected by the bloom. They are also consistent with studies from Florida, which have shown that the commercial shellfisheries, tourism and the seafood industry are most negatively affected by red tides (reviewed by Backer 2009). Negative impacts from other (non-red tide) HAB species in Texas are suspected, especially from *A. lagunensis*, but to date no economic analyses have been conducted. This should be a future priority.

d. *Water quality trend analysis*

Many coastal watersheds in Texas have experienced rapid population growth and urbanization over the past 2-3 decades, while others have a significant imprint from agricultural activities. Increasing non-point and point source nutrient loads from these coastal watersheds have been documented (e.g., Montagna & Palmer 2012; Bugica et al. 2020). This can lead to a phenomenon known as eutrophication, whereby increased nutrient loads from watersheds stimulate algal (including HAB) growth and other symptoms such as hypoxia and fish kills in estuarine and coastal waters (Bricker et al. 2008).

From the analysis of Bugica et al. (2020), symptoms of eutrophication in the Coastal Bend region were most clearly pronounced in Baffin Bay-Upper Laguna Madre and Oso Bay. Baffin Bay has experienced a long-term increase in chlorophyll and recurring blooms of *A. lagunensis* (Wetz et al. 2017), as well as other symptoms of eutrophication. In addition, several HAB taxa other than *A. lagunensis* have been observed in Baffin Bay in recent years (Table 1). Stakeholder-led efforts are now underway to find solutions aimed at reducing nutrient loadings to the bay. Oso Bay is subjected to significant loadings from municipal wastewater facilities and displays high nutrients, chlorophyll and presence of several HAB taxa has been documented (Wetz et al. 2016; Wang et al. 2018; Wetz unpubl. data).



Long-term trends in chlorophyll, an indicator of algal biomass. Red dots indicate increasing chlorophyll. From Bugica et al. 2020.

Aside from these bays, long-term increases in chlorophyll were observed in Port Bay (a tributary of Copano Bay) and upper San Antonio Bay adjacent to Austwell, Texas.

VI. Texas Coastal Bend HAB monitoring plan

The following recommendations utilize the aforementioned data sources to prioritize needed additions to existing marine HAB monitoring, thereby addressing weaknesses identified by stakeholders such as the need for routine monitoring and increased spatial coverage of monitoring. In addition, several recommendations take advantage of potential collaborative opportunities to add HAB monitoring capabilities in high priority (from an ecological, economic, or human health standpoint) regions that have been ignored in the past, but currently face stresses imposed from external sources.

To summarize, priority consideration is recommended to expanding HAB monitoring capabilities in: 1) Baffin Bay-Upper Laguna Madre due to clear eutrophication pressures, history of prolonged HABs, and its economic/ecological importance (e.g., Jones and Tanyeri-Abur 2001), and 2) Corpus Christi Bay due to its history of *K. brevis* blooms and the apparent increase in their frequency, as well as proximity to dense population centers and economically-important industries that rely on clean water. Secondary consideration should be given to: 1) San Antonio Bay, which is showing localized signs of eutrophication and presence of emerging HAB species, and is habitat for some large oyster reefs, 2) Oso Bay, a portion of which is highly eutrophic, has a number of emerging HAB taxa present, and supports important bird and fish populations, and 3) Port Bay, which is a tributary of Copano Bay that is displaying symptoms of eutrophication and has a rapidly industrializing watershed, and which also supports seagrass and important fish populations.

Baffin Bay-Upper Laguna Madre

Background - Baffin Bay is often regarded as the "jewel" of the Texas coast because of its ability to support renowned recreational and commercial fisheries, while the adjacent Upper Laguna Madre supports extensive seagrass beds that are critical fisheries habitat. Considering the substantial evidence that these systems are undergoing eutrophication and regularly experience HAB events, additional attention is needed on water quality and HAB monitoring in them.

Existing sampling - There are two stations in Baffin Bay and on station in the Upper Laguna Madre that are visited on a quarterly basis as part of the Texas Commission on Environmental Quality's water quality monitoring program. Data from these sites have been invaluable for assessing long-term trends in water quality conditions (see e.g., Palmer and Montagna 2010; Bugica et al. 2020) and every effort should be made to maintain the sampling at those stations. In addition, researchers at Texas A&M University-Corpus Christi (TAMU-CC) have sampled monthly at six sites in Baffin Bay since May 2013. Results from this program have guided stakeholder-led efforts aimed at reducing nutrient loads (e.g., Wetz et al. 2017) and have led to improved understanding of nutrient-phytoplankton dynamics in the system (Cira and Wetz 2020; Cira et al. in review). At each site, vertical profiles are performed and discrete surface and near-bottom samples collected.

Recommendations – The recommendations for Baffin Bay-Upper Laguna Madre center on increasing spatial-temporal coverage of sampling efforts. They include:

- Initiation of HAB sampling in the Upper Laguna Madre, where no sampling currently takes place. Sampling should overlap with the TCEQ sampling station to facilitate a broader perspective on water quality conditions. New sampling in the Upper Laguna Madre is justified by the historic presence of *A. lagunensis* blooms as well as evidence of nutrient pressures as noted by Bugica et al. (2020). In the near term, monthly sampling is likely sufficient to achieve a base-level understanding of HAB presence and frequency.
- Increased temporal coverage of sampling in Baffin Bay. At present, the impact of short-term weather events that can trigger HABs, as well as the cause of many fish kills in Baffin Bay, cannot be determined due to low frequency of sampling. In addition, uncertainty still remains in terms of temporal relationships between *A. lagunensis* and relevant environmental drivers. Options for addressing these challenges include increasing the frequency of ongoing sampling from monthly to biweekly and/or deployment of automated water quality (salinity, temperature, dissolved oxygen) and HAB sensors at strategic locations in Baffin Bay. The IFCB is not sufficient for detection of *A. lagunensis* because of its small size. However, the recently developed Cytosense imaging flow cytometer appears promising for this purpose (Haraguchi et al. 2017). A strategic location for the deployment of automated sensors would be TAMUC-CC site 3 in western Baffin Bay. This site is part of ongoing discrete sampling efforts and is also near the mouth of the Laguna Salada, which appears to be a reservoir for *A. lagunensis* and other HABs (Cira and Wetz 2020; Cira et al. in review).

Approximate costs:
Biweekly discrete sampling: $125,000/year
Addition of an Upper Laguna Madre discrete sampling site: $10,000/year
Automated sensor deployment: $200,000 (one-time cost), $5,000-10,000/year maintenance

Map of Baffin Bay-Upper Laguna Madre showing existing sampling stations.

Table 2. Description of ongoing or proposed monitoring programs in Baffin Bay-Upper Laguna Madre.

Discrete (TCEQ)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic & organic nutrients	Quarterly
Discrete (TAMU-CC)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic nutrients, dissolved & particulate organic carbon/nitrogen, phytoplankton abundance & taxonomic composition	*Currently:* Monthly *Proposed:* Biweekly
Proposed (TAMUCC Site #3): Automated sensors	Hydrolab or YSI sondes coupled w/ automated phytoplankton detection sensor; Salinity, temperature, pH., D.O., chlorophyll fluorescence, phytoplankton abundance and identification	Continuous, real-time

Corpus Christi Bay

Background - Corpus Christi Bay contains several popular beaches and supports a variety of waterborne recreational activities, particularly on its southern shoreline. It is worth noting that a large oyster hatchery is in the design phase for placement near the juncture of Nueces and Corpus Christi Bay, and a desalination plant has been proposed in the Inner Harbor of Corpus Christi Bay.

The watershed encompasses densely urbanized lands including the Corpus Christi (population ca. 325,000) and Portland (population ca. 17,000). Despite the potential pressures associated with this urbanization, Bugica et al. (2020) did not observe indications of widespread water quality degradation. However, Tominack et al. (in press) recently documented a long-term increase in the frequency of *K. brevis* blooms. A significant challenge is obtaining data to verify the spatial extent of blooms, which are often patchy in nature. This information would facilitate greater public confidence in the safety of specific regions of the bay when a bloom is occurring (i.e., by lessening any "halo" effect whereby a bloom in one area leads to loss of public confidence in another area). It will also prove valuable to the proposed oyster hatchery and desalination plant. Aside from *K. brevis*, the presence of several emerging HAB taxa has been noted (Table 1).

Existing sampling - At present, TCEQ conducts quarterly water quality sampling at five locations in Corpus Christi Bay. In addition, the Mission-Aransas National Estuarine Research Reserve (NERR) has a station on the Corpus Christi Ship Channel where they collect discrete and continuous water quality measurements. An IFCB is also located on the Ship Channel.

Recommendations – Because of the increasing frequency of *K. brevis* blooms as well as the presence of emerging HABs, it would be advantageous to add additional HAB monitoring capabilities to characterize the spatial extent of blooms. The following recommendations are put forth:

- Deploy an IFCB in the upper estuary, possibly co-located with the proposed oyster hatchery or desalination facility. Because of the necessary benefits to each facility, it is conceivable that a mutually beneficial partnership could be developed that provides sustained support for the IFCB. Another option would be to deploy an IFCB and other water quality sensors on a Port of Corpus Christi tugboat, which would provide for much greater spatial coverage of HAB detection. This would be akin to the FerryMon program (http://paerllab.web.unc.edu/projects/ferrymon/), which is a university-state agency partnership whereby passenger ferries are outfitted with sensors for continuous, high spatial resolution mapping of water quality.

Approximate costs:
Additional IFCB deployment: $150,000 (one-time cost), $5,000-10,000/year maintenance

Map of Corpus Christi Bay showing existing and proposed sampling stations.

Table 3. Description of ongoing or proposed monitoring programs in Corpus Christi Bay.

Discrete (TCEQ)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic & organic nutrients	Quarterly
Discrete (NERR)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic nutrients	Monthly
Continuous (NERR)	Salinity, temperature, pH, D.O.	Continuous
IFCB	Phytoplankton abundance & taxonomic composition	Continuous, real-time
Proposed: 2nd IFCB	Phytoplankton abundance & taxonomic composition	Continuous, real-time

San Antonio Bay

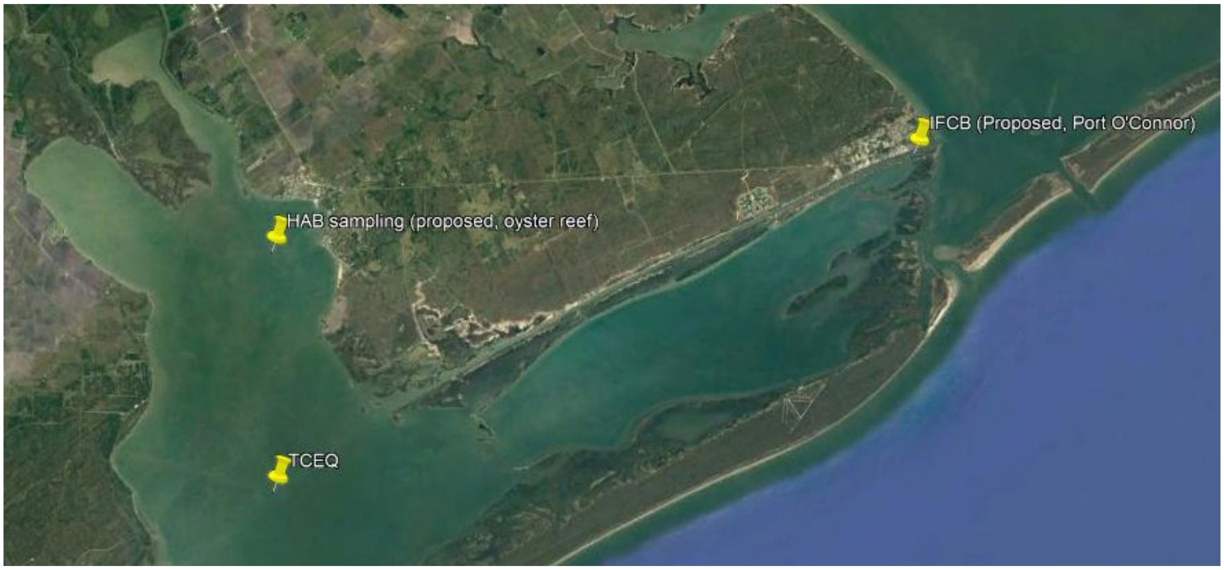
Background - San Antonio Bay supports extensive oyster reefs as well as recreational and commercial fishing opportunities. Although symptoms of water quality degradation are not widespread, there is some evidence of eutrophication in the upper reaches of the bay (Bugica et al. 2020). In addition, several emerging HAB taxa have been documented in the system, and it has been affected by previous *Dinophysis* blooms.

Existing sampling – At present, there is one TCEQ quarterly water quality monitoring station in San Antonio Bay. However, there is no active HAB monitoring at this point.

Recommendations – Given the presence of numerous harvestable oyster reefs as well as evidence for HABs in the system, some level of HAB monitoring is needed. To rectify this, the following recommendations are put forth:

- Initiation of HAB sampling in San Antonio Bay. Sampling should overlap with the TCEQ station to facilitate a broader perspective on water quality conditions. Additional sampling should occur at a key oyster reef. Monthly sampling would likely suffice, although higher frequency sampling should be considered during the time of year when *Dinophysis* blooms occur (late winter-early spring).
- Should funds become available, consideration should be given to deployment of an IFCB at Port O'Connor, which lies adjacent to Pass Cavallo and the Matagorda Ship Channel. This would facilitate early detection of ocean-derived HABs (*Dinophysis*, *Karenia*) that could affect shellfish beds in both San Antonio Bay and Matagorda Bay.

Approximate costs:
Monthly discrete sampling: $40,000/year
IFCB deployment: $150,000 (one-time cost), $5,000-10,000/year maintenance



Map of San Antonio Bay showing existing and proposed sampling stations.

Table 4. Description of ongoing or proposed monitoring programs in San Antonio Bay.

Discrete (TCEQ)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic & organic nutrients	Quarterly
Proposed: Discrete (TBD)	Phytoplankton abundance & taxonomic composition	Monthly
Proposed: IFCB	Phytoplankton abundance & taxonomic composition	Continuous, real-time

Oso Bay

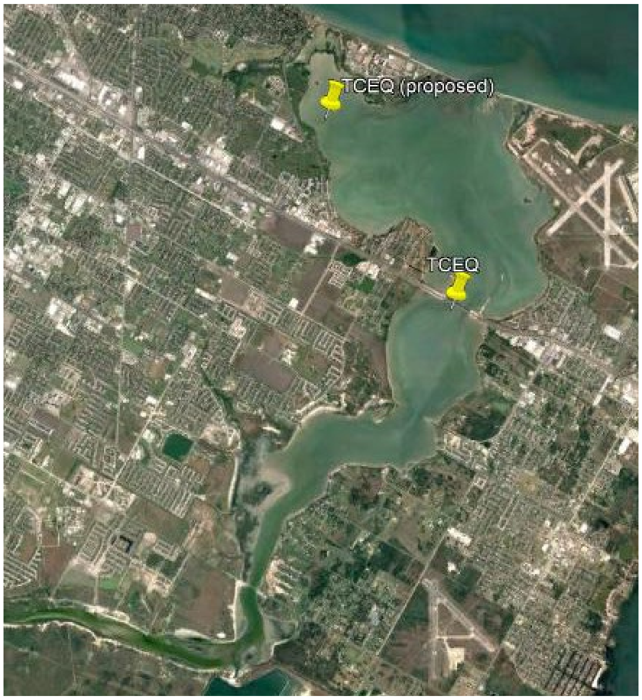
Background - Oso Bay (Corpus Christi, TX) is a critically important habitat for numerous bird species, including several threatened or endangered species, as and is home to the Suter Wildlife Refuge. Oso Bay is also a popular destination for recreational fishermen. In the past several decades, significant urbanization and land use change has occurred in the Oso Bay watershed, a trend that is projected to continue for the foreseeable future. At present, several municipal wastewater treatment plants and numerous smaller entities contribute point source discharges to the Oso system. In recent years, the Oso has begun to exhibit harmful symptoms of eutrophication, including low oxygen conditions in Oso Bay, persistent phytoplankton blooms (Wetz et al. 2016; Wang et al. 2018) and presence of HAB species (Wetz unpubl. data; Table 1).

Existing sampling - At present, there is one TCEQ quarterly water quality monitoring station in Oso Bay. However, there is no active HAB monitoring at this point.

Recommendations – The lack of HAB sampling in Oso Bay is troubling given the widespread symptoms of eutrophication, occasional fish kills and previous studies documenting presence of HABs. To rectify this, the following recommendations are put forth:

- Initiation of monthly HAB sampling in Oso Bay. Sampling should overlap with the existing TCEQ sampling station and also at a planned TCEQ sampling station in the Blind Oso to facilitate a broader perspective on water quality conditions. One possibility to reduce costs while maximizing public engagement/participation would be for the sampling to be conducted by trained volunteers. Select volunteers would need adequate training with HAB identification as well as access to suitable microscopes, but this has been accomplished elsewhere, such as with the Texas Sea Grant's Red Tide Rangers and NOAA's Citizen Science Phytoplankton Monitoring Network. The very shallow nature of Oso Bay is also conducive for a volunteer sampling program, as most sampling could be done without boats.
- A Satlantic RiverLOBO buoy-based observing system or similar device should be deployed in at the planned TCEQ station in the Blind Oso. This region of the bay is most affected by wastewater effluent. The RiverLOBO provides real-time, continuous measurements of water quality variables of interest, including in situ nitrate and chlorophyll. In conjunction with the discrete sampling, sufficient data will be available for both HAB detection and to improve understanding of nutrient-phytoplankton relationships in Oso Bay.

Approximate costs:
Monthly discrete sampling: $25,000/year
LOBO deployment: $80,000 (one-time cost), $5,000/year maintenance



Map of Oso Bay showing existing and proposed sampling stations.

Table 5. Description of ongoing or proposed monitoring programs in Oso Bay.

Discrete (TCEQ)	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic & organic nutrients	Quarterly
Proposed: Discrete (Individual researchers or volunteer network)	Phytoplankton abundance & taxonomic composition	Monthly
Proposed: Automated sensors	Salinity, temperature, pH., D.O., chlorophyll fluorescence, nitrate	Continuous, real-time

Port Bay

Background - Copano Bay supports extensive seagrass habitat as well as oyster reefs. Although there are no indications of widespread water quality degradation, a long-term increase in chlorophyll was observed in Port Bay (a tributary of Copano Bay; Bugica et al. 2020). In addition, numerous large industries exist or are being built adjacent to Port Bay, likely further increasing stresses on this tributary.

Existing sampling - At present, there is one TCEQ quarterly water quality monitoring station in Port Bay. However, there is no active HAB monitoring at this point.

Recommendations – Given evidence of eutrophication as well as the rapid industrialization on adjacent lands, some form of HAB sampling is recommended. The main recommendation would be:

- Initiation of monthly HAB sampling in Port Bay. Sampling should overlap with the existing TCEQ sampling station to facilitate a broader perspective on water quality conditions. One possibility to reduce costs while maximizing public engagement/participation would be for the sampling to be conducted by trained volunteers. Select volunteers would need adequate training with HAB identification as well as access to suitable microscopes, but this has been accomplished elsewhere, such as with the Texas Sea Grant's Red Tide Rangers and NOAA's Citizen Science Phytoplankton Monitoring Network. The very shallow nature of Port Bay is also conducive for a volunteer sampling program, as most sampling could be done without boats.

Approximate costs:
Monthly discrete sampling: $10,000/year

Map of Port Bay showing the existing sampling station.

Table 6. Description of ongoing or proposed monitoring programs in Port Bay.

Program	Parameters	Frequency
TCEQ	Salinity, temperature, pH, D.O., chlorophyll *a*, inorganic nutrients	Quarterly
Proposed: Discrete (Individual researchers or volunteer network)	Phytoplankton abundance & taxonomic composition	Monthly

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