Red Tide Report (Task 2.4)

For Corpus Christi Variable Salinity Desalination Demonstration Project
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Introduction

Desalination plants face many operational challenges, and one that has emerged in recent years is the threat from harmful algal blooms (HABs) (Anderson and McCarthy 2012). HABs, commonly known as red tides, are blooms of microscopic (phytoplankton) or macroscopic (seaweeds) algae that cause harm in many ways. In the past, these impacts have affected human and ecosystem health, including fisheries, tourism, and coastal aesthetics. For instance, HABs have caused mass mortalities of fish and marine mammals, and they have sickened and killed humans through consumption of contaminated seafood or through recreational exposure. Non-toxic HABs also cause many problems, primarily through biomass effects such as the decay of dense blooms, leading to oxygen depletion and mass mortalities of selected marine life (Anderson and McCarthy 2012, Villacorte et al. 2014).

The threat from HABs to desalination plants is not new, but it is growing in scale, concern, and significance, due to the expansion and increased frequency of both HABs and desalination plants globally (Anderson and McCarthy 2012). High biomass HABs can restrict flow in desalination plants by clogging filters, and they can also cause fouling of surfaces due to dissolved organic materials that can compromise the integrity of reverse osmosis (RO) membranes. A recent HAB outbreak in the Middle East is a clear example of the risk posed by these phenomena. That bloom, which lasted nearly eight months in the Persian Gulf-Arabian Sea region in 2008-2009, closed or restricted the operation of multiple desalination plants, some for almost two months (Richlen et al. 2010).

Phytoplankton are an essential component of coastal food webs. The photosynthetic production of organic material by this diverse group of microscopic algae provides the primary source of nutrition for many higher forms of life in highly productive bays, estuaries, and nearshore waters. However, these microalgae can reach very high abundances during periods of optimal growth and reduced grazing pressure by herbivores. Such localized mass proliferations are known as algal or phytoplankton blooms. “Red tides” are the most common and well known type of algal bloom in the Gulf of Mexico (Walsh et al. 2006, Steidinger 2009).

In the Gulf of Mexico, the most common and widespread HAB is caused by the dinoglagellate *Karenia brevis,* which causes almost annual outbreaks of red tide on the west coast of Florida, and infrequent but increasing, red tides along the Texas coast. The longest-lasting HAB event ever recorded, however, the Texas brown tide, occurred in the Laguna Madre of Texas for 7 years during the 1990s, and there are other smaller scale HAB events and species that can occur in isolated areas along the Texas coast (Buskey et al. 1996, 2001).

The purpose of this report is to provide an overview of research on the characterization and incidence of red tide events in Corpus Christi Bay, Oso Bay, and Nueces Bay. The report will also describe the similarity and differences of red tide species in the Corpus Christi coastal areas compared to red tide species that have been studied in the Middle East, and it will cover Middle East desalination plant experiences and control measures.

Characterization of Red Tide and Other HABs in Texas

Red Tide. *Karenia brevis*, the ichthyotoxic dinoflagellate that causes marine animal mortalities, neurotoxic shellfish poisoning (NSP), and human respiratory irritations and other problems, was first described to science by Charles C. Davis in 1948 from a major 1946-1947 red tide bloom along the west coast of Florida (Davis 1948). It is distributed throughout the Gulf of Mexico and up the east coast of the United States to the Carolinas. Although noteworthy fish kills had been recorded off Florida, Texas, and Mexico for hundreds of years in the older literature, it was not until this official description and attention that it was documented as the causative agent (Magana et al. 2003, Steidinger 2009). *K. brevis* appears to be ubiquitous at background levels of <1 cell/ml throughout Gulf of Mexico waters, and blooms occur at cell counts of >10 cells/ml (Hetland and Campbell 2007). The human eye can detect discolored surface seawater at about 1000 cells/ml, and satellites can detect chlorophyll from *K. brevis* blooms when cell counts are between 50,000 and 100,000 cells/ml (Steidinger 2009). Fish kills occur between 100,000 to 2,500,000 cells/ml, and shellfish beds must be closed at 5 cells/ml (Steidinger 2009).

K. brevis (also previously known as *Gymnodinium breve* and *Ptychodiscus brevis* in the literature) is an unarmored, or naked, small to medium sized (18-45 micro m wide), photosynthetic marine dinoflagellate (Steidinger 2009). The planktonic vegetative population of *K. brevis* can reproduce either asexually or sexually.

Temperature and salinity tolerances of *K. brevis* in field studies suggest ranges of 9-33 degrees C and 17 to >40 ppt, respectively, while optima are 20-28 degrees C and 31-37 ppt (Finucane and Dragovich 1959, Rounsefell and Dragovich 1966, Dragovich and Kelly 1966, Steidinger and Ingle 1972). Likewise, early researchers determined the nutrient needs and effects on *K. brevis* and reported that inorganic phosphorus concentrations from 0.1 to 1.0 micro moles supported maximum growth but >1.0 micro moles did not yield increased cell biomass (Wilson and Collier 1955, Wilson 1966, Collier et al. 1969). Organic nitrogen is also a growth requirement and has been shown to increase biomass (Shimizu and Wrensford 1993).

Brown Tide. *Aureoumbra lagunensis* is the micro-flagellate, phytoplankton species that causes brown tide in the Laguna Madre of Texas. This microscopic alga was unknown to science before the brown tide outbreak in the Laguna Madre between December 1989 and October 1997 (Buskey et al. 2001). It was described as a new species by Hudson DeYoe et al. (1997) in what has become the longest, uninterrupted phytoplankton bloom on record. The bloom began in three small embayments of Baffin Bay, following a prolonged drought in Texas (Buskey et al 1997). A collapse of grazer populations before the bloom (Buskey et al. 1997), along with the ability of the brown tide organism to grow at maximum rates under the Laguna’s hypersaline conditions

(Buskey et al. 1998) are probably important factors in bloom initiation. Nutrient pulses released by the decomposition of a large fish kill in a severe freeze in December 1989 may also have intensified the initial bloom (Whitledge 1993; DeYoe and Suttle 1994).

The reasons for the extraordinary persistence of the Texas Laguna Madre bloom are less apparent, but may be due in part to the limited water exchange with the Gulf of Mexico and lack of freshwater inflow into the system, causing prolonged residence time of its waters (Shormann (1992). In addition, field studies (Buskey and Stockwell 1993) and laboratory studies (Buskey and Hyatt 1995) have documented that *A. lagunensis* is poor food for zooplanktonic grazers, thus reducing grazing pressure and persistence of the brown tide. Fortunately, *A. lagunensis* does not appear to be toxic to adult fish or benthic invertebrates (Montagna et al. 1993, Buskey et al. 1996), but high cell densities decrease light availability and have reduced the distribution and biomass of seagrasses in Laguna Madre (Dunton 1994, Onuf 1996).

Aureoumbra lagunensis is only 4-5 micro m in diameter, and blooms occur in cell densities or counts of 500,000 to 5,000,000 cells/ml. At bloom concentrations, as the name implies, the water color is brown. Brown tide continues to exist in the Laguna Madre system, especially in Baffin Bay, but its concentrations and distribution fluctuate greatly from year to year.

Other HABs. A second "red tide" dinoflagellate (*Alexandrium monilata,* previously known as *Gonyaulax monilata*) is known from Texas coastal waters, and it has been recorded to occasionally bloom, but blooms have been more localized and there is less information available (Buskey et al. 1996). Reported fish kills in bayous leading into Galveston Bay were assumed to be caused by this species, and reports of annual blooms in East Bay occurred in the 1950s-1960s. In addition, two blooms offshore from Galveston in 1971-1972 were confirmed to be this species (Wardle et al. 1975). Bloom concentrations in that area have apparently not reappeared since the 1971-1972 events, although local blooms have occurred in various parts of South Texas (Buskey et al. 1996). Jensen and Bowman (1975) reported on a documented *A. monilata* bloom and fish kill during August-September 1972 in the Viola Turning Basin of the Corpus Christi Inner Harbor, and then they recorded its reappearance during July-September 1975 with a maximum recorded concentration of 5,140 cells/ml. There are no substantiated later occurrences or records of *A. monilata* along the Texas coast.

During a study of the decline and recovery of the persistent brown tide in the Laguna Madre of Texas during 1997 and 1998, Buskey et al. (2001) discovered two other major phytoplankton blooms in the study areas of Laguna Madre, Baffin Bay, and Corpus Christi Bay. One of these was a dense diatom bloom (primarily *Rhizosolenia punctiger*) in Baffin Bay during October 1997, and the other was a dense cyanobacterial bloom (primarily *Synechococcus*-like cyanobacteria) observed and centered in the Laguna Madre during April 1998. Although low cell count concentrations of these two blooms were recorded in Corpus Christi Bay, there were no recorded environmental impacts from them (Buskey et al. 2001). There have not been any further scientific reports of these kinds of blooms since this study.

Incidence of Red Tide and other HABs in Texas and the Corpus Christi Area

The incidence of *K. brevis* red tide in the Corpus Christi area is the main focus of this section, as it is the HAB of most concern in the area regarding the desalination of seawater in the area. The brown tide has remained persistent within the Laguna Madre, but it is non-toxic, and it is mainly distributed further to the south around Baffin Bay. The other red tide species in Texas (*A. monilata*) has not bloomed in coastal Texas for several decades, but it should be monitored.

Monitoring red tides/HABs in Texas. The Texas Parks and Wildlife Department (TPWD) maintains a Harmful Algal Blooms (HABs) webpage at http://www.tpwd.state.tx.us/landwater/water/environconcerns/hab/. In addition to this website, they maintain a 24-hour communication center at (512) 389-4848, and they are a member of the Texas HABs Task Force that communicates regularly and puts out notices about all Texas HABs (fresh water and coastal/marine). The webpage on the Texas Parks and Wildlife website maintains information on red tides, brown tides, and HAB research in Texas. Important for the Desalination Project is information on timing and dates of past blooms since the site opened in 2005. The Texas Department of State Health Services (TDSHS) also reports red tides along the Texas coast, and they are responsible for testing fish and shellfish, as well as closing fishing waters to protect the public from the brevitoxins produced by red tide organisms.

Table 1 provides a historical incidence of red tide events in Texas during 1935 through August 2014. Unfortunately, there is not consistency in recording exact initiation and ending dates or localities (Magana et al. 2003, Tester et al. 2004). However, the historical record does clearly reveal an increasing frequency of red tide events in Texas, and it does show that the primary timeframe for the red tides is late summer to late fall with September and October usually being the peak season. The TPWD Kills and Spills Team is the primary lead group for recording red tide blooms, and they are usually alerted to these events by reported fish kills or reddish brown colored water reports. TPWD biologists then collect water samples to identify the causative species and make cell counts for the record.

Table 1. Incidence of red tide (*Karenia brevis* blooms) along the Texas coast, 1935 to 2014.

Year	Timing	Location	Citation
1935	June to mid-September	South Texas Coast	Lund, 1936
1948	?	South Texas Coast	Gunter, 1952
1955	September	Port Isabel into Mexico	Wilson & Ray, 1956
1972	?	Galveston	Magana et al. 2003
1974	October	Port Isabel into Mexico	Magana et al. 2003, Tunnell, personal obs.
1986[1]	late August to late October	Texas Coast (entire)	Trebatoski, 1988
1987		Corpus Christi Bay	Campbell & Loret, 2001
1990	November to December	Brownsville Ship Channel	Buskey et al, 1996
1996	?	Texas Coast	Tester et al. 2004, Magana et al. 2003
1997	?	Texas Coast	Tester et al. 2004, Magana et al. 2003

1999	October to November	South Padre Island to Texas Coast	Tester et al. 2004, Magana et al. 2003
2000[1]	early August through November	Texas Coast & Bays (entire)	Denton & Contreras, 2004
2001-2002	?	Port Aransas	Magana et al. 2003
2005	mid-September to early November	Corpus Christi Bay area	TPWD[2]
2006	late September to late October	Texas Coastal Bend (patchy), including Corpus Christi Bay	TPWD
2009-2010	late September to early February	Began at South Padre Island, up to Corpus Christi Bay	TPWD
2011-2012	mid-September to February	Began at Brownsville Ship Channel, extended to Galveston Bay	TPWD
2012	August only	Galveston Bay and nearshore beaches	TPWD

[1]Major red tide event
[2]TPWD HABS Website: http://www.tpwd.state.tx.us/landwater/water/environconcerns/hab/

Predicting red tides in Texas. Since red tides cause fish kills, respiratory irritation in humans, and Neurotoxic Shellfish Poisoning (NSP), if ingested, they can cause significant economic problems to coastal communities. Outdoor laborers, fishermen, and tourists/recreationalists are all affected by red tide outbreaks. This has led to new and interesting research in recent years on predicting red tide events, as well as semi-automated technology for recognition of the red tide species in the water column. Laser scanning cytometry has been proposed as an early warning technology specifically for desalination plants (Vardon et al. 2011), and FlowCAM, a flow-through seawater system with image recognition software, has been used regularly in Port Aransas in the Corpus Christi Ship Channel by the University of Texas Marine Science Institute for early detection in the Texas Coastal Bend for a number of years (Buskey and Hyatt 2006). The latter system is used regularly to assist the TPWD Kills and Spills Team with their local red tide early warning in the Corpus Christi Bay area.

Some recent and promising research involves remote sensing and models to predict the years and localities with most potential for red tide/HAB outbreaks (Walsh et al. 2006, Hetland and Campbell 2007, and Thyng et al. 2014). These researchers have used decades of bio-physical information and data to understand the initiation and spread of red tides in the northwestern Gulf or along the Texas coast. A combination of winds, currents, and other environmental parameters combined are important in understanding and predicting the red tide events.

Desalination operational issues with red tide/HABs. Although there is a substantial literature on the biology and ecology of HAB species and their impact on human and environmental health, there is little information on the potential impact HABs may have on desalination plant operations (Caron et al. 2010). Two potential impacts include: 1) algal toxins in sea water pose a significant treatment challenge for a reverse osmosis system to ensure that the toxin molecules are effectively removed (Derby et al. 2005, Caron et al. 2010, Laycock et al. 2012), and 2) increased turbidity, total suspended solids, and total organic content resulting from algal biomass and growth challenge the entire desalination facility's treatment train (Anderson and McCarthy 2012, Villacorte et al. 2014). Knowing the seasonality and duration, as well as the vertical and horizontal spatial distribution of HABs is important for siting and operations. Early warning systems that alert about an impending bloom at or near intakes can be critical for water quality and plant operations (Caron et al. 2010). Because of recent large scale and widespread impacts to desalination plant operations due to red tides/HABs in the Middle East, we can learn from new and emerging efforts there that should be applicable in Texas.

Comparison of Texas and Middle East Red Tides

Although there appears to be convincing evidence of increasing frequency of HAB events in both Texas and the Middle East (primarily Arabian Gulf and Gulf of Oman), a clear difference is the lower diversity of bloom species in Texas compared to the Middle East. Red tide in the Gulf of Mexico, including Texas, has primarily been caused by *K. brevis* over the past 6-7 decades, as discussed above, with the brown tide *A. lagunensis* persisting in the Laguna Madre at varying concentrations and distributions for the past 15 years. However, in the Arabian Gulf 38 potentially bloom-forming or harmful algal taxa have been reported (Subba-Rao and Al-Yamani 1998), and in the adjacent Gulf of Oman between 1976 and 2004, 66 red tide events were recorded (Richlen et al. 2010). It was not until a massive, catastrophic red tide during 2008-2009 in that region that triggered an overall, region-wide concern for the impact of red tides on human and environmental health, as well as desalination plant operations (Richlen et al. 2010, Anderson and McCarthy 2012, Villacorte et al. 2014).

Middle East Desalination Plant Issues with Red Tides

Middle East Workshop No. 1 (2012). In 2012, a multi-agency, multi-country workshop was convened to determine the way forward regarding red tides/HABs and their impacts on desalination operations (Anderson and McCarthy 2012) in the Middle East. The overall objective of this important workshop, held at the Middle East Desalination Research Center in Muscat, Oman, was "to exchange information about harmful algal blooms and the threats they present to desalination plants, and to identify problem areas and potential research, education, technology exchange programs that could address these issues" (Anderson and McCarthy 2012). Through plenary discussions and working group deliberations, the attendees came up with a list of 15 important activities or targets to be achieved. These 15 items are listed below to show the collective thinking of these world experts (from Anderson and McCarthy 2012):

1. Produce a *Manual of Practice for HABs and Desalination* that would describe and recommend options available to mitigate the impacts of HABs. Key elements of this manual will include:

- Definitions
- Background on HAB diversity, toxins, bloom types, ecology, etc.
- Case histories

- Water characterization
- Predictive indicators
- Siting considerations
- Treatment processes
- Cost estimates for mitigation alternatives
- Operating strategies
- Troubleshooting techniques

2. Conduct a survey to obtain information from plants having prior experience with HABs during operations. The survey would quantify actual bloom data where available, and identify the mitigation measures that have been attempted, and their success or failure.
3. Develop guidelines to aid in choosing between potential desalination plant intake options, (e.g. depths, locations, types, etc.) and pretreatment technologies and operational procedures to minimize the impacts of HABs.
4. Conduct a horizontal study of pre-treatment processes to allow more consistent water production during blooms. This suggested project would assess three common pretreatments for reverse osmosis, Dissolved Air Flotation (DAF), Dual Media Filters (DMF) and Ultrafiltration (UF), for the removal of toxins and taste and odor compounds as well as the organic material produced by red tide algal blooms.
5. Identify unknown taste and odor compounds from common algal blooms and HAB species and conduct laboratory studies of the extent of removal of these compounds using cross-flow reverse osmosis.
6. Conduct laboratory studies to mimic shock chlorination in the presence of ammonia in seawater to determine N-nitrosodimethylamine (NDMA) formation potential.
7. Test for removal of common HAB toxins by reverse osmosis.
8. Encourage countries and regional programs such as ROPME to support large and small scale oceanographic surveys and modeling activities to characterize the currents, water column structures, and biological dynamics of near shore coastal waters.
9. Encourage desalination plants to add new parameters to those that are already measured on a routine basis. This might include phytoplankton species composition (with emphasis on known HAB species), measurements of toxin in intake and treated waters, measurements of TEP and other organic material in water samples, and automated measurements of chlorophyll, turbidity, and related parameters using instrumented buoys. To help in the development of such capabilities, training workshops should be organized and supported.
10. Encourage the deployment of instrumented buoys by national and local governments and by the desalination plants as well, in order to obtain real–time data on readily measured parameters that guide plant operators. Training workshops on this technology are needed.
11. Develop capabilities to interpret satellite remote sensing images of near shore waters to better characterize the nature and extent of algal blooms. Mechanisms for the dissemination of these images are also needed, as are training workshops, as desalination plant operators typically are not provided with such images under current programs and policies, nor are they familiar with the methods for interpretation and analysis.
12. Encourage the sharing and common use of HAB cultures and analytical methods so that results obtained by different groups can be comparable and complementary. This could be accomplished, for example, through the establishment of a *HAB and Desalination Program* coordination activity conducted by MEDRC, IDEC or others working with these agencies.
13. A second meeting on HABs and desalination should be convened that builds upon the

progress initiated in this first workshop and that is more global in scope. Such a meeting is already in the planning stages, to be organized through a joint effort between a team representing the Intergovernmental Panel on Harmful Algal Blooms (IPHAB) of the Intergovernmental Oceanographic Commission (IOC) of UNESCO), MEDRC, and other partners. One goal of that workshop or conference should be to review and identify scientific and engineering needs in this topic area, and to develop a consensus on many aspects of the HAB/desalination problem, working towards common design and operating principles or guidelines that can be used going forward.

14. Encourage funding entities such as MEDRC, and IDEC to support proposals that address priority projects identified here. This might be accomplished by emphasizing specific priority areas in annual or semi-annual calls for proposals.

15. Identify individuals who would be willing to coordinate the formation of research teams to prepare proposals on priority topics such as the risk of HAB toxins in water or the development of a manual for desalination plant operators. Potential funding sources for these activities should also be identified.

Middle East Workshop No. 2 (2014). Chief among these 15 activities will be the *Manual of Practice for HABs and Desalination.* After contact with Don Anderson, lead organizer and author of the above-mentioned proceedings (Anderson and McCarty 2012), regarding the status of the *Manual of Practice*, it was revealed that a second Workshop on Harmful Algal Blooms and Desalination had been held in Muscat, Oman, during 16-17 April 2014 (Wes Tunnell, personal communication with Don Anderson, 3 September 2014). Dr. Anderson, a world authority on red tides/HABs at Woods Hole Oceanographic Institution, related that the Manual was still under development and would not be ready for another year or more. Dr. Anderson provided a link to the meeting at http://www.medrc.org/home/habd, but he related that the presentations were not available to the public.

The MEDRC website for the April 2014 HABs-Desalination conference in Oman relates that "the recognition of potential problems that HABs may pose to desalination is new and has, so far, largely been speculative." Furthermore, it notes that toxic blooms in the vicinity of desalination plants are often unrecognized events, and that plant operators are generally unaware of the threat that algal toxins pose to their facility. Because of this situation, no measurements of marine algal toxins before and after desalination have been made at any large-scale desalination plant.

The two-day 2014 HABs and Desalination conference brought together scientists, engineers, managers, and government officials, and it immediately followed the Sultan Qaboos *University International Conference on Desalination, Environment, and Outfall Systems*, held in Muscat 13-15 April. At the HAB conference, presentations by scientists and engineers covered topics that included the following;

1. A general overview of HABs, their impacts, and trends
2. Case studies and descriptions of impacts of HABs on desalination facilities
3. Results of experimental and pilot studies on HAB toxin removal during desalination
4. Results of experimental studies on the removal of HAB biomass using Dissolved Air Flotation (DAF), ultrafiltration, and other methods
5. Design considerations for desalination plants in areas subject to recurrent HABs

6. New technologies and approaches to HAB detection and forecasting
7. Approaches to direct bloom control or suppression
8. Action plans or management strategies to follow during HAB outbreaks
9. Regulatory issues
10. Research priorities and future plans.

Desal Plant Experiences and Control Measures

There have been no surveys or summaries of desal plant experiences with red tides/HABs during operations, and most of this kind of information that is available is anecdotal (Anderson and McCarty 2012). Quantifying whatever information is available will be part of the manual development mentioned above. Below are some of the topical subjects and experiences discussed in the 2012 Desal-HAB Workshop in Oman

Regarding **plant siting guidelines**, a brief survey of the conference attendees prior to the workshop was summarized by Tom Pankratz as follows (from Anderson and McCarty 2012):

- *Dissolved air flotation (DAF) systems* – Sixteen of the 18 respondents thought that a pretreatment system including DAF offered the best possibility of ensuring that a SWRO would operate during HAB events. Many noted that tapered flocculation was a necessary part of successful DAF operation. Some recommended installing a DAF but using it only when HABs occurred or were likely.
- *Microfiltration/ultrafiltration (MF/UF) systems* – Every respondent considered a well-designed filtration system as necessary, and two-thirds of the respondents said that they preferred MF/UF over a single or two-stage granular media filter. Many of those who recommended MF/UF said that provisions should be made to lower flux during HABs. A few respondents thought that a conservative, low-flux MF/UF design alone was sufficient for all but the most severe blooms.
- *Intake location* – The location and type of intake were considered to be important methods of mitigating HAB impacts. Most preferred deeper intakes as a way of minimizing risks.
- *Others* – Some suggested changing coagulants during HABs (e.g. polyaluminum chloride versus ferric sulfate), or adding powdered activated carbon. Some thought the use of chlorophyll analyzers would offer earlier warning.

Most respondents at the workshop acknowledged that the final decision on what strategy would be employed was dependent on many factors, including a site's susceptibility to HABs and a facility's capacity reliability requirement. One respondent summed up his response by saying, "One frequently overlooked strategy is to simply shut a plant down during a severe bloom."

In light of these comments from the respondents, the recommendation from the working group was to develop guidelines to aid in choosing between potential intake options, (e.g. depths, locations, types, etc.), as well as pretreatment technologies and operational procedures to minimize the impacts of HABs.

Regarding **toxins and extracellular organic matter**, suggested projects and attention focused on pre-treatment for RO desalination plants . The consensus seemed to be for assessing three common pre-treatments for RO: dissolved air flotation (DAF), Dual Media Filters (DMF), and Ultrafiltration (UF), for the removal of toxins and taste and odor compounds, as well as the organic material produced by HABs. Other suggested projects needed for assisting in decisions about algal blooms focused on novel taste and odor compounds, and others focused on the ability of RO to remove toxins, such as saxitoxins, brevetoxins, and domoic acid, all common components of selected algal bloom species (Laycock et al. 2012).

Lastly, workshop participants and presenters focused on **environmental monitoring and coastal oceanography as control measures** before or during HABs outbreaks. Knowing and understanding coastal wind and current regimes and peak seasons for algal bloom outbreaks is critical (Anderson and McCarty 2012). Remote sensing of coastal waters for red tides/HABs in the Arabian Gulf are now being considered as a potential great assistance to predicting and monitoring (Al Muhairi et al. 2010 and 2011, Zhao and Ghedira 2014, and D. Anderson, personal communication with W. Tunnell, 3 September 2014).

Other **control measures** suggested of having great potential are the use of beach galleries or subsurface intakes, which use the ocean bottom as a filter to keep out unwanted algal bloom constituents ((Missimer et al. 2013, Al-Mashharawi et al 2014). These are very expensive compared to traditional intake systems, but they are believed to be the best protection against algal bloom contamination to intake water systems at desalination plants.

Summary and Conclusions

The threat from HABs to desalination plants is not new, but it is growing in scale, concern, and significance, due to the expansion of both HABs and desalination plants globally (Anderson and McCarthy 2012). Recent events highlight the vulnerability of traditional plant designs to blooms, and they emphasized how little is known about important processes, such as toxin removal during treatment or the best methods for removing algal biomass and extracellular products during pretreatment (e.g., Richlen et al. 2010) . Likewise, design features of plants, including the specific location and nature of intakes, need to account for the types of bloom events and species that might occur in a given region.

Probably of most concern in the Corpus Christi area, regarding red tides/HABs, will be the siting or location of the intake. Today, red tides/HABs are still episodic and not as regular (yearly) as on the West Coast of Florida; however, they have been increasing in recent decades. In addition, today the need for desalinated water in the Corpus Christi area is mainly supplemental to reservoir and Mary Rhodes Pipeline water, so shutting down the plant during a red tide event, might not seem as critical. In the future, however, if desalinated water is a significant part of the water system, closing of the plant could be problematic. Considering these two issues and the long-term projection for increasing water needs, the most appropriate option appears to be an offshore intake away from the possibility of coastal red tides/HABs.

Conclusions drawn from this literature review on red tides/HABs and desalination plants include:

1. Desalination plants face many operational challenges, and one that has emerged in recent years is the threat from harmful algal blooms (HABs).
2. The threat from HABs to desalination plants is not new, but it is growing in scale, concern, and significance, due to the expansion and increased frequency of both HABs and desalination plants globally.
3. High biomass HABs can restrict flow in desalination plants by clogging filters, and they can also cause fouling of surfaces due to dissolved organic materials that can compromise the integrity of reverse osmosis (RO) membranes.
4. A recent HAB outbreak in the Middle East, which lasted nearly eight months in the Persian Gulf-Arabian Sea region in 2008-2009, closed or restricted the operation of multiple desalination plants, some for almost two months.
5. Red tides, caused by the dinoflagellate *Karenia brevis*, are the most common and well known type of algal bloom in the Gulf of Mexico.
6. Red tides in the Gulf of Mexico occur on an almost annual basis on the west coast of Florida, but less frequently along the Texas coast.
7. Table 1 provides the historical incidence of red tide events in Texas during 1935 through August 2014.
8. The historical record reveals an increasing frequency of red tide events in Texas, and it does show that the primary timeframe for the red tides is late summer to late fall with September and October usually being the peak season.
9. Brown tide, caused by the micro-flagellate *Aureoumbra lagunensis*, occurs only in the Laguna Madre of Texas, and after 7 years of continuous bloom remains present in localized areas and occasionally flairs up again.
10. Some other HABs have been occasionally recorded along the Texas coast and in the Texas Coastal Bend.
11. Texas Parks and Wildlife Department monitors red tides/HABs along the Texas coast and maintains an archive of those events since the early 2000s.
12. Some Texas marine scientists have proposed predictive models for red tide events in Texas, and others have an active flow through imaging system to detect the red tide organism in Port Aransas.
13. Texas deals with only several species, mainly one (*Karenia brevis*), for red tide blooms, whereas the Middle East (Persian/Arabian Gulf) has as many as 38 potential species.
14. Two very important and relevant conferences were recently held in 2012 and 2014 in the Middle East focusing on red tides/HABs and their potential impacts to desalination plants.
15. Fifteen relevant studies and activities were identified at the two Middle East HAB-Desal conferences, and key among them was the development of a *Manual of Practice for HABs and Desalination,* which should be completed sometime in late 2015 or 2016.
16. Regarding plant siting, the location and type of intake are important methods of mitigating HAB impacts to desal plants, and the most preferred way of minimizing risks or impacts is to have the plant intakes located in deeper water (offshore)

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