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Fifty-Five Years of Fish Kills in Coastal Texas

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Abstract The designation of Texas as a "hotspot" for fish mortalities relative to the other 22 coastal US states is of serious concern for scientists, resource managers, and the public alike. We investigated the major sources and causes of fish kills in coastal Texas from 1951 to 2006. During this 55-year period, more than 383 million fish were killed, 72% of which were Gulf menhaden (*Brevoortia* spp.). We examined the relationships between climate and the physical features of Texas bays and estuaries as well as the consequences of high-density industrialization and urbanization along several coastal centers on fish kills, including the impact of eutrophication, algal blooms (toxic and nontoxic), and hypoxia. Galveston and Matagorda Bays had the highest number of fish kill events and total number of fish killed. The largest number of fish kill events and the highest number of fish killed occurred during the warmest months, particularly in August. The leading cause of fish kills was found to be low dissolved oxygen concentrations caused by both physical and biological factors. From 1958 to 1997, about two thirds of the mortalities from low oxygen concentrations were caused by human activities. With the population predicted to double in Texas by 2050, mostly along the coastal areas, natural resources will require additional protection. Further increases in nutrient loading are expected in areas unable to keep up with construction of sewage treatment facilities. Defining the sources and causes of fish kill events in Texas will allow better management and conservation efforts.

Keywords Fish kills · Hypoxia · Eutrophication · Gulf menhaden · *Brevoortia patronus* · Texas

Abbreviations

DO	dissolved oxygen
DCPP	dissolved concentration potential of pollutant
EPA	Environmental Protection Agency
KAST	Kills and Spills Team
NOAA	National Oceanic and Atmospheric Administration
PRISM	Pollution Response Inventory and Species Mortality
TCEQ	Texas Commission on Environmental Quality
TPWD	Texas Parks and Wildlife Department

Introduction

Fish show a variety of responses to stress including reduced food intake, which leads to a reduction in growth, inhibition of reproduction, and a compromise of fertilization success and larval survival (Poon et al. 2002). In the case of hypoxia, fish attempt to maintain oxygen intake by increasing gill ventilation and oxygen delivery via increased circulation, show avoidance strategies, and other signs of sensitivity (Breitburg 2002). In extreme situations, however, environmental stressor(s) are so significant that fish kills are observed. Dying fish float to the surface or wash onto shore, creating a dramatic and visible manifes-

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tation of ecosystem disruption, particularly when fish numbers are in the millions. As much as 80% of dead fish cannot be counted due to turbid water, sinking to the bottom, or being washed away (Biernacki 1979). Fish kill events can be related to specific human activities such as accidental spills (e.g., oil, pesticides) or the discharge of high levels of chlorine disinfectant from wastewater treatment plants. Events are also linked to phenomena such as oxygen depletion resulting from sustained periods of hot weather, coupled with low-flow conditions (Lowe et al. 1991; Breitburg 2002; Diaz 2002). The occurrence of fish kills thus provides useful information on the spatial and temporal distributions of pollutants (including excess nutrients) and problems (including hypoxia) in coastal estuaries.

Eutrophication-induced decline in ecosystem function has resulted in the increased reporting of fish disease, fish kills, algae blooms, red and/or brown tide, and the persistence of low dissolved oxygen (DO) concentrations. In some cases, however, a positive relationship between nutrient loading and fisheries yields has been observed; this seeming contradiction is discussed in detail in Breitburg (2002). While hypoxic and anoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely exacerbated by eutrophication and human activities (Rabalais 1998; Diaz 2002). Fish kills occurring in inland water bodies are also significant and, in some areas, occurring with greater frequency. *Prymnesium parvum*-associated fish deaths accounted for more than 17 million fish lost in Texas lakes in the last 5 years (Roelke et al. 2007). Freshwater fish kills will not be discussed further herein. Instead we will focus on fish kills in estuaries and coastal systems.

Three percent of the fish kill events in Texas from 1961 to 1975 occurred in coastal waters and accounted for 41% of the fish killed during this period, indicating that on average, fish kill events occurring in coastal waters are much larger than those in rivers and streams (Biernacki 1979). The consequences of widespread fish kills include economic losses of commercially and recreationally important fisheries, human health risks, habitat degradation, and decreased water quality. Understanding the cause(s) of fish kill events is important for the management of fish populations, particularly those of economically important species. Knowing the cause of these events and who, if anyone, is responsible will also enable conservation to be focused more effectively.

Efforts to identify, report, and assess the sources and causes of fish kills in coastal rivers, bays, marshes, and estuarine waters started in the USA in the early 1950s. National and state agencies such as the National Oceanic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), and Texas Parks and Wildlife Department (TPWD) document fish kill events. These agencies record the magnitude, probable cause, species affected, and other details which may identify the causal agent. Although reports indicate that fish kills are not a pervasive problem, areas with recurring kills have been labeled as “hotspots.” Texas was identified as one of these “hotspots,” in particular Galveston Bay, by Lowe et al. (1991). Three of the top five fish kill events in terms of the largest number of fish killed between 1980 and 1989 occurred in the Galveston Bay watershed (Lowe et al. 1991). An estimated 159 million fish were killed in Texas during this period. Florida and Maryland fell second and third with 77 and 68 million fish killed, respectively, during the same period. In the period from 1961 to 1975, fish kills involving more than one million dead fish accounted for 1% of the total events, but 77% of the fish killed. Texas (14 events) ranked second after Florida (15 events) in number of events killing more than one million fish (Lowe et al. 1991). The reporting of fish kill events continues to rise both in the USA and around the world (Thurston 2002), particularly in areas affected by urban and industrial wastewater discharges (e.g., Basque County, Northern Spain, Franco et al. 2002; Lakes Võrtsjärv and Peipsi, Estonia, Tuvikene et al. 2002).

TPWD has been investigating mass mortality events of fish and wildlife in Texas since 1951 and compiling them in the Pollution Response Inventory and Species Mortality (PRISM) database. More than 4,500 incidents have been recorded since the program was initiated. From 1958 to 1997, the leading cause of fish kills was human-induced factors such as construction of dead-end canals in industrial or residential developments along the coast, the release of pollutants into the water, and the reduction or stoppage of flow in a stream. Of the fish kill events that were caused by low oxygen concentrations, two thirds were caused by human activities (Contreras 2003). This paper will focus on defining the causes and sources of fish kills in Texas, more specifically Galveston Bay, over the last 55 years (1951–2006).

While a large number of fish species are affected by fish kills, we focused on Gulf menhaden (*Brevoortia patronus*) and Finescale menhaden (*B. gunteri*), as they are the most commonly killed fish species in Texas and throughout the coastal USA. The Clupeidae family (menhaden, shad, herring) were involved in 36% of the fish kill events throughout the 22 coastal states and accounted for 61% of the fish killed (Lowe et al. 1991). Menhaden support the second largest commercial fishery by weight in the Gulf of Mexico (Vaughan et al. 2007). Menhaden are also important ecologically, being crucial to the diet of tuna, cod, haddock, halibut, mackerel, bluefish, weakfish, striped bass, swordfish, king mackerel, summer flounder, and drum as well as marine birds and mammals. But even more importantly, the menhaden are filter feeders that live on plankton, cellulose, and detritus. Each adult fish can filter four to eight gallons of water a minute while purging the suspended particles and increasing water clarity by decreasing turbidity, allowing sunlight to penetrate the water column. This stimulates the growth of aquatic plants that release dissolved oxygen into the system. Menhaden's filter feeding may also prevent the formation of devastating algal blooms (Franklin 2007).

Methods

Study Area

The physical and hydrologic parameters of the seven major bays and estuaries in Texas are presented in Table 1. These systems are generally very shallow in nature (average depth <2.5 m), have low tidal energy (average height 0.03 to 0.34 m), circulation patterns which are generally wind driven, and experience low flushing rates (Table 1). The average time for freshwater to displace the entire volume of these estuaries ranges from 15 days in Sabine Lake to 4,317 days for Baffin Bay (Fig. 1; Table 1). Salinities are generally high (average 18 to 39 psu) along with temperatures (average annual water, 29.3°C to 31.7°C; air, 20.5°C to 23.3°C). This leads to a stabilization of the water column such that large areas of bays and estuaries have low DO, particularly in the spring/summer. Clement et al. (2001), in a survey of estuaries across the USA, cited Corpus Christi Bay and Laguna Madre as having amongst the highest levels of eutrophication in the Gulf of Mexico. Corpus Christi Bay is known to experience seasonal hypoxia (Montagna and Kalke 1992; Martin and Montagna 1995; Ritter and Montagna 2001); similar information is lacking for the other Texas estuaries. Engle et al. (2007) calculated the dissolved concentration potential of pollutant (DCPP) for Texas bays and estuaries. This parameter integrates nutrient loads with estimates of estuarine dilution (proportional to estuarine volume) and flushing (calculated from the replacement of the freshwater component of the total system volume by river flow). DCPP values varied from 0 for the Upper Laguna Madre to as high as 19.6 mg l^{-1} for Aransas Bay (Table 1). Generally, the bays and estuaries with low flushing rates (>700 days) had higher DCPP values.

Galveston Bay is the largest estuary on the Texas coast (about 1,456 km^2; Engle et al. 2007). Of all the bays and estuaries in Texas, it is the focus of gravest conservation issues due to the high density of industrialization and urbanization in its watershed. About 47% of the total state population (almost ten million people) live within the

Table 1 Physical (area, depth, volume) and hydrologic (tide height, tidal prism volume, flow) parameters of Texas bays and estuaries

	Total EDA area (km^2)	Estuary area (km^2)[a]	Average depth (m)	Estuary volume ($m^3 \times 10^9$)	Average summer salinity (psu)	Tide height (m)	Tidal prism volume ($m^3 \times 10^9$)	Average monthly river flow (m^3 day^{-1})	DCPP (mg l^{-1})	PRE (days)	Average annual air temp. (°C)	Average annual water temp. (°C)
Sabine Lake	12,444	265	1.9	0.660	*7.7*	0.24	0.125	**44,055,103**	0.5	*15*	20.6	**31.7**
Galveston Bay	11,505	**1,456**	2.0	**2.707**	18	0.16	0.449	24,279,600	0.5	112	*20.5*	29.5
Matagorda Bay	**15,161**	1,115	1.7	2.430	13	0.12	0.221	9,925,832	1.7	245	21.3	30.4
San Antonio Bay	4,013	587	*1.5*	0.728	18	0.21	0.111	6,590,391	1.8	110	21.6	29.9
Corpus Christi Bay	5,063	571	2.2	1.280	30	0.21	0.230	492,324	7.5	2,600	21.9	29.7
Aransas Bay	6,945	524	**2.5**	0.847	19	0.21	0.121	586,665	**19.6**	1,443	21.7	29.7
Baffin Bay	8,774	*239*	2.0	*0.311*	**52**	*0.03*	*0.014*	*72,149*	9.3	**4,317**	22.4	30.1
Upper Laguna Madre	*2,638*	591	1.6	0.447	43	**0.34**	0.090	1,534,003	*0.0*	292	22.7	29.9
Lower Laguna Madre	14,474	1,308	1.7	0.997	39	0.25	**0.511**	1,534,003	1.3	650	**23.3**	*29.3*

Largest values for a particular parameter are in bold text while the smallest are in italics. Data and definitions from Engle et al. (2007).
EDA estuarine drainage area defined by NOAA's Coastal Assessment Framework (NOAA 2003) represents the sum of land and water area for the watershed, *DCPP* dissolved concentration potential of pollutant—integrates nutrient loads with estimates of estuarine dilution (proportional to estuarine volume) and flushing (calculated from the replacement of the freshwater component of the total system volume by river flow), *PRE* time for freshwater to displace entire volume of estuary

[a] Only water area for the watershed.

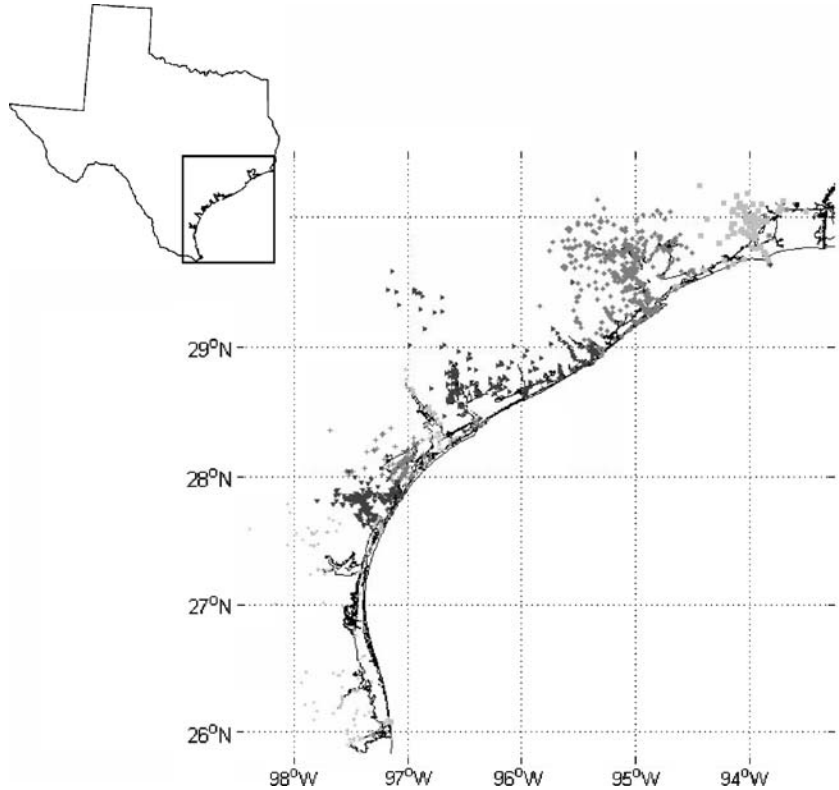

Fig. 1 Fish kill events recorded for Texas bays and estuaries from 1951 to 2006. *Each point* refers to a fish kill event; *symbols refer* to the respective system in which the kill occurred. Sabine Lake (*gray square*), Galveston Bay (*gray diamond*), Matagorda Bay (*right arrowhead*), San Antonio Bay (*asterisk*), Copano and Aransas Bays (*cross*), Corpus Christi Bay (*down arrowhead*), and Laguna Madre (*gray circle*)

watershed (Moulton et al. 2004). The five counties bordering Galveston Bay have more than four million people living in them, using an estimated 1.4 billion gallons of freshwater daily (TWDB 2007). Galveston Bay is the most productive of all Texas' estuaries with an oyster production that is unsurpassed in the USA (about 1,800 metric tons with a value of $8 million), a commercial fishery industry that is one third of the state's commercial fishing income (Galveston Bay contributed approximately $99 million from 1994 to 1998) and a recreational fishery that made a gross direct contribution to the local economy of $171.5 million in 1986 (GBEP 2001; Lester and Gonzalez 2002; Pinckney 2006; TWDB 2007). Galveston Bay is home to important recreational and commercial fisheries consisting of oysters (two species), shrimp (13 species), crab (17 species), and fish (more than 150 finfish species; Lester and Gonzalez 2002). The Port of Houston, located on the northwestern section of Galveston Bay, moves more than 200 million tons of cargo annually (PHA 2006). Dredging for the Houston ship channel, as well as for two smaller ports (Texas City and Galveston), and various other activities have greatly altered circulation patterns in this shallow system (average depth 2 m).

Meta-analysis

We used the information on fish kill events in the PRISM database (1951–2006) to determine what trends, if any, could be linked to fish kills across the seven major bays and estuaries in Texas (Fig. 1). The type of information stored in PRISM included incident type (fish kill, wildlife kill, pollution event), start and end date, habitat type and size affected, notification record (event ID), Texas Commission on Environmental Quality (TCEQ) water quality segment number, location (latitude and longitude), source and cause, and information about species, sizes, and numbers of fish killed. The ten major causes of fish kills identified for Texas are summarized in Table 2. Unfortunately, in many cases, environmental parameters, especially DO content, were not determined immediately, but were measured some days later. For this reason, some of the conclusions drawn are based only on indirect signs.

According to the standard operating procedures manual for the Kills and Spills Team (KAST 2006), TPWD is authorized to investigate fish kills and any type of pollution that may cause loss of fish or wildlife, take necessary action to identify the cause and party responsible, estimate the monetary value of lost resources, and seek compensation. The KAST biologists are typically notified of a kill/pollution event by citizens or other agencies. The biologist determines from the information provided by the informant (location, magnitude, known or suspected source, whether incident is ongoing, when incident started) whether the incident should be further investigated. The biologist makes this decision based on the magnitude of the event, the likelihood that an investigation will reveal the source,

Table 2 There are ten general causes that account for all the fish kill events in Texas bays and estuaries

Cause	Consequence
Low dissolved oxygen	Low levels of oxygen in the water caused by algal respiration, bacterial respiration/decay, dead end canals, reduced flow, rainfall events washing excess nutrients into the water causing an algal bloom
Biotoxin	Toxic algal blooms caused by *Karenia brevis* (formerly *Gymnodinium brevis*), *Pfiesteria piscicida*, and *Prymnesium parvum*
Disease	Caused by various bacteria, viruses and other parasites
Inorganic compounds	Ammonia, chlorine, pesticides/herbicides, hydrogen sulfide, metals, drilling mud
Organic compounds	Sewage, pesticides/herbicides, diesel fuel
Physical damage /trauma	Damage to fish caused by seismic activity or by-catch activity
Pollutant	Crude oil, acid, gasoline, liquid hexamethylene diamine, triphenylboron
Temperature	Extreme hot or cold temperatures. Cold temperatures cause the fish to freeze. Cold snaps are particularly hazardous. Hot temperatures can evaporate water quickly leaving pools too small for the fish to survive
Other	Fish kill events with a known cause besides the others listed
Unknown	Fish kill events where a cause has not been determined

Definitions and examples are provided

whether the incident is ongoing and a threat to fish and wildlife exists, and federally or state listed species are threatened. If the incident is being investigated further, water quality information will be collected from the site following the procedures in the TCEQ Surface Water Quality Monitoring Program's procedures manual (www.tceq.state.tx.us). In summary, the investigator will take photographs and videos of the site whenever possible. GPS units are used to identify and record the latitude and longitude at the points where the event began and ended, and also the locations of transects for counting dead fish. Impacted fish and wildlife are identified to the lowest practical taxonomic level, and estimates of total number killed are performed. Established guidelines for conducting systematic sampling include a random start (providing an unbiased starting point) where sample sites are positioned an equal distance apart throughout the area or length of the kill. Specimens may also be collected for further lab analyses.

All pollution and wildlife kill events in the PRISM database that did not cause any fish deaths were not included in our analysis. The remaining events were used to determine the sources, causes, and consequences of fish kills. For all calculations involving fish species killed, the event ID was used to correlate the fish kill information in the events database to the species information in the species database. We would like to point out that interpretation of the findings presented and the conclusions drawn must be treated with some caution because of the limitations associated with the data. The biggest issue relates to the proportion of data collected and deposited in the database between 1951 and 2006 relative to the actual number of fish kills. At least 70% of all fish kills in Texas during the period are thought to be included in the PRISM database (Winston Denton, TPWD, personal communication). The response to fish kills by national and state agencies is primarily dependent on resources and the perceived severity of an event. Other factors that influence the reporting include economic importance of fish species, size of population in surrounding watershed (i.e., how many people witness/report the event), and timeliness of response. The largest and severest events are typically recorded. In addition, not all the events documented contain the same information regarding direct causes and numbers killed. Nonetheless, while the actual numbers are a function of the above caveats, the sources, causes, and consequences are real, as are the general trends.

Results

Trends and Seasonal Variations for Texas

From 1951 to 2006, more than 2,200 fish kill events were recorded in the PRISM database for the coastal counties in Texas. In Fig. 1, the location of specific fish kill events during this 55-year period is indicated with a marker specific to the bay or estuary in which the kill was recorded. These events involved more than an estimated 383 million fish killed, with Galveston and Matagorda Counties having had the largest recorded numbers of fish killed, 37% and 29%, respectively. Sabine Lake (2.6%) had the fewest recorded fish killed. Galveston and Matagorda Bays also had the highest number of recorded fish kill events, 400 and 109, respectively.

Overall, the number of fish kill events recorded and the number of reports recorded increased between 1951 and 2006. We log-transformed the observations given the large

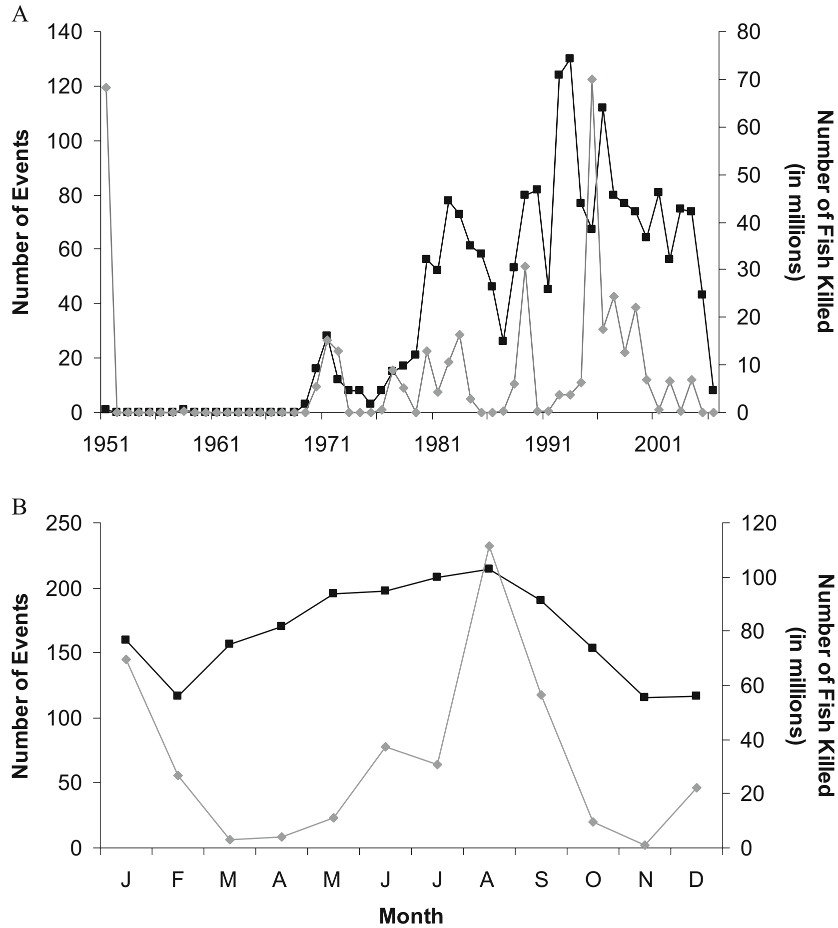

Fig. 2 Trends in fish kills events from 1951 to 2006. **A** The number of events recorded (*filled square*) increased while the number of fish killed (*gray diamond*) showed no trend during this 55-year period. **B** The number of events (*filled square*) varied by month with most kills occurring during the warmer summer months. The number of fish killed (*gray diamond*) peaked in the warm summer months. A second peak in the winter reflected fish kills due to cold freezes

yearly variation and to account for the many years with zero or no fish killed or reported killed. The resulting linear regressions on the log-transformed data gave a correlation of r^2=0.479 for number of fish killed and r^2=0.765 for number of fish reported killed (Fig. 2A). The latter indicates that recording more events did not bias the data towards increased numbers of fish killed. The highest number of fish kills reported in 1 year occurred in 1993 (Fig. 2A), with a total of 130 reports. The greatest number of fish killed in a single year occurred in 1995 with more than 70 million deaths. In 1998, major fish kills occurred in East and West Bays following Tropical Storm Frances as stagnant waters were pushed out of Galveston Bay (TPWD 1998; Lester and Gonzalez 2002). In 1983 and 1989, 31 million fish were killed as a result of cold fronts/freezes when temperatures decreased precipitously.

Like other southern states, Texas is warmest between May and September and coolest between October and April (Quigg et al. 2007). The largest number of fish kill events (64.5%) and highest number of fish killed (more than 247 million) occurred during the warm months (Fig. 2B). The month with the single greatest number of events (214) and the greatest number of fish killed (111 million) was August (Fig. 2B). In contrast, the month with the fewest number of events (116) and the least amount of fish killed (834,000) was November (Fig. 2B). Many fish were killed in winter due to cold fronts and freezes (Fig. 2B).

Sources, Causes, and Consequences for Texas

Sources cited for fish kills along the Texas coastal system include ten different categories: agriculture, commercial fishing, individual, industry, mining, municipal, natural processes, none, reservoir management, and weather (Fig. 3A). Of these, weather (low temperatures, non-point source runoff from precipitation) accounted for 39% of fish kill events, while municipal (unpermitted/permitted discharge, reduced flow leading to low DO) accounted for 23% (Fig. 3A). Natural processes (disease, algal blooms) and industry (oil/gas spills, chemical spills, electric power plant discharges, crude oil spill, inorganic/organic compound spills) constituted another 15% and 11%, respectively. Four percent of kills were caused by “other” sources which included: agriculture (farming, ranching), commercial fishing (shrimping, seining), individual (unpermitted dumping), mining (dredging), or reservoir management

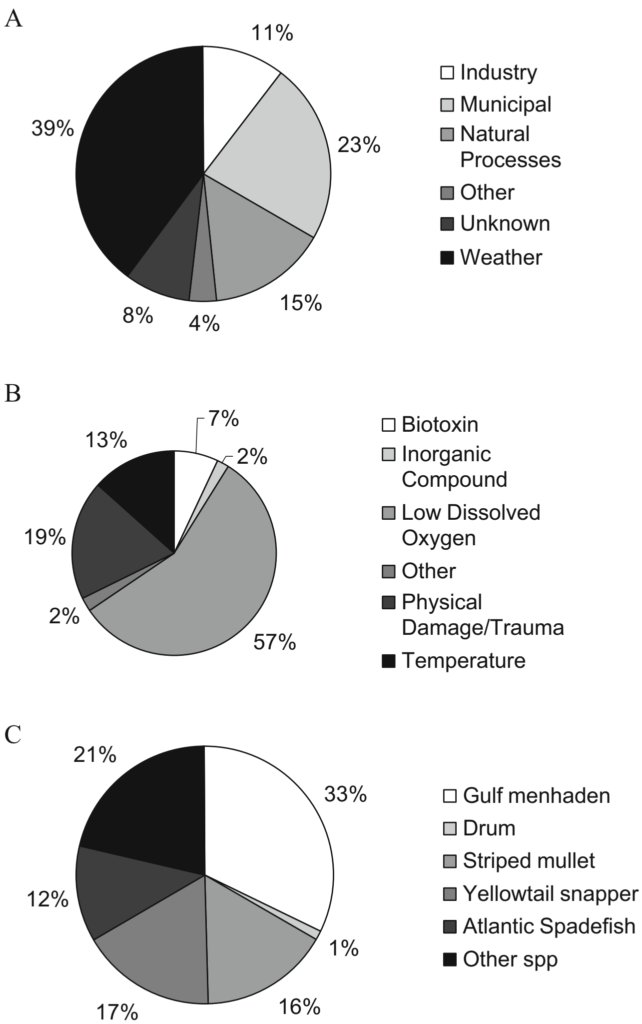

Fig. 3 Fish kills in Texas bays from 1951 to 2006. **A** Sources; **B** causes; and **C** consequences (types of fish killed). The category "other" includes all the causes/sources that were individually responsible for 1% or less of fish kills. All species listed in "other species" individually constitute less than 2% of the total

(decreased flow). A small percentage (8%) was cited as having an unknown source.

There were ten general causes that accounted for the fish kill events in the Texas bays given in the PRISM database; these were summarized in Table 2. The majority of fish kill events in Texas bays (57%) between 1951 and 2006 were caused by low levels of DO concentrations (Fig. 3B). Second to this was physical damage or trauma to the fish, which accounted for 19% of the fish kill events (Table 2 for definition). Biotoxins, produced by harmful algae, accounted for 7%, while 13% were attributed to temperature, typically cold snaps. Inorganic compounds were responsible for 2% of the kill events (Fig. 3B). The category "other" included fish killed due to disease, pollutants, organic compounds, and unknown causes; these collectively caused less than 2% of all events (Fig. 3B).

Reduction in the DO concentrations (hypoxia and sometimes, anoxia) in Texas bays and estuaries predominately occurred in dead-end canals, man-made lakes and embayments (Contreras 2003), particularly in the coastal areas of Houston, Corpus Christi, and South Padre Island. Constructed water bodies for residential or industrial purposes were the site of large fish kills because of poor circulation. Physical and chemical factors including hot weather and seepage from residential septic systems near the canals combined at times to cause the DO level to plummet in canals, killing schools of fish which were not able to move out of the area quickly enough. Menhaden (*B. patronus* and *B. gunteri*) were the most commonly killed fish species in Texas and accounted for 33% of all fish killed (Fig. 3c). Yellowtail snapper (*Lutjanus chrysurus*, 17%), Striped mullet (*Mugil cephalus*, 16%), Atlantic spadefish (*Chaetodipterus faber*, 12%), and spotted sunfish (*Lepomis punctatus*, 2%) made up an additional 47% of the total. Four species of drum (black—*Pogonias cromis*; red—*Sciaenops ocellatus*; star—*Stellifer lancolatus*; banded—*Larimus fasciatus*) accounted for only 1% of the total (Fig. 3c). All these fish species are important components of Texas' commercial and recreational fishery. All other fish species accounted for 21% (less than 1% each) of the total fish killed.

Geographical Distributions

Before 1994, there were relatively few fish killed in Matagorda Bay (Fig. 1; Table 3). However, in the period between 1995 and 1999, low DO levels in a canal off the Colorado River killed 50 million Gulf menhaden. During that period, an additional 24 million were killed in several smaller events caused by low DO, bringing the total killed to more than 74 million (Table 3). Thereafter, no additional kills of such magnitude were recorded for Matagorda Bay. Large numbers of fish were killed in Laguna Madre during 1995 to 1999 (35 million) and 2000 to 2006 (7.3 millions). These kill events were attributed to a cold freeze and low DO levels. A bloom of *Karenia brevis*, a toxic alga, was responsible for fish killed in early 2000 (Denton and Contreras 2004). Mass kill events in Corpus Christi Bay between 1980 and 1984, 1985 and 1989, and 1995 and 1999 were caused by low DO, a gasoline spill and seismic exploration, respectively. Approximately eight million fish were killed during these events (Table 3). Sabine Lake, San Antonio Bay, and Copano and Aransas Bays had similarly large fish kills that were also attributed to low DO (Table 3).

Galveston Bay

Galveston Bay is the largest and most economically and recreationally important estuary in Texas. Although there were no general trends with time between 1951 and 2006 in

Table 3 The number of fish killed (millions) in 5-year intervals from 1970 to 2006 varied as a function of ecosystem

	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	2000–2006
Sabine Lake	0.002	0	0.007	0.370	1.1	6.1	0.001
Galveston Bay	31.2	14.4	26.1	6.8	9.6	8.0	8.3
Matagorda Bay	0.005	0.510	2.1	1.0	1.0	74.1	11.8
San Antonio Bay	0	0	0.003	0.014	0.016	14.0	0.141
Corpus Christi Bay	0.001	0	2.1	2.8	0.018	3.1	0.031
Copano & Aransas Bay	0	0.052	1.0	0.003	4.0	6.1	0.509
Laguna Madre[a]	2.2	0.025	1.4	0.005	0.067	35.2	7.4

The source, cause and consequence of major events were reported in the text. The years 1951–1969 were not included because very few events were recorded during this time.

[a] Upper and Lower Laguna Madre were combined.

terms of fish kill events and number of fish killed, five significant mass mortality events were recorded:

(a) 1971–72—25.7 million, low DO, permitted discharge and a hydrogen sulfide spill;
(b) 1977—nine million, low DO from an unknown cause;
(c) 1980—12.9 million, low DO, sewer line spill and non-point source runoff;
(d) 1983 and 1989—15.7 and 22 million, respectively, cold freezes; and
(e) 2000—6.8 million, caused by a toxic algal bloom of *K. brevis*.

Although these fish kills had varied sources, the majority were caused by low DO (78%; Fig. 4A), mainly in small streams and canals. The majority of fish killed in Galveston Bay (Fig. 4B) were menhaden (*B. patronus* and *B. gunteri*), which accounted for 72% of all reports. A total of 101 different species of fish accounted for the remaining 28%: striped mullet (*M. cephalus*; 13%), pinfish (*Lagodon rhomboids*; 5%), and Atlantic croaker (*Micropogonias ungulatus*; 2%) accounted for other significant losses (Fig. 4B). The sources of the low DO that caused the menhaden kill events were predominately associated with weather (cold fronts; 26%), industry (physical damage from seismic operations; 14%), or municipal (runoff from agricultural and urban areas; 23%) practices in Galveston Bay (Fig. 4C). Eight percent had other sources including agriculture, natural processes, and reservoir management, while 29% of sources remain unknown.

Discussion

Designation of Texas as a “hotspot” for fish mortalities relative to the other 22 coastal US states is of serious concern for scientists, resource managers, and the public alike. We investigated the major sources and causes of fish kills in Texas from 1951 to 2006 and the consequences. Primarily, an estimated 383 million fish were killed over the

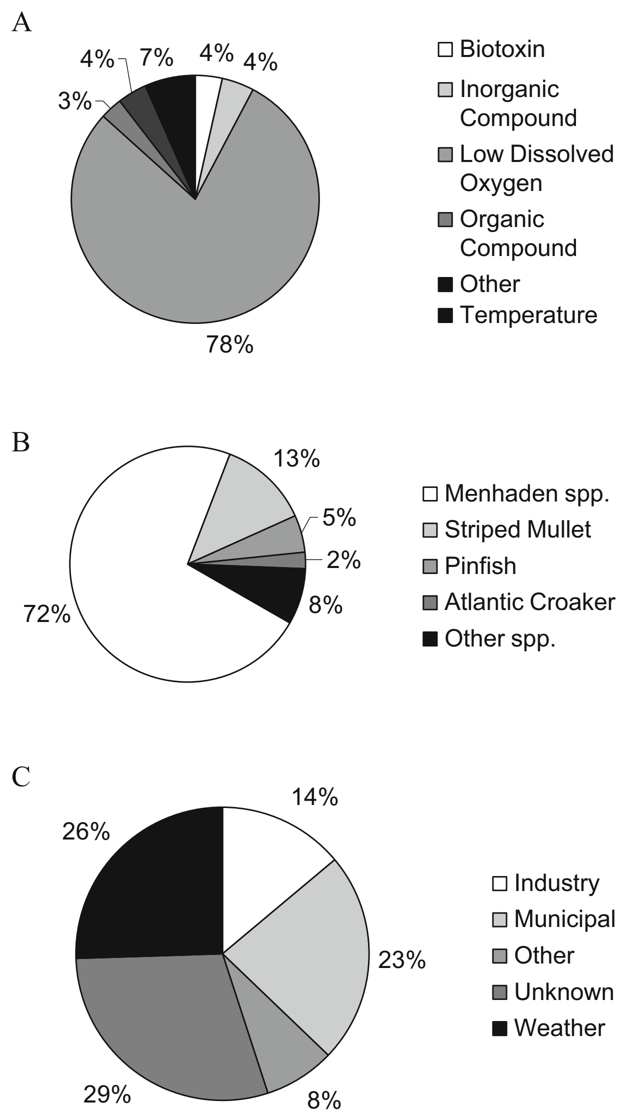

Fig. 4 Galveston Bay fish kill events from 1970 to 2006. **A** Causes; **B** Species of fish killed; and **C** Sources of *Menhaden* spp. kill events from 1970 to 2002 in Galveston Bay. The category “other” includes all the causes/sources that were individually responsible for 1% or less of fish kills. All species listed in “other species” individually constitute less than 2% of the total

55-year period, mostly menhaden. Of particular concern was that this number is likely to be an underestimate, that is, not all fish kill events were recorded, and not all dead fish were accounted for if they were not visible or had been washed away from the area of a kill. Smaller events will, over time, potentially account for an additional large number of fish killed in the state. Of particular interest to us was to determine if the high incidence of fish kill events was a function of the climate and the physical features of Texas bays and estuaries or, alternatively, a function of the high density of industrialization and urbanization along Texas coastal centers. With the population predicted to double in Texas by 2050, mostly along the coastal areas, natural resources will be placed under additional stress and consequently require additional protection. Defining the sources and causes of fish kill events in Texas will allow better management and conservation efforts.

Thermal stratification is common in the bays and estuaries along the Texas coast due to their shallow nature, low flushing rates and, in some cases, large area along with high average air and water temperatures (Table 1). Hydrographic data indicated that hypoxia in Texas estuaries was predominately a transient event (hours) caused by a combination of biotic (i.e., respiration) and abiotic processes (i.e., low mixing potential). Coastal systems in Texas which have already received much attention are Corpus Christi Bay, in which hypoxia induced by eutrophication was first documented in 1988 (Montagna and Kalke 1992; Martin and Montagna 1995; Ritter and Montagna 2001), and Galveston Bay and its various embayments, which have a long history of recorded fish kills and hypoxia (Gunter 1942). In Lake Madeline and Offatts Bayou (Galveston Bay), algal blooms and prolonged dry periods lead to bottom water hypoxia which lasts from several weeks to months (Roehrborn 2006; Skinner 2007).

The population centers in Texas are expected to double by 2050 (TWDB 2007). In many situations, cities are not prepared to handle the increase in pollutant loading. DCPP is a measure of the nutrient concentration potential of a pollutant in a watershed. In Texas, those bays and estuaries with low flushing rates and large surface areas had higher DCPP values (Table 1). This was exacerbated in locations that were highly urbanized (e.g., Aransas Bay) and/or industrialized (e.g., Corpus Christi Bay). Galveston Bay had a low DCPP (0.5 mg l^{-1}) despite being the largest urban and industrial center on the Texas coast, perhaps because it also has a relatively fast (112 days) flushing rate compared to other systems.

Eutrophication, Algal Blooms, and Low DO

Overloading marine ecosystems with inorganic nitrogen (most often in the form of ammonia and nitrite) has led to eutrophication of many systems (Breitburg 2002; Diaz 2002). There has been a concurrent increase in nuisance or toxic algal blooms in eutrophic waters in many estuaries and coastal seas worldwide, including those in Texas. During the 1980s, toxic blooms of dinoflagellates and brown-tide organisms caused extensive die-offs of fish and shellfish in many Texas estuaries. Aquatic life in the Laguna Madre in south Texas, for example, was devastated by a recurring bloom of the brown tide organism, *Aureoumbra lagunensis*. Interestingly, it was thought that nitrogen from decomposing fish that died as a result of a freeze in December 1989 may have played a role in fueling the initial bloom in Laguna Madre (Buskey et al. 2001).

Biotoxin (defined in Table 2) was responsible for 19 major fish kills recorded for Texas. Of these, 14 were caused by *K. brevis* (dinoflagellate), one each was caused by *Microcystis aeruginosa* (cyanobacteria) and *P. parvum* (haptophyte). The responsible organism for the other three events is unknown. An extensive red tide bloom of *K. brevis* impacted the Texas coast in 2000 (Denton and Contreras 2004). Neurotoxic shellfish poisoning has been documented in Texas waters (NRC 2000), but this was not always associated with fish kills despite toxin accumulation in fish and shellfish. A frequently cited link between harmful algal blooms, nutrient pollution, and fish kills in other systems is the dinoflagellate *Pfiesteria*. In North Carolina estuaries and in Chesapeake Bay, this organism was associated with fish kills and, in addition, linked to a variety of human health effects, including severe learning and memory problems (Boesch et al. 2001; Burkholder et al. 2001). However, Morris et al. (2006) found that in the absence of an outbreak situation or the identification of a particularly toxic strain, the routine occupational exposure to estuarine waters in which *Pfiesteria* is known to be present does not represent a significant human health risk. *Pfiesteria*- and *Pfiesteria*-like-organism-associated fish kills typically occur in watersheds that are heavily polluted by hog and chicken farm wastes and by municipal sewage. *Pfiesteria* has been found in low cell densities in Texas bays and estuaries, but has never been cited as the casual factor in a fish kill.

One consequence of algal blooms (harmful and non-harmful) is the development of hypoxia as the bloom decays through the water column (Boesch et al. 2001; Breitburg 2002; Wu 2002; Contreras 2003; Granéli and Turner 2006). Bloom-induced hypoxia affects thousands of square kilometers around the world and has caused mass mortality of marine animals, benthic defaunation, and decline in fisheries production in many places. Since the 1960s, increasing hypoxia and anoxia have been blamed for the replacement of the highly valued demersal fish species with less desirable planktonic omnivores (Diaz 2002). Of the 26 commercial species fished in the Black Sea in the

1960s, only six still supported a fishery in the 1990s (Mee 1992). At a minimum, nutrient delivery into hypoxic systems must be reduced in an effort to restore healthy populations and decrease the occurrence of eutrophication (Mee 2006). Due to rapid human population growth and global warming, along with overfishing of menhaden, the problem of hypoxia is likely to worsen in coming years. Menhaden are able to filter at least four gallons of water a minute or 5,760 gallons a day. Because of overfishing of menhaden, the population has been drastically reduced, particularly along the east coast (Franklin 2007). As the menhaden population decreases, the phytoplankton populations are allowed to bloom without being kept in check by menhaden consumers. If the menhaden population decreases from overfishing and fish kill events, we can expect to see an even larger increase in blooms in the coming years. Indirect or sublethal effects of hypoxia may include impacts on fish distribution, behavior, feeding rate, competition, and vulnerability to predators (Sklar and Browder 1998; Wannamaker and Rice 2000; Breitburg 2002). Sensitive fish species have been permanently or periodically removed in many places (Wu 2002). Decreases in fish species diversity and species richness are well documented, and changes in trophodynamics and functional groups have also been reported. Unfortunately, such studies have not been performed in Texas estuaries. They should be considered in future programs if there is to be a proper evaluation of fisheries populations in these systems.

According to Lowe et al. (1991), low DO levels were the leading cause of major fish kill events in 22 coastal states from 1980 to 1989, with menhaden and other small, schooling fish being the most affected in estuarine areas. Menhaden are an important commercial species to the Texas coast and are a primary prey species for highly sought recreational species both in Texas and the Gulf of Mexico (Vaughan et al. 2001). Gulf menhaden are obligate filter feeders attracted to bayou channels with low flow and high chlorophyll. They utilize these tidal streams as nursery areas and are usually present in dense numbers (1,000s to 100,000s) near the surface, making them susceptible to DO depletion kill events. Wannamaker and Rice (2000) found that Atlantic menhaden (*Brevoortia tyrannus*) strongly avoided low DO concentrations when given a choice. So do many other fish including juvenile spot (*Leiostomus xanthurus*), pinfish (*Lagodon rhomboides*), croaker (*Micropogonias undulatus*), white mullet (*Mugil curema*), mummichog (*Fundulus heteroclitus*), and brown shrimp (*Penaeus aztecus*; Wannamaker and Rice 2000; Wu 2002). Perhaps what makes *Brevoortia* spp. particularly susceptible to low DO in Texas is that (1) they are attracted to high chlorophyll concentrations to feed, which also happen to be the most oxygen-depleted as a bloom decays, (2) they school in large numbers, and (3) they require an ample supply of oxygen such that a dense school is quite vulnerable to oxygen depletion. Although direct effects of low DO are more easily quantified, the indirect effects may be of equal or greater importance in understanding the links between water quality, fish populations, and estuarine community health.

Other Concerns

Gross external pathological abnormalities (e.g., fin erosion, cutaneous ulcers, cataracts, tumors) are used as indicators of anthropogenic influences in estuarine and marine waters. Demersal fish are often more impacted than pelagic fish, a phenomenon associated with high sediment contaminant loading (Fournie et al. 1996; Breitburg 2002). Among estuaries along the Gulf of Mexico and the mid-Atlantic, pathological abnormalities were found to be most prevalent in Galveston Bay (TX), while the lowest were recorded for Long Island Sound (RI) and the Mississippi Sound (LA; Fournie et al. 1996). There are no studies which have documented in a comprehensive manner external abnormalities on fish in Texas between 1951 and 2006; hence, we cannot correlate this bioindicator with findings for fish kills. We hypothesize that the effect of stressors such as pollutants on fish is amplified in the presence of hypoxic conditions, particularly those induced by eutrophication. Future investigations should examine if there are any correlations between early warning signs of environmental perturbations on fish, such as gross pathological abnormalities, with the dominant environmental cause of fish deaths, low DO. Such a study may help explain why Texas, and Galveston Bay in particular, is a hotspot for fish kills.

Significance of Fish Kills to Human Health and Climate Change

The possibility that toxins produced by *K. brevis*, *Microcystis aeruginosa*, *Pfiesteria*, and/or other phytoplankton might affect human health either directly by exposure in the environment or indirectly by consumption through fish or shellfish has been a public concern. The US EPA (1999) stated that “There is no evidence that shows that people can get sick from eating fish or shellfish that have been caught in coastal waters that contain toxic *Pfiesteria piscicida*,” but it goes on to warn that to be safe, people should avoid eating fish with lesions. Similar such warnings are posted by other agencies (e.g., TPWD) for this and other toxin-induced fish deaths. However, public awareness remains limited.

An understanding of climate influences on fisheries and ecosystems requires an evaluation of the thermal limits of resident species and their ability to cope with changing temperatures. Pörtner and Knust (2007) found that there is a mismatch between fisheries demand for oxygen and the capacity of ecosystems to supply sufficient oxygen. Although the reduction in nocturnal DO levels is in itself not normally lethal, enhanced eutrophication and other anthropogenic impacts, concurrent with warmer waters which carry less DO, will likely lead to lowered aerobic fish performance (Breitburg 2002; Franco et al. 2002; Tuvikene et al. 2002). If prolonged, this may lead to relocation of fish to cooler waters and/or extinction.

Conclusion

Coastal areas are home to more than 53% of the US population, despite comprising only 17% of the land mass (UNEP 1991; NRC 2000). In addition, coasts of the USA are a source of valuable commodities. Thirty-one percent of the gross national product and 85% of commercially harvested fish are dependent on estuarine habitats (Benson and Summers 2002). For states such as Texas, where the combination of physical, climatic, and anthropogenic factors will conflict with expected population growth (TWDB 2007), fish kills remain a serious concern. Further increases in nutrient loading into coastal waters can be expected, since it is unlikely that construction of sewage treatment facilities will keep up with rapid population growth in coastal population centers (Eric Wilson, personal communication). Second, the use of fertilizers, loss of wetlands and riparian areas coincident with the increased release of nitrogen oxides into the atmosphere will further enhance eutrophication. While habitat protection is recognized as important, the links between habitat quality and fish population responses remain largely unclear. The results of this study provide a basis for understanding the major sources, causes, and consequences of fish kills in Texas bays and estuaries, particularly Galveston Bay. Understanding the relationships between these parameters is an important basis for developing effective policy which in turn is crucial for present and future attempts to protect and enhance our coastal and estuarine environments.

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References

Benson, W.H., and J.K. Summers. 2002. The ecological condition of estuaries: A focus on the Atlantic Ocean and Gulf of Mexico Coasts of the United States. In *Proceedings of the sixth international symposium, fish physiology, toxicology, and water quality*, ed. R.V. Thurston, 297–310. Athens, Georgia: Ecosystems Research Division.

Biernacki, E. 1979. *Fish kills caused by pollution*. Washington, DC: Environmental Protection Agency, 0-277-208.

Boesch, D.F., R.B. Brinsfield, and R.E. Magnienc. 2001. Chesapeake bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. *Journal of Environmental Quality* 30: 303–320.

Breitburg, D. 2002. Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries* 25: 767–781.

Burkholder, J.M., H.B. Glasgow, and N. Deamer-Melia. 2001. Overview and present status of the toxic Pfiesteria complex (Dinophyceae). *Phycologia* 40: 186–214.

Buskey, E.J., H. Liu, C. Collumb, and J.G.F. Bersano. 2001. The decline and recovery of a persistent Texas brown tide algal bloom in the Laguna Madre (Texas, USA). *Estuaries* 24: 337–346. doi:10.2307/1353236.

Clement, C., S.B. Bricker, D.E. Pirhalla. 2001. Eutrophic conditions in estuarine waters. I. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Contreras, C. 2003. Thirty years of investigating fish and wildlife kills and pollution in Texas. Texas Parks and Wildlife Department, WRTS-2003-001. Austin, TX.

Denton, W., and C. Contreras. 2004. *The red tide (Karenia brevis) bloom of 2000*. Austin, TX: Texas Parks and Wildlife Department.

Diaz, R.J. 2002. Hypoxia and anoxia as global phenomena. In *Proceedings of the sixth international symposium, fish physiology, toxicology, and water quality*, ed. R.V. Thurston, 183–202. Athens, Georgia: Ecosystems Research Division.

Engle, V.D., J.C. Kurtz, L.M. Smith, C. Chancy, and P. Bourgeois. 2007. A classification of U.S. estuaries based on physical and hydrologic attributes. *Environmental Monitoring and Assessment* 129: 397–412. doi:10.1007/s10661-006-9372-9.

EPA. 1999. *What you should know about fish lesions*. Washington, DC: United States Environmental Protection Agency Office of Water.

Fournie, J.W., J.K. Summers, and S.B. Weisberg. 1996. Prevalence of gross pathological abnormalities in estuarine fishes. *Transactions of the American Fisheries Society* 125: 581–590. doi:10.1577/1548-8659(1996)125<0581:POGPAI>2.3.CO;2.

Franco, J., E. Aspillaga, I. Muxika, V. Pérez, O. Solaun, and Á. Borja. 2002. Hypoxia and anoxia in small temperate estuaries: patterns of oxygen deficiency, effects, and recovery. In *Proceedings of the sixth international symposium, fish physiology, toxicology, and water quality*, ed. R.V. Thurston, 79–94. Athens, Georgia: Ecosystems Research Division.

Franklin, H.B. 2007. *The most important fish in the sea*. Washington, DC: Island Press.

GBEP. 2001. The comprehensive and management plan for the Galveston Bay Ecosystem. http://gbic.tamug.edu/GBPlan/GBPlan.html. Last accessed 28 Nov 2007.

Granéli, E., and J.T. Turner. 2006. An introduction to harmful algae. In *Ecology of harmful algae*, eds. E. Granéli, and J.T. TurnerBerlin: Springer.

Gunter, G. 1942. Offatts Bayou, a locality with recurrent summer mortality of marine organisms. *American Midland Naturalist* 28: 631–633. doi:10.2307/2420894.

KAST. 2006. Kills and Spills Team standard operating procedures manual. In TPWD (ed.).

Lester, J., and L. Gonzalez. 2002. *The state of the bay: A characterization of the Galveston Bay ecosystem*. The Galveston Bay Estuary Program.

Lowe, J.A., D.R.G. Farrow, A.S. Pait, S.J. Arenstam, and E.F. Lavan. 1991. *Fish kills in coastal waters: 1980–1989*. National Oceanic and Atmospheric Administration.

Martin, C.M., and P.A. Montagna. 1995. Environmental assessment of LaQuinta Channel, Corpus Christi Bay, Texas. *Texas Journal of Science* 47: 203–222.

Mee, L. 1992. The black sea in crisis: a need for concerted international action. *Ambio* 21: 278–286.

Mee, L. 2006. Reviving dead zones. *Scientific American* 295: 78–85.

Montagna, P.A., and R.D. Kalke. 1992. The effect of freshwater inflow on meiofaunal and macrofanal populations in the Guadalupe and Nueces Estuaries, Texas. *Estuaries* 15: 307–326. doi:10.2307/1352779.

Morris, J.G., L.M. Grattan, L.A. Wilson, W.A. Meyer, R. McCarter, H.A. Bowers, J.R. Hebei, D.L. Matuszak, and D.W. Oldach. 2006. Occupational exposure to Pfiesteria species in estuarine waters is not a risk factor for illness. *Environmental Health Perspectives* 114: 1038–1043.

Moulton, D.W., L.D. McKinney, and D.L. Buzan. 2004. Texas coastal ecosystems: past, present and future. In TPWD.

NRC. 2000. *Clean coastal waters: Understanding and reducing the effects of nutrient pollution*. Washington, DC: National Academy Press.

PHA. 2006. The Port of Houston Authority. Houston, TX. http://www.portofhouston.com. Last accessed 12 Nov 2007.

Pinckney, J.L. 2006. System-scale nutrient fluctuations in Galveston Bay, Texas (USA). In *Functioning of microphytobenthos in estuaries*, eds. J.C. Kromkamp, Jody F.C. de Brouwer, G.F. Blanchard, R.M. Forster, and V. Créach, 141–164. Amsterdam, The Netherlands: Royal Netherlands Academy of Arts and Sciences.

Pollution Response Inventory and Species Mortality Database. Unpublished data 1951–2006. Texas Parks and Wildlife Department.

Poon, W.L., C.Y. Hung, and D.J. Randall. 2002. The effect of aquatic hypoxia on fish. In *Proceedings of the sixth international symposium, fish physiology, toxicology, and water quality*, ed. R. V. Thurston, 31–50. Athens, Georgia: Ecosystems Research Division.

Pörtner, H.O., and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* 315: 95–97. doi:10.1126/science.1135471.

Quigg, A., S.E. Davis, and D.F. Roelke. 2007. Changes in freshwater inflows and how they effect texas bays. Final Report of the Coastal Coordination Council pursuant to National Oceanic and Atmospheric Administration Award No. NA05NOS4191964.

Rabalais, N.N. 1998. *Oxygen depletion in coastal waters*. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Roehrborn, L. 2006. Seasonal analysis of abiotic factors impacting phytoplankton assemblages in Offatts Bayou, Galveston, Texas, Texas A&M University, College Station, TX. 273 pp.

Ritter, M.C., and P.A. Montagna. 2001. Cause and effects of hypoxia (low oxygen) in Corpus Christi Bay, Texas. Coastal Management Program, TR/01/001. Austin, Texas.

Roelke, D.L., R.M. Errera, R. Kiesling, B.W. Brooks, J.P. Grover, L. Schwierzke, F. Ureña-Boeck, J. Baker, and J.L. Pinckney. 2007. Effects of nutrient enrichment on *Prymnesium parvum* population dynamics and toxicity: results from field experiments, Lake Possum Kingdom, USA. *Aquatic Microbial Ecology* 46: 125–140. doi:10.3354/ame046125.

Skinner, A.C. 2007. Belly-up in the Bayou, who's the culprit? Physical, chemical, and biological parameters of Offatts Bayou, Galveston, Texas, Texas A&M University at Galveston, Galveston, TX. 64 pp.

Sklar, F.H., and J.A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* 22: 547–562. doi:10.1007/s002679900127.

Thurston, R.V. 2002. *Fish physiology, toxicology, and water quality proceedings of the sixth international symposium*. La Paz, B.C.S. Mexico: Ecosystems Research Division.

Tuvikene, L., P. Nõges, and T. Nõges. 2002. Hypoxia/anoxia in Lake Vortsjarv, Estonia. In *Proceedings of the sixth international symposium, fish physiology, toxicology, and water quality*, ed. R. V. Thurston, 147–162. Athens Georgia: Ecosystems Research Division Athens.

TWDB. 2007. Highlights of the 2007 State Water Plan. Texas Water Development Board.

TPWD. 1998. Frances' Rains Leave Deadly Legacy: Fish Kills. Austin, TX. http://www.tpwd.state.tx.us/news/news/980928a.htm. Last accessed 7 May 2007.

UNEP. 1991. The state of the world environment. Nairobi.

Vaughan, S.L., C.N.K. Mooers, and S.M. Gay. 2001. Physical variability in Prince William sound during the SEA study (1994–98). *Fisheries Oceanography* 10: 58–80. doi:10.1046/j.1054-6006.2001.00034.x.

Vaughan, D.S., K.W. Shertzer, and J.W. Smith. 2007. Gulf menhaden (*Brevoortia patronus*) in the U.S. Gulf of Mexico: fishery characteristics and biological reference points for management. *Fisheries Research* 83: 263–275. doi:10.1016/j.fishres.2006.10.002.

Wannamaker, C.M., and J.A. Rice. 2000. Effects of hypoxia on movements and behavior of selected estuarine organisms from the southeastern United States. *Journal of Experimental Marine Biology and Ecology* 249: 145–163. doi:10.1016/S0022-0981(00)00160-X.

Wu, R.S.S. 2002. Hypoxia: From molecular responses to ecosystem responses. *Marine Pollution Bulletin* 45: 35–45. doi:10.1016/S0025-326X(02)00061-9.