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Tropical Storm and Hurricane Impacts on a Gulf Coast Estuary: Apalachicola Bay, Florida

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ABSTRACT

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Since 1985, various long-term monitoring programs have been in place in the Apalachicola Bay area that can be utilized to determine the effects of tropical storms and hurricanes on the natural resources of the area. The size, speed of movement, severity, angle and direction of landfall, as well as storm surge height and the amount and location of precipitation all play a role in determining impacts. Short-term impacts seen in the bay from these tropical events include water quality alterations, such as salinity and turbidity changes, water level changes, and loss of sea turtle nests. Long-term impacts include changes to the structure of the beach, dunes, and bayside areas on a barrier island, loss of or changes in submerged aquatic vegetation distribution, and the physical alteration of oyster reefs as well as oyster populations. In particular, Hurricane Dennis in 2005 caused the complete loss of fresh and brackish submerged aquatic vegetation in the upper areas of the bay. Larger storms in 1995 and 2004, such as Hurricane Opal and Hurricane Ivan, caused relatively little damage to natural resources. Hurricane Elena in 1985 caused massive damage to the local oyster industry, which took several years to recover.

ADDITIONAL INDEX WORDS: *Water quality, coastal erosion, oyster reefs, submerged aquatic vegetation, sea turtles.*

INTRODUCTION

Between 1851 and 2004, 273 hurricanes impacted the U.S. coastline between Maine and Texas. Of these, 92, more than one-third, had direct hits on Mississippi, Alabama, and the northwest Florida panhandle (BLAKE *et al.,* 2005). This number does not include tropical storms that may also have impacted these states. During the last 10 years the frequency of direct hits of hurricanes in the southeastern United States has increased and is expected to remain high in the near future (EMANUEL, 2005; GOLDENBERG *et al.,* 2001; WEBSTER *et al.,* 2005).

Recent analysis of the ecological effects on estuarine and coastal areas from the 2004 hurricane season, a record-breaking year for the number of storms, demonstrates initial impacts on the environment but generally not long-term catastrophic changes such as those which occur to human infrastructure (GREENING, DOERING, and CORBETT, 2006). Typical impacts associated with hurricane activity include increased nutrients, hypoxia, fish kills, increased pollutant loading, increased coliform and pathogen loading, exotic species expansion, and potential harmful algal blooms events. However, it is important to realize that no two hurricanes are the same, and impacts to the environment, infrastructure, and human society vary with differing characteristics associated with individual storms (MALLIN and CORBETT, 2006).

Damage to both artificial structures and natural resources, including physical, chemical, and biological impacts, is typically caused by wind, wave action, storm surge, precipitation, or a combination of these. The amount or severity of damage can be related to the direction of hurricane movement relative to the coastline, the speed or forward movement of the storm, the strength of the wind, and the overall size of the storm, as well as the size of the central core, the number of tornadoes spawned, the amount of precipitation, the size and severity of the storm surge, the tidal conditions at the time of impact, the overall size of associated wave action, and the shoreline configuration and bottom topography of the area (DOEHRING, DUEDALL, and WILLIAMS, 1994). Depending on the severity of many of the above factors, even tropical storms can cause severe damage to property and natural resources.

National Estuarine Research Reserve System-Wide Monitoring Program

The Apalachicola Bay National Estuarine Research Reserve (ANERR), located in the eastern panhandle of Florida,

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is within the hurricane zone described above. A coordinated national monitoring program called the System-Wide Monitoring Program (SWMP) was established in 1995 "to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds." The SWMP was designed to be a phased monitoring approach that focused on three different ecosystem characteristics:

- *Abiotic Factors,* including atmospheric, water quality, and physical parameters (salinity, tidal range, groundwater, freshwater inflow, bathymetry, *etc.*)
- *Biological Monitoring,* including biodiversity, habitat, and population characteristics
- *Watershed and Land Use Classifications,* including changes in consumptive and nonconsumptive uses (National Oceanic and Atmospheric Administration, 2007).

An initial analysis of SWMP datasets from numerous NERR sites in 2002 found that abrupt decreases in water temperature (from 1 °C to >5 °C) were commonly found before storm passage and the amount of cooling was strongly related to the intensity of the approaching storm. Whereas this phenomenon has been widely studied in open oceans, it has received little attention in estuarine and coastal systems (Sanger *et al.,* 2002). Short-term changes in salinity and depth were variable and appeared to be dependent on the fetch of approaching tropical systems. Initial increases in both parameters were generally followed by decreases due to precipitation and strong winds driving water out of the systems following passage of the storms. Changes in water quality were generally abrupt and short-lived, lasting less than 24 hours. Some long-term effects, lasting several weeks and related to salinity, were probably caused by excessive runoff (Sanger *et al.,* 2002).

Increased spatial and temporal information, the addition of nutrient data, and increased biological data collection programs at the individual NERR sites enable the tracking and identification of local and regional impacts of tropical systems on the natural resources of estuarine and coastal systems. The ability to compare natural disaster effects on relatively pristine systems, like the NERR sites, to more developed estuaries across the Gulf of Mexico should provide useful information to coastal managers trying to determine how to reduce or mitigate future impacts from these events. This article is a compilation of impacts noted from these authors and others in and around Apalachicola Bay from tropical storms and hurricanes.

METHODS, TECHNIQUES, MATERIALS, AND STUDY AREA

Study Site

The Apalachicola Bay system is a wide, shallow estuary that covers an area of approximately 54,390 ha behind a chain of barrier islands (Gorsline, 1963). Its primary source of freshwater is the Apalachicola River. The Apalachicola River basin is only part of the larger Apalachicola-Chattahoochee-Flint (ACF) River system. The Chattahoochee River flows 702 km from its source in the Blue Ridge Mountains of northern Georgia and drains a land area of 22,400 km². The Flint River flows 563 km from its source south of Atlanta and drains a land area of 22,000 km². The Apalachicola River is a large alluvial river formed by the confluence of the Chattahoochee and Flint Rivers, flows 172 km to Apalachicola Bay, and drains a land area of approximately 6,216 km² (U.S. Army Corps Of Engineers, 1978). The entire ACF basin covers the north-central and southwestern part of Georgia, the southeastern part of Alabama, and the central part of the Florida panhandle. It drains an area covering approximately 50,760 km² (Figure 1).

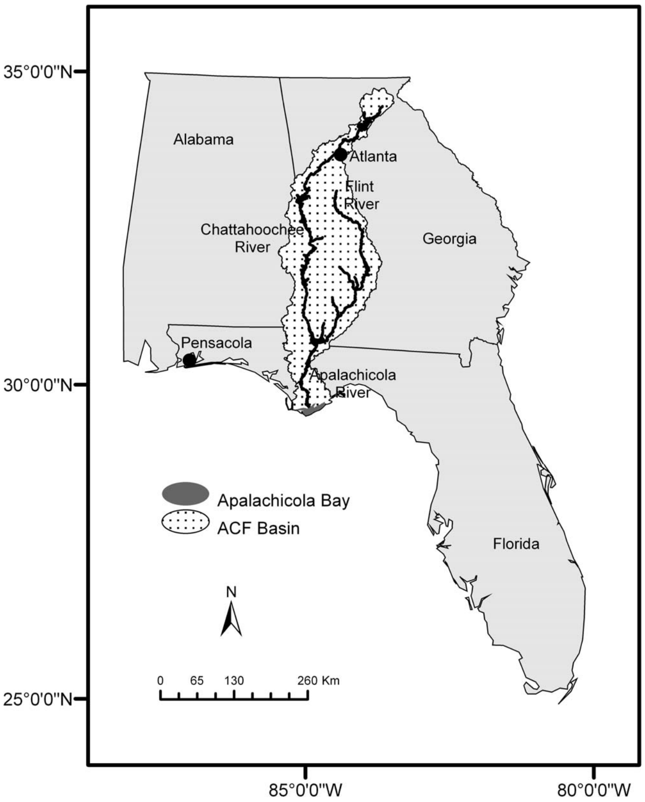

Figure 1. Apalachicola-Chattahoochee-Flint (ACF) river system.

Apalachicola Bay is behind a well-developed barrier island complex composed of four islands: St. Vincent, Cape St. George, St. George, and Dog Island, lying roughly parallel to the mainland. The estuarine system may be divided into four sections based on both natural bathymetry and artificial structural alterations: East Bay, St. Vincent Sound, Apalachicola Bay, and St. George Sound (Figure 2). Average depth in these bays ranges from 0.9 m in East Bay to 2.7 m in Apalachicola Bay, with maximum depths up to 6.1 m occurring toward the barrier islands (Dawson, 1955; Gorsline, 1963). Major estuarine habitats found within the bay include oyster bars, submerged vegetation, tidal flats, soft sediment, tidal marshes, and open water habitats (Edmiston and Tuck, 1987).

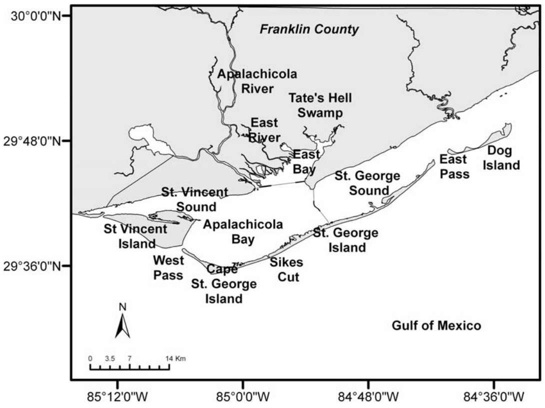

Figure 2. Major components of the Apalachicola Bay System.

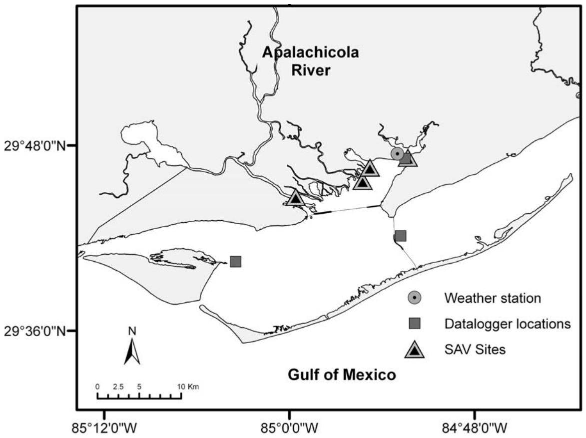

Figure 3. Sampling station locations in Apalachicola Bay.

Water Quality Monitoring

Water quality data are collected continuously at three locations within Apalachicola Bay (Figure 3). The Cat Point site is located in St. George Sound on the east side of the Bay, at a latitude of 29°42.12′ N and longitude 84°52.81′ W. Water depth at the site is approximately 2.5 m, and mixed tides vary from 0.3 m to 1.0 m. Salinity ranges from 0‰ to 32‰. Freshwater influencing Cat Point comes from the Apalachicola River and runoff from Tate's Hell Swamp, whereas high salinity Gulf water comes mainly from East Pass at the eastern end of St. George Island. The Dry Bar site is located in the western part of Apalachicola Bay, about 0.8 km east of St. Vincent Island. The datalogger is located at 29°40.48′ N and 85°03.50′ W. Water depth is approximately 2 m, and the mixed tides range from 0.3 m to 1.0 m. Salinity varies from 0‰ to 34‰. Freshwater reaches the site from the Apalachicola River and Gulf water from West Pass and Sikes Cut. The Cat Point and Dry Bar sites are located on two of the most productive oyster beds in the bay, with bottom types of oyster bed and no vegetation except for attached algae during the summer months.

The East Bay site is located in East Bay, north of Apalachicola Bay, and is primarily influenced by tannic freshwater runoff from Tate's Hell Swamp, the East Bay marshes, and distributary flow from the Apalachicola River via the East River. The datalogger is located at 29°47.15′ N and 84°52.52′ W, and water depth at the site is 2.2 m. Salinity ranges from 0‰ to 30‰. Tides are mixed and range from 0.3 m to 1.0 m. The bottom sediment is soft silt and clay, with no vegetation present.

Data have been collected at 30-minute intervals continuously since May 1992 and 15-minute intervals since December 2006 at all three sites. Since 1995, data have been collected as part of NOAA's NERR SWMP, and all standardized SWMP methods have been followed. Hydrolab dataloggers were used at some sites from 1992–2001, and YSI 6600 Extended Deployment System (EDS) dataloggers have been used from 1999 through the present. The sondes collect the following parameters every 15 minutes: temperature (°C), conductivity (mS/cm), salinity (‰), dissolved oxygen saturation (% and mg/L), water level (m), pH (pH units), and turbidity (NTU). The EDS sondes, which minimize fouling due to wiper brushes, are switched out every 2 to 3 weeks. At each deployment and retrieval, discreet measurements of dissolved oxygen, pH, salinity, and temperature are taken to compare readings with those of the datasondes. Before and after deployment all probes are calibrated to lab standards, downloaded, analyzed for anomalies and missing data, and submitted to a website for public availability following SWMP protocols (Small, 2004).

Coastal Erosion Monitoring

Erosion profiling is conducted at six sites on Cape St. George Island. Cape St. George Island is a narrow barrier island more than 14.5 km long and varying from 0.4 km to 1.6 km wide. Profiles have been conducted once or twice yearly since 1995 and three to four times annually since 2003 (Figure 4). The profiling program consists of four sites on the Gulf side of the island and two on the bay side. These sites were selected to provide a picture of erosion around the entire

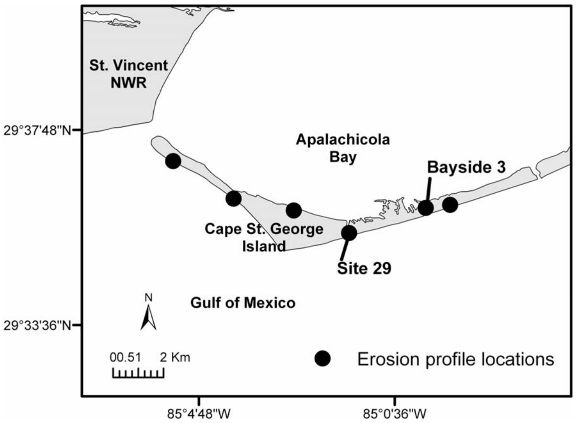

Figure 4. Cape St. George Island profile monitoring sites.

Table 1. *Tropical events impacting the Apalachicola Bay area.*

Storm Name (category)	Landfall Date	Wind Speed at Landfall (km/h)	Direction and (distance-km) of Landfall	Local Storm Surge (m)	Rainfall: Local (upbasin) (cm)	Local Wind Conditions–Sustained (km/h)	Speed of Storm (km/h)
Elena (H3)	09/1985	204	West (387)	3	29	86.4	*
Juan (TS)	10/1985	102	West (242)	*	*	*	*
Kate (H2)	11/1985	158	West (47)	3.3	12	100	*
Alberto (TS)	07/1994	93	West (173)	0.9	7 (37–71)	42.6	16.7
Beryl (TS)	08/1994	93	West (98)	0.9	12 (13)	51.8	5.6
Allison (TS)	06/1995	102	East (58)	*	27 (14–23)	62.9	22.2
Erin (H2)	08/1995	157	West (242)	*	*	*	*
Opal (H3)	10/1995	185	West (238)	1.5–1.8	6	51.8	37
Earl (H1)	09/1998	130	West (98)	2.4	6 (2–17)	*	18.52
Bonnie (TS)	08/2004	74	Direct hit (0)	0.8	10 (2–7)	*	*
Frances (TS)	09/2004	93	East (94)	0.8	6	57.4	*
Jeanne (H3)	09/2004	194	South (543)	*	3 (10–18)	*	*
Ivan (H3)	09/2004	194	West (268)	1.8–2.7	10 (1–10)	*	18.5–25.9 (over land)
Dennis (H3)	07/2005	194	West (207)	2.5	5 (8–32)	75.9	*
Katrina (H3)	08/2005	204	West (441)	*	7	51.8	*

island and were already marked by U.S. Geological Survey markers with known elevations. Surveys are conducted using an auto level and extendable stadia rod. A hand-held compass is used to ensure surveys are consistently conducted along the same bearing. Readings are taken directly before, in the middle of, and after any change in beach slope or contour. Using known survey marker elevations, the corresponding distance and elevations are calculated to create contour lines representative of the beach profile.

Sea Turtles

Sea turtles nest along area beaches, including Carrabelle, St. George Island, and Cape St. George Island. The beaches have been monitored during the months of April through November for nesting and hatching sea turtles since 1990. Volunteers patrol St. George Island beaches daily and staff patrols Cape St. George one to three times per week. Nests are located, measured, and marked with flags. On Cape St. George Island, nests are also covered with a flat, self-releasing screen to prevent predation.

Submerged Aquatic Vegetation Monitoring

Submerged aquatic vegetation (SAV) monitoring started in 2002 and began with fixed transects at four sites (Figure 3) to gather information on vegetative characteristics (species composition, coverage, and density). The SAV monitoring occurred two to three times during the growing season, April through October, and initially started utilizing the Braun-Blanquet method. The chosen transects are widely distributed within East Bay and the lower Apalachicola River. Fixed transects offer a precise reference of what is present in a given location at a particular time and thus provide the capability to detect short-term change. However, due to the variability of SAV species and coverage as well as turbidity issues, the 2005 monitoring was shifted to focus on the overall distribution of SAV throughout East Bay. Submerged videography, using a JW Fishers underwater towable camera system (TOV-1) with a Sea-Trak GPS receiver and Garmin GPS 72 unit, was used to map the distribution and extent of the SAV beds in June 2005. Video transects, based on historical information and data recently collected, encompassed the major shallow areas of East Bay. Transects were set up perpendicular to the shoreline until the vegetation ceased in either direction. The width of the transects varied with visibility but were generally 0.5 m wide. Video efforts continue to document change as well as species density in order to determine losses, recovery, and changes in SAV.

Oyster Monitoring

Field resource assessments at various oyster reefs are undertaken between one to three times annually by the Florida Department of Agriculture's Shellfish Assessment Section. Between one and four stations are occupied randomly on each bar with each station consisting of five quadrats. A 0.25 m^2 polyvinyl chloride grid is used to delineate quadrants, all of which are subtidal. All live oysters, shell, associated fauna, and debris are collected within the quadrat to a depth of 15 cm and removed. All live oysters are measured length-wise to the nearest 0.5 cm. Length-frequency distributions are calculated from the data, and standing stocks are estimated from the information. An estimate of harvestable oysters/m^2 is calculated using the percentage of live oysters equal to or greater than 75 mm. This estimate is further extrapolated to production levels on the various oyster bars, defined as bags/ha with a bag holding an average of 225 oysters (BERRIGAN, 1988).

RESULTS

Hurricane Information

Tropical storm and hurricane data were collected from NOAA's National Hurricane Center and other sources (BLAKE *et al.,* 2005; DOEHRING, DUEDALL, and WILLIAMS, 1994). Storms included in this data analysis occurred between 1985 and 2005 (Table 1, Figure 5) and were chosen based on the amount of local information available as well as storm data available (landfall location, rainfall, distance away, intensity, storm surge, local wind, *etc.*). Many storms,

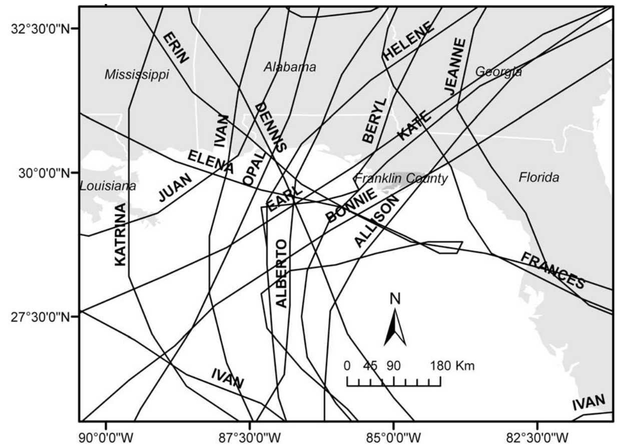

Figure 5. Storm tracks of historical tropical events impacting the Apalachicola Bay area.

such as hurricanes Elena and Juan (1985), experienced landfall some distance away but affected the Apalachicola coastline for long periods of time before moving ashore. Other storms, such as Alberto and Beryl (1994), were slow moving storms that dropped large amounts of precipitation either locally or in the watershed of the Apalachicola River and Bay system (Table 1).

Water Quality

Water quality data recorded from *in situ* deployed dataloggers provide a history of changes in the estuary during hurricanes. Analysis of water quality data for all four sites was conducted by determining the harmonic means for all parameters annually. The harmonic standard deviation was then determined. Incidents falling outside the harmonic mean plus or minus three harmonic standard deviations were further examined. The most visible changes in water quality parameters following tropical events involve salinity and depth. At all four datalogger sites, the only consistent statistically significant component to each storm was large changes in water level. Further examination of the data also demonstrates that storms can decrease the water level of the bay as commonly as they can increase it (Figures 6–8).

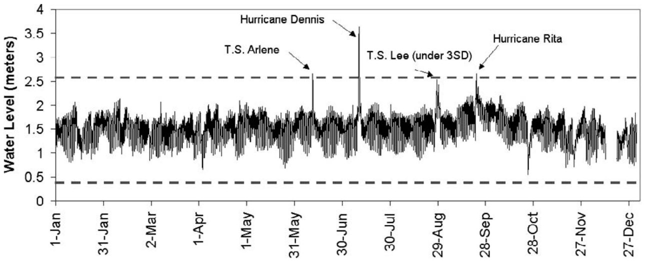

Figure 7. Water level at Cat Point, 2005 (critical water levels are shown as dashed lines at 2.54 m and 0.40 m).

Except for a few particular storms with noticeable impacts in the past two decades such as hurricanes Ivan (Figure 6), Dennis (Figure 7), and Opal (Figure 8), some tropical events considered significant to the area may not cause a large change in water level. Big winter storms, cold fronts, and large thunderstorms moving through the bay can also exhibit water level changes that are significant statistically. This phenomenon is well illustrated by the 2004 hurricane season, which included four major storms that impacted the area (Figure 6). Tropical Storm Bonnie and Hurricane Ivan both made landfall to the west of Apalachicola Bay. These storms were characterized by a storm surge and an increase in water depth, turbidity, and salinity. However, Tropical Storm Bonnie did not exhibit a statistically significant change in water level like Hurricane Ivan, although it caused local damage. Tropical Storm Bonnie was a direct hit in the area, unlike most of the storms that had westerly landfalls. Throughout December 2004, low tides also dropped below or close to the critical harmonic mean minus three standard deviations during normal winter storm events (Figure 6). Hurricane Dennis exhibited the highest storm surge seen to date. No other parameters exhibited statistically significant changes in values.

Tropical Storm Francis and Hurricane Jeanne both made landfall east of Apalachicola Bay. These storms caused a decrease in the water level as the water was driven from the bay by strong northerly winds (Figure 6). Turbidity levels

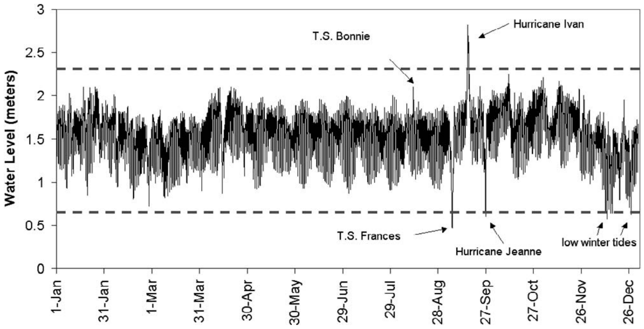

Figure 6. Water level at Cat Point, 2004 (critical water levels are shown as dashed lines at 2.32 m and 0.66 m).

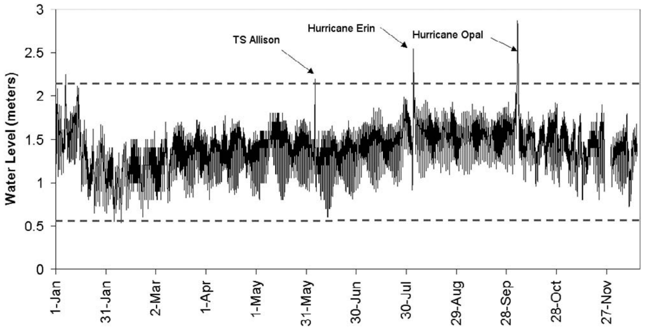

Figure 8. Water level at Cat Point, 1995 (critical water levels are shown as dashed lines at 2.12 m and 0.54 m).

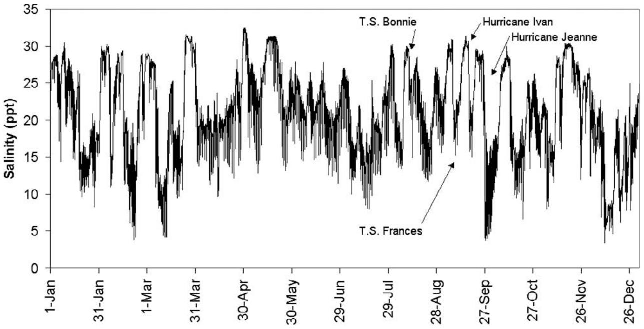

Figure 9. Salinity at Cat Point, 2004.

spiked with the fall in water level and the increased wind speed, but these changes were not statistically significant. The salinity decreased after these storms as the higher salinity water was driven offshore (Figure 9). Dissolved oxygen either increased or remained the same during the storm events as there was increased mixing due to sea level rise and increased wind speed. However, none of these changes were outside the range of conditions seen throughout the season associated with seasonal meteorological events (Figure 9).

During Hurricane Ivan and Hurricane Jeanne, there was also significant rainfall at Apalachicola and to the north. River flow increased due to the rainfall and salinity decreased in response (Figure 9). Substantial rainfall events are common in the Apalachicola Bay system. However, during the summer and early fall, it is unusual to have flood conditions occur in the river unless related to tropical events.

Tropical Storm Alberto (1994) made landfall in the Florida panhandle on July 3 and moved northwest to Atlanta by July 5. The storm drifted over southwest Georgia and southeast Alabama, delivering up to 71 cm of rain in some areas and leading to severe widespread flooding.

Coastal Erosion

In 1995, Hurricane Opal severely impacted the dunes and shoreline of the local barrier islands. Because of this event, the reserve began quarterly shoreline profiles to track changes in the beach, dune, and vegetation structure on an uninhabited and mostly unaltered island. Shoreline profiles of Cape St. George Island beach and bayside demonstrate that seasonal changes are normal, with the most dynamic area occurring between the secondary dune out to the high water mark. During the hurricane seasons of 2004 and 2005, dramatic changes in the surf/beach interface occurred. Large amounts of sand were displaced along the island, with the east side of the island losing more sand than the west side of the island. Not only was there more than 0.5 m of elevation lost on the primary and secondary dunes, but a similar amount was lost from the dunes to the water's edge (Figure 10). Much of the associated dune vegetation was also lost during the storms, which made landfall to the west of Apalachicola Bay, driving water onto the barrier islands.

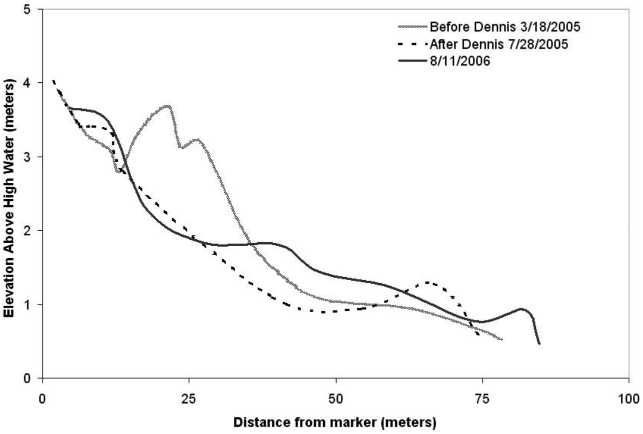

Figure 10. Shoreline profile, Site R29, on Cape St. George Island.

The powerful surge (up to 3 m) from Hurricane Dennis moved huge quantities of sand landward, and in some cases, moved the sand to the other side of the barrier island, over 400 m. On the eastern beach side of the island (Site 29), the entire primary dune including vegetation was destroyed. More than 1 m of sand height was either washed away or displaced back behind the old dune system (Figure 10). The nearby bayside profile survey marker (Bayside 3) was buried under approximately 0.6 m of sand (Figure 11). Low elevation dunes were completely flattened, removing any remaining vegetation.

Sea Turtles

Species that utilize beach areas are particularly susceptible to the forces of hurricanes and tropical storms. The most common nesting sea turtle in this area is the loggerhead (*Caretta caretta*), although leatherback (*Dermochelys coriacea*) and green (*Chelonia mydas*) sea turtles have been known to nest infrequently. In 1994, two tropical storms and a tropical depression washed out nests, nest markers, and inundated

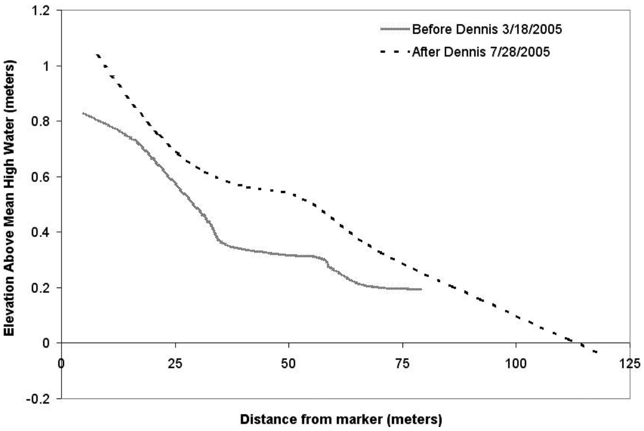

Figure 11. Shoreline profile, Bayside 3 Site, Cape St. George Island.

Table 2. *Sea turtle nest loss on St. George and Cape St. George Islands due to tropical events.*

Year	Nests Lost on Cape St. George Island (%)	Nests Lost on St. George Island (%)	Total Nests Lost (%)	Total Number of Nests/y	Hurricanes/y	Tropical Storms/y
1990	0	0	0	28	0	0
1991	0	0	0	21	0	0
1992	0	0	0	30	0	0
1993	0	0	0	119	0	0
1994	*	*	*	98	0	2
1995	12**	62**	42**	212	2	1
1996	24	14	19	177	0	1***
1997	2	2	2	287	1***	0
1998	45	54	51	345	2	0
1999	9	22	18	364	0	1***
2000	6	4	5	288	0	1
2001	32	19	25	164	0	1
2002	39	4	15	144	0	1
2003	4	11	8	227	0	1***
2004	45	55	51	183	2	2
2005	73	65	67	162	1	2

* 1994 data was lost due to a flood.
** Percentages were estimated.
*** Storms not included in Table 1.

most remaining nests with as much as 0.4–0.6 m of tightly packed sand. Three hurricanes, Allison, Erin, and Opal, impacted area beaches in 1995 causing severe beach erosion, leveling the entire primary dune system, and eliminating more than 40% of the nests on two islands. Most incubating nests that were left after the first two hurricanes were destroyed when Hurricane Opal came ashore in early October 1995 (Table 2).

Sea turtle nests can be inundated, washed out, or buried by the high tides and increased wave action associated with a tropical system. In 1998, Hurricane Earl destroyed 54% of the nests on St. George Island and 45% of nests on Cape St. George Island. Combined, the 2004 and 2005 hurricane seasons have been the worst to-date, with 51% and 67% of the nests destroyed, respectively. Approximately 100 nests were lost on the two islands in each year. Other tropical storms and hurricanes within the Gulf of Mexico that have minimal impacts on the bay area also often result in the loss of sea turtle nests, but to a lesser extent (Figure 12, Table 2).

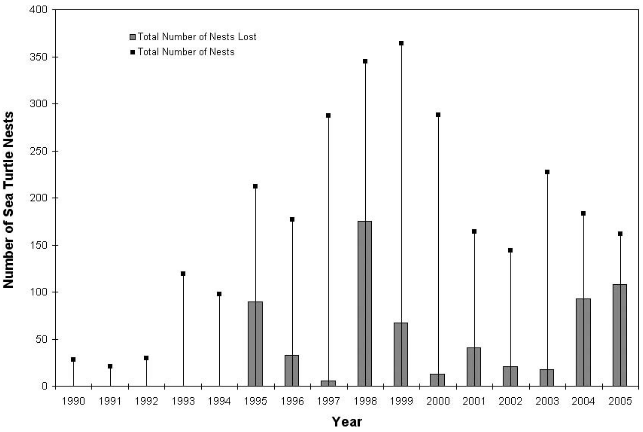

Figure 12. Sea turtle nests on St. George and Cape St. George Islands.

Submerged Aquatic Vegetation

The SAV found in the system includes freshwater, brackish, and marine species that are confined to the shallow perimeters of the system because of high turbidity, limiting the depth of the photic zone (CONTINENTAL SHELF ASSOCIATES, 1985; LIVINGSTON, 1980). The SAV covers approximately 7% of the entire bay bottom, with much of it located in regions of high salinity and low turbidity (LIVINGSTON, 1984). Dominant brackish water species, including *Vallisneria americana, Ruppia maritima, Najas guadalupensis, Zannichellia palustris, Stuckenia pectinata, Hydrilla verticillata, Potamogeton pusillus, Chara* spp., and *Myriophyllum spicatum,* are found in East Bay along with other freshwater species that are tolerant of low salinity. Historically SAV has covered as much as 14 km^2, or up to 36% of the bottom habitat of East Bay (LIVINGSTON, 1980). In the Apalachicola River, SAV is only found in the lower 10 km near the mouth, but it accounts for more than 10% of the habitat in the lower river (AGER *et al.,* 1984; LEITMAN, 1983).

Five days of field transects during June 2005, utilizing a towable underwater auto-focus video camera, produced a fairly detailed survey of the distribution of SAV species and coverage in East Bay. The towable camera enabled a much larger area to be surveyed rather quickly. It also allowed deeper areas to be surveyed that had never been surveyed by the reserve or other researchers. The detection of large areas of SAV that had not been mapped previously has significantly expanded the distribution of known SAV in East Bay (Figure 13). No surveys were done in the East Bay tributaries or the lower river in June 2005. Percent coverage estimates using the video are somewhat crude, but can give a fairly good estimate over a broad range (sparse, moderate, dense).

The unusually high storm surge associated with Hurricane

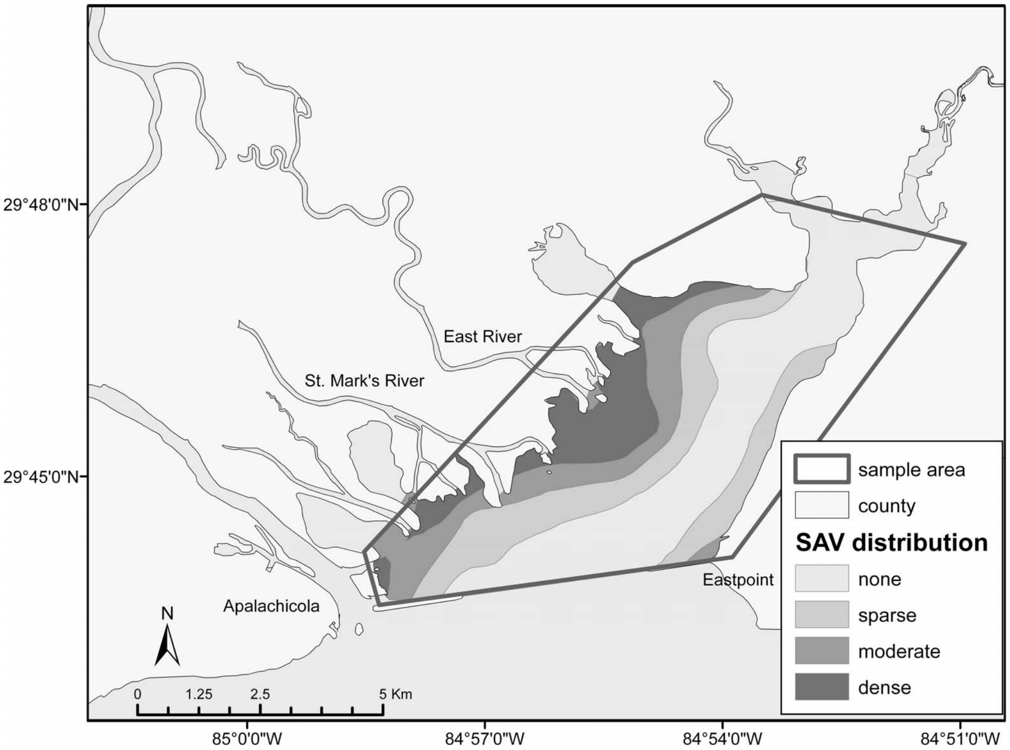

Figure 13. Submerged aquatic vegetation distribution in East Bay, spring 2005.

Dennis in July 2005 impacted the SAV in East Bay. Posthurricane surveys confirmed a complete loss of SAV in East Bay and the lower Apalachicola River. Subsequent surveys, both visual and utilizing the underwater camera, in late summer showed a complete lack of SAV in East Bay and the lower Apalachicola River. Additional surveys conducted several months later at the end of the growing season also showed no re-establishment of SAV beds posthurricane. Visual assessments during the spring growing season of 2006 showed some re-establishment of SAV species; however, *Microspora* spp., a green filamentous algae, became dominant, outcompeting most other species. By the end of the growing season in 2006, *Vallisneria americana* still had not reappeared in East Bay or the lower river.

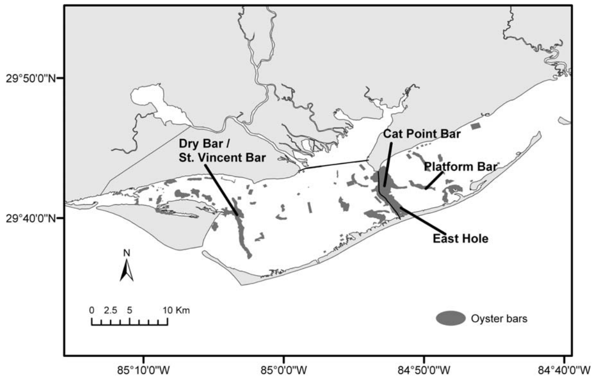

Figure 14. Major oyster reefs in Apalachicola Bay.

Oysters

In 1985, the most devastating storm to impact the Apalachicola Bay oyster resources in recent history lasted from August 29 to September 2. Hurricane Elena produced extreme tides, hurricane force winds, and heavy rainfall along the coast, impacting oyster reefs. After the storm, surveys conducted by the Department of Agriculture and Consumer Services (DACS) on the oyster reefs showed that most areas in Apalachicola Bay were impacted so severely that the levels remaining (less than 494 bags of oysters per hectare) would not support commercial harvesting (BERRIGAN, 1988).

The eastern part of St. George Island Sound suffered minimal damage; however, East Hole, Platform Bar, and Cat Point, all in the western part of the Sound, suffered extensive damage (Figure 14). Production on East Hole dropped from more than 494 bags/ha to 49 bags/ha. On Cat Point, production dropped from more than 988 bags/ha to approximately 247 bags/ha. Oyster reefs in the western part of Apalachicola Bay and in St. Vincent Sound, while suffering less damage, exhibited populations that could not support commercial production, and on September 11, 1985, the bay was closed to harvesting (BERRIGAN, 1988). Typically, when the density of oysters on a bar falls below 494 bags per hectare, the State of Florida closes the bar to let it recover. Hurricane Kate,

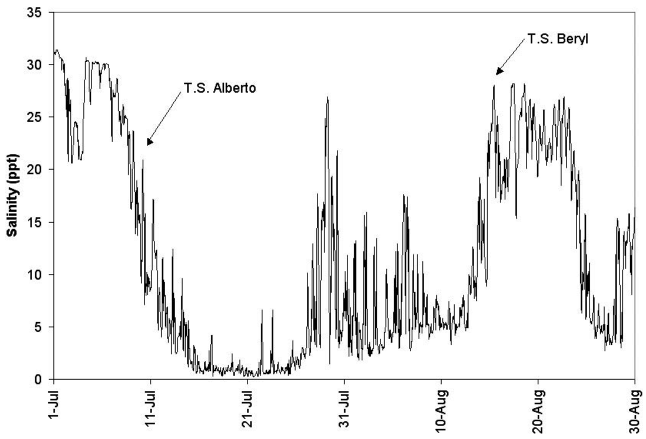

Figure 15. Salinity at Dry Bar, July–August 1994.

which made landfall in late November of the same year, produced high tides and winds but did not appear to produce any additional physical damage to the oyster bars (LIVINGSTON *et al.,* 1999).

Tropical storms Alberto and Beryl (1994) produced floodwaters from upstream and local precipitation. Tropical Storm Alberto produced between 37 cm and 70 cm of precipitation in the upper watershed of the river and very little locally. This rainfall resulted in the second highest flow ever recorded in the Apalachicola River and an extended period of low salinity bay water. Salinity in the western part of the bay, more influenced by river discharge, fell to 0‰ and persisted for up to 2 weeks. Oysters in the western part of the system, at the Dry Bar/St. Vincent reefs, suffered high mortality (80–90%) due to extended periods of low salinity water (Figure 15). In the eastern part of the bay at the Cat Point and East Hole reefs, salinity also fell to 0‰; however, since riverine influence is less in this area, the salinity varied from 0‰ to 10‰ (Figure 16). This region of the bay suffered less damage, resulting in only 10–15% oyster mortality (FLORIDA DEPARTMENT OF NATURAL RESOURCES, 1994). Tropical Storm Beryl, impacting the area 1 month later, produced 27 cm of precipitation locally, but less upstream, and did not have the same impact on river flow or salinity as the previous storm. No impacts were noted on the oyster reefs from this storm, although local flooding was a problem.

During Hurricane Dennis, July 2005, storm surge levels were up to 3 m. The oysters were not impacted significantly as the storm surge arrived at high tide and moved away rather quickly. The oysters were sufficiently submersed to protect them from the wave action associated with the storm. There was also little wind from this storm. Hurricane Katrina, which occurred 2 months later, while not causing any local damage, did impact the local economy. Although Hurricane Katrina experienced landfall west of the area, its offshore movement coincided with an offshore red tide event. The south winds associated with the storm moved the bloom from offshore into the bay, closing oyster harvesting for more than 3 months. Oysters are not harmed by the red tide brevetoxin and are able to depurate it after the bloom ends.

DISCUSSION

Estuaries are characterized by the dynamic interface between freshwater habitats and marine habitats. Changes in these habitats happen on many temporal scales, from mere minutes for the salinity to change to the formation of barrier islands, which may take many thousands of years. Estuaries with large watersheds and alluvial river systems in particular exhibit both wide and rapidly changing physical and chemical characteristics, seasonally and annually, based on varying climatic conditions. Species that utilize these estuaries are successful because of their ability to cope with these natural perturbations in their environment. Hurricanes offer an opportunity to document how sudden extreme changes in estuarine conditions may alter certain physical and chemical parameters, habitats and also to understand how species deal with these changes.

An inherent problem in trying to compare and contrast storms is that in reality very few storms are alike. They approach from different directions, have different size wind fields and wind strengths, impact coastal areas for varying time periods, drop significantly different amounts of precipitation locally and upbasin, move ashore at various distances from the local area, and have unpredictable storm surges associated with them. For example, Hurricane Dennis, which impacted the Apalachicola Bay area in July 2005, actually had landfall near Santa Rosa, Florida, 207 km to the west. Its storm surge was not predicted to be large but reached a height of almost 3 m.

Tropical events cause short-term changes in water quality conditions such as salinity, dissolved oxygen levels, turbidity, and temperature, but these changes resolve themselves usually within days after each storm and are not considered significant for the Apalachicola Bay system. These findings corroborate those of other researchers studying hurricane impacts (GREENING, DOERING, and CORBETT, 2006; MALLIN and CORBETT, 2006). The water characteristics in the bay

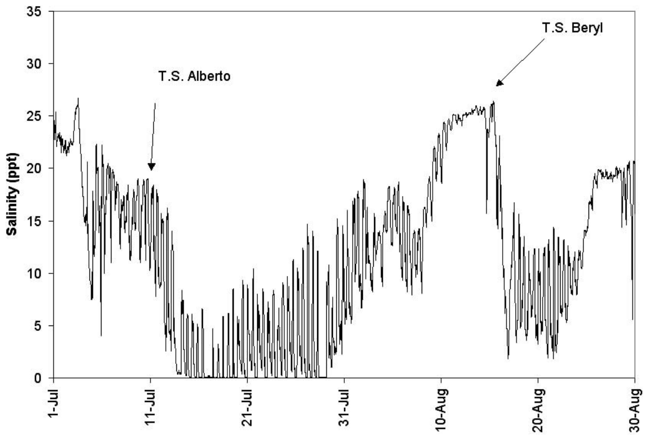

Figure 16. Salinity at Cat Point, July–August 1994.

result from a mixing between freshwater inputs from the Apalachicola River and surrounding forests and saltwater inputs from the Gulf of Mexico through various passes between barrier islands. Due to seasonal variations, meteorological and climactic conditions, and shallow depth, the estuary is very dynamic. Because of these factors, the water quality features mentioned above vary widely under so-called "normal" conditions.

Sudden changes in temperature or salinity from an impending storm do not vary much, if at all, from ordinary Apalachicola Bay water characteristics. For this reason, water level readings from the dataloggers are the only physical water quality parameter that could be significantly linked to hurricanes and tropical storms in the Apalachicola Bay. This technique, dealing with harmonic means and three standard deviations, appears to work well in identifying tropical events that not only have surges associated with them but also storms that tend to drive water out of the estuary. It also can be utilized to identify large winter storms, which tend to evacuate water from the estuary. These changes in water level, while not seemingly large compared to some coasts, must be looked at within the context of the historically occurring "natural" water level ranges in Apalachicola Bay brought on by tides, winds, and river discharge levels. The overall low elevation of all of the northwest Florida coastal area makes these surges significant with regard to existing habitats that may be affected.

Alterations to salinity regimes vary considerably among storms. This is not only due to landfall location, surge height, and the amount of precipitation, but also the location within the watershed where the precipitation occurs and its effect on river flow. The extent of change also varies considerably within the estuary, again depending on local *vs.* watershed impacts.

Water quality changes associated with storms in the Apalachicola basins have not always been directly related to the magnitude of the storm but usually are directly related to the point of landfall. Storms making landfall to the east of the area tend to have less severe impact on the bay because the severity of the storm tends to be less on the western half of the storm. Likewise, when storms make landfall to the west of the area, the impacts are much greater due to the greater forces on the northeast quadrant of the storm. The location of landfall relative to the bay also determines the direction and severity of the local wind. Because of the orientation of the bay, in an east-west direction, and its shallowness, wind speed and direction have a significant effect on the depth of the water in the bay and the movement of water masses within the bay. A storm having landfall to the east of Apalachicola Bay will impact with a north wind, driving water out of the bay. A storm to the west will drive water into the bay with a southerly wind and increasing surge.

The three storms during the last 20 years that caused the most environmental damage locally, Hurricane Elena (1985), Tropical Storm Alberto (1994), and Hurricane Dennis (2005), had landfall from 170 km to more than 373 km westward. Because of the dynamic nature of the rivers flowing into the Apalachicola Bay system, conservative properties such as salinity vary widely both spatially and temporally in the bay. Salinity can change, spatially and temporally, rapidly and may vary up to 10‰ within an hour. On any given day salinities within the estuary can range from 0‰ to 35‰, depending on river flow, tides, and meteorological conditions (NIU, EDMISTON, and BAILEY, 1998). Extreme conditions such as hurricanes may prolong or exacerbate these variables, but they do not alter the annual range of conditions.

The storm with the largest impact on salinity in the bay, Tropical Storm Alberto (1994), caused extended periods, up to 2 weeks, of low salinity conditions due to extreme flooding (Figure 15). Regions to the east of the river, farther away from the influence of freshwater, also suffered extended periods of low salinity water. However, because of the influence of high tides, higher salinity water was brought in, allowing bottom salinities to rise daily (Figure 16).

The shoreline suffered significant loss of beach during the 1985 hurricanes. Unfortunately, no coastal erosion profiles were surveyed on a regular basis at that time. Coastal profile surveying began after Hurricane Opal (1995) to track shoreline erosion and restoration as well as dune recovery. Some loss of beach has been measured during storms of the late 1990s and early 2000s. In addition, changes in the beach structure are noted both seasonally and annually even when tropical events do not occur. However, in 2005 with the advent of Hurricane Dennis, a significant loss of beach, sand, dunes, and dune vegetation was measured on the outside beach. Changes on the bayside of the island were also measured. While some of the sand was removed off the beach and carried into the Gulf, much of it was driven across the narrow island, 400 m wide at the bayside profile site (Figure 11), and into the southern edge of Apalachicola Bay. Much of this sand is from primary and secondary dunes that were literally "smeared" across the island. The resulting accretion of sand at the Bayside 3 site primarily derives from this source. On the beach, Site 29, the loss of beach elevation, dunes, and vegetation was measurable, and recovery of the beach structure is not complete more than 1 year later (Figure 10).

Storm events appear to have little effects on the actual nesting of the adult female sea turtles; however, they do play a role in sea turtle nest survival. Hurricanes and tropical storms alter sea turtle nesting beaches by erosion, movement of sand, and loss of sand dunes. A decrease in sand dune height can increase the amount of artificial lighting that illuminates the nesting beaches, which has a negative impact on nesting sea turtles and hatchlings. Beach width is also critical for the available nesting area for sea turtles. Nests located near the mean high water line have an increased chance of inundation or washout by storm surge and associated high tides. If the nests are inundated with water for a prolonged time period, the embryos will not develop correctly. Storm impacts on sea turtle populations may not be visible for 20–30 years because of the age of maturity.

The SAV may be an indicator of productivity and water quality along with providing food and refuge from predation to many economically and ecologically important species (ZIEMAN and ZIEMAN, 1989). Natural events, such as hurricanes, can adversely affect submerged and emergent vegetation by an increase in salinity, turbidity, wave action, scouring, sedimentation, and storm surge. Many exotic and native brackish water SAV species have delicate root systems along with slender stems and leaves making them susceptible to water turbulence. In the mid-1980s, *Myriophyllum spicatum,* an invasive species, became a dominant species in many of the small bays in the northern area of East Bay, covering up to 90% of the bay bottoms and extending along the river channels into East Bay itself (CONTINENTAL SHELF ASSOCIATES, 1985; LIVINGSTON, 1980). The storm events of 1985 (Table 1) uprooted and eliminated most of this noxious aquatic plant for many years (AGER *et al.,* 1986). It eventually re-established and spread, along with *Hydrilla,* another invasive aquatic plant, in the lower river distributaries. In 1995, Hurricane Opal uprooted and significantly reduced the distribution and density of both species. These invasive species have not re-established their dominance to-date, but their coverage changes annually and could become a problem again in the future.

Hurricane Dennis (2005) eliminated all SAV from East Bay and the lower Apalachicola River. An important species of SAV, *V. americana,* has not recovered to-date. The timing of this early summer storm could prove to be a crucial event eliminating the seed bank for the future growing seasons. Scientific data conclude that the early growing season, May through July, is most crucial for *V. americana* establishment and procurement. Therefore, environmental stresses during this time can affect its survival (FRENCH and MOORE, 2003). In addition, growth and survival rates of *V. americana* exposed to higher salinities, above 15‰ for more than 1 week, will be affected (KRAEMER *et al.,* 1999). The initial disappearance of *V. americana* could be attributed to the increased wave action and high storm surge from Hurricane Dennis, but prolonged periods of high salinity may contribute to the lack of re-establishment.

Hurricanes detrimentally affect oysters through the processes of mechanical disturbance, sedimentation, and extreme salinity changes. These resultant effects are typically from storm surge, high winds, and high rainfall and indirectly from increased river flow and salinity alterations. Our observations show that there are varying degrees of hurricane impacts on the oyster population and that the impact due to storm severity is not necessarily predictable.

The two storm events that had the greatest impact on oyster reefs in the bay during the last 20 years did so for different reasons. Hurricane Elena (1985) caused actual physical damage and structural alteration of the reefs, especially in the western part of St. George Sound. The Cat Point and East Hole reefs are probably the largest commercially harvested bars in the bay. On these severely impacted reefs, the damage was caused by transport and deposition of shell and sediment, abrasion, and scouring. During the storm, shell and live oysters apparently became suspended, and the substrate was fluidized. Suspended material was transported across the reefs and deposited on soft sediments, which could not support oysters. Reefs near sandy areas were often covered by sand. In the western part of Apalachicola Bay and in St. Vincent Sound, the reefs had less damage with less evidence of scour, suspension of reef material, or major disruption of the oysters (BERRIGAN, 1988).

Hurricane Alberto (1994) caused serious damage to the oyster reefs without causing structural or physical damage. Impacts from this storm were caused by high river flow resulting from upstream precipitation. The extremely high river flow resulted in protracted periods (up to 2 weeks) of low salinity in the bay directly affecting the oyster population itself. Due to this extended period of low salinity water (Figure 14) on the Dry Bar/St. Vincent reefs, oysters were unable to open and feed, causing extremely high mortality (80–90%). In the eastern part of the bay, although salinity reached 0‰, riverine influence is less, and high tides were able to bring in some salt water daily (Figure 15), resulting in only 10–15% oyster mortality (FLORIDA DEPARTMENT OF NATURAL RESOURCES, 1994). This incoming salt water enabled the oysters to open and feed and suffer less loss. Many other storms and hurricanes of greater magnitude or closer landfall, such as Hurricane Opal and Tropical Storm Bonnie, have had less impact than this tropical storm on oyster resources in the bay.

Physical and environmental damage may be amplified or lessened by the height of the tide during the surge and landfall of a tropical storm or hurricane. The oyster reefs were completely submerged at high tide when the storm surge from Hurricane Dennis made landfall in the summer of 2005. Mechanical damage and sedimentation appear to have been minimized, reducing the force of the storm surge and wave action, resulting in little damage to the oyster resources.

CONCLUSIONS

Impacts on the natural resources of an area from tropical storms and hurricanes are hard to predict and measure. Many of the impacts are short-lived and actually mimic natural variability experienced from other events such as floods, winter storms, or low river flow events. Other impacts can be long-term and are related to the loss of biological resources, habitats, or commercially important fisheries. The strength, size, distance from landfall, orientation, speed, and precipitation, as well as tidal conditions at landfall all play a role in determining the severity of the damage to estuarine and coastal resources by tropical events. In order to determine the impacts to natural resources and potential recovery or restoration, it is necessary to have long-term datasets that can be used to delineate and monitor situations representing "normal variability and change" both seasonal and annual. Future long-term monitoring, coupled with short-term studies and proper management of natural resources, will enable more detailed analysis of the impacts of hurricanes on estuarine systems.

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