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THE 2005 HURRICANE SEASON IN SOUTH FLORIDA

by

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EXECUTIVE SUMMARY

Documenting hydrologic events such as hurricanes, storms, and droughts provides supporting information for water management decision making. The years 2004 and 2005 were very extreme hurricane seasons for South Florida. Based on a historical record of tropical systems, the combined impact of the 2004 and 2005 hurricane seasons on the South Florida Water Management District (SFWMD or District) area was a series of rare events. This paper presents the hydrologic impact of Hurricanes Dennis, Katrina, Rita, and Wilma on the District during the 2005 hurricane season. Based on available data, the spatial distribution and the magnitude of rainfall from the hurricanes are presented, along with an estimate for frequency of occurrence of extreme rainfall events. Analysis of wind direction and magnitude from Hurricane Wilma are included, as well as an estimate for the highest wave run-up, or surge, on the Lake Okeechobee levee from Hurricane Wilma. Water level changes at key water management system locations and surface water flows through major structures are provided. Finally, the path of the 2005 hurricanes that impacted the District area and estimates of radar rainfall are shown.

Hurricane Dennis

Hurricane Dennis started as a tropical wave that moved westward from the coast of Africa in late June. It made landfall on southeastern Cuba as a Category 4 hurricane. On July 9, 2005, Dennis crossed over water and made landfall on western Cuba, weakening to Category 3. As the hurricane crossed the Gulf of Mexico to the Florida Panhandle, it contributed rainfall to the Florida Keys and south-southwest Florida.

Hurricane Katrina

Hurricane Katrina developed as a tropical depression in the Bahamas, about 175 miles southeast of Nassau, on August 23, 2005. Katrina moved toward South Florida, making landfall on the Broward/Miami-Dade County line on August 25, 2005 as a Category 1 hurricane. The hurricane caused fatalities and damages to trees, power lines, homes, and businesses. As the hurricane moved west-southwestward through the southern tip of Florida, it dumped over a foot of rainfall on some areas. It stayed six hours over land, mostly over the Everglades wetlands, and crossed to the Gulf of Mexico just north of Cape Sable, on August 26. It finally made landfall on August 29 at the mouth of the Pearl River at the Louisiana/Mississippi border and caused unprecedented damage to Louisiana, Mississippi, and Alabama. Most of the rainfall was observed on the south-east and south-west quadrants of the hurricane as it crossed South Florida. A high-intensity rainfall was observed in Homestead totaling 13.24 inches in a 24-hour period, causing flooding. This amount of rainfall on the area in a 24-hour period is a rare frequency of a 1-in-100-year return period. On August 25, there was a high rainfall intensity of almost seven inches over two hours, which resulted in heavy flooding.

Hurricane Rita

Hurricane Rita developed as a tropical depression, just east of the Turks and Caicos Islands, On September 17, 2005. On September 19, Rita became a tropical storm and moved through the Central Bahamas. On September 20, the storm reached Category 2 hurricane status as it passed through the Florida Straits to the Gulf of Mexico. Although the hurricane's center did not pass through the Florida Keys, it had significant impact such as downed trees, high surge, and flooding. As the hurricane moved southwest through the Florida Straits, it contributed rainfall to the Keys and South Florida. The highest areal rainfall was observed in the Everglades National Park (ENP or Park) followed by Miami-Dade, the Big Cypress Basin, Broward, and Water Conservation Area 3. Rainfall for Key West was 7.35 inches during September 2005 compared to the monthly average of 5.45 inches.

Hurricane Wilma

Hurricane Wilma formed as a tropical depression on October 15, 2005, east-southeast of Grand Cayman. On October 18, Wilma became a hurricane moving west-northwestward. On October 19, Wilma strengthened to a Category 5 hurricane, with a record low pressure (882 millibars) for an Atlantic hurricane. On October 21, it made landfall on the island of Cozumel, Mexico, as a Category 4 hurricane. On October 22, Wilma crossed to the Yucatan Peninsula and, after prolonged battering of the northeastern section, it emerged in the Gulf of Mexico on October 23. Heading toward South Florida, it made landfall as a Category 3 hurricane near Cape Romano on October 24 and hit South Florida as a Category 2 hurricane, crossing the Atlantic in four and a half hours. The eye of Hurricane Wilma passed through South Florida, inflicting extensive damage from the front end and back end of the hurricane. Most of the rainfall from the hurricane was on the headwaters of Lake Okeechobee and the southwest. Because the hurricane crossed South Florida quickly, the rainfall was not extreme. But the location of the rainfall, the amount of runoff generated, and the high antecedent water levels in lakes and impoundments impacted the water management system hydraulically and environmentally.

Hurricane Wilma passed over the six Stormwater Treatment Areas (STAs) at the south and south-eastern edges of the Everglades Agricultural Area. As such, the STAs were impacted significantly. The impacts included resuspension of settled sediment, vegetation damage, dislocation of wetland vegetation and pushing vegetation onto levee banks, lack of power and levee and pump station damages. The downed power lines on levees and roads also limited access to facilities.

In the Upper Kissimmee Basin, Lakes Myrtle, Mary Jane, Gentry, Tohopekaliga, and Kissimmee were above regulation schedule following Hurricane Wilma, which generated over six inches of areal average rainfall over the basin. A sharp increase in the water level of Lake Kissimmee depicts the rainfall impact of Hurricane Wilma on the Upper Kissimmee Chain of Lakes. Also, the sharp increase in surface water flow in the Kissimmee and surrounding basins is shown by the sharp increase in outflows from Lake Kissimmee (S-65), outflows from Lake Istokpoga (S-68) and inflows into Lake Okeechobee through the Kissimmee River (C-38 canal) through structure S-65E. Inflow into Lake Okeechobee through the Kissimmee River (S-65E) between October 24, 2005 (landfall of Hurricane Wilma) and December 31, 2005 was 525,369 acre-feet. There are additional inflow points to the lake. Kissimmee River floodplain water levels at the restoration area climbed over 7 feet due to surface water flow increases from the hurricane rainfall. The weather station with the lowest maximum gust wind speed from Hurricane Wilma is WRWX (50 miles per hour, or mph), which is located in the Upper Kissimmee Basin at the Disney Wilderness Preserve. Wind speed during Hurricane Wilma was also relatively lower in the Lower Kissimmee Basin. Maximum instantaneous wind gust speed of 117 mph was recorded at Belle Glade. Wind speed was generally very high from Lake Okeechobee in the north to Miami-Dade in the south.

Lake Okeechobee was fully impacted by Hurricane Wilma. Lake Okeechobee is impounded with an earthen levee, except at Fisheating Creek, where there is an open water connection, with numerous inflow and outflow water control structures. The impact zones of wind-generated high waves on Lake Okeechobee depend on the path of the hurricane, wind speed, wind direction, and duration of impact. There are four weather stations within Lake Okeechobee. Three of the weather stations (except for L005) had gust wind speed, average wind speed, and wind direction data collected during Hurricane Wilma. Weather station L001, at the northern side of the lake, registered instantaneous maximum gust wind speed of 107 mph; weather station L006, at the south-side of the lake, registered instantaneous maximum gust wind speed of 112 mph. Instantaneous maximum gust wind speed (sampled every 10 seconds; maximum in 15 minutes) and 15-minute average wind speed and direction over the lake correspond with the area of levee erosion and high water levels. Wind direction over the lake is clearly shown as east-northeast (ENE) from the front side of the hurricane and northwest (NW) from the backside of the hurricane. Both the gust and average wind-speed data show that the back side of the hurricane had higher wind speed than the front side. Hurricane winds blow vegetation from the lake toward the levee banks. Water control structures built in the levees get clogged with massive vegetation and debris impeding emergency operations. The wind wave action stirred up the lake, thereby suspending settled sediment and impacting water quality. High sediment concentration reduced the depth of light penetration into water, reducing the growth and maintenance of submerged aquatic vegetation. High sediment concentration is associated with increase in nutrient concentration. Due to the high water level in the lake, water had to be discharged. The quantity and quality of the discharge impact the receiving systems.

Structural damage from hurricanes can occur in several ways. High rainfall on the lake's watershed from hurricanes results in high surface water inflows. This results in rising water level in the lake when outflow conveyance capacity is lower than inflow. High water level in the lake increases seepage through the levee, which could result in levee failure. Hurricane winds can generate high waves, and the energy from the back-and-forth battering of an earthen levee can result in cutting the levee. Also, failure can occur around structures on the levee. High water level creates the potential for high wind to generate high waves that could wash the lake-side of the levee, or even overtop and erode the outside of the levee. On the U.S. Army Corps of Engineers web site and in newspaper reports, it is stated that normal Lake Okeechobee operation is below 16.5 feet National Geodetic Vertical Datum (ft NGVD); 16.5 to 17.49 ft NGVD elevation initiates levee inspection at intervals of 7 to 30 days, varying by reach. Water levels of 17.5 to 18.49 ft NGVD initiate inspection at intervals of 1 to 7 days and levels greater than 18.5 ft NGVD initiate daily inspection.

Seepage is the slow movement of water from the lake through the levee due to the hydrostatic force created by high water level in the lake. Seepage is an inherent problem of earthen dams. When the rate of seepage increases, soil material moves through the levee along with the seepage water (i.e., boiling). Boiling starts with fine material movement followed by course material movement and results in levee breach. It was reported that there will be problems when the stage approaches 18.5 ft NGVD and levee breach is likely expected at 21 ft NGVD. Also increased flow rates from high rainfall can create failure at a water control structure. High rainfall can create earthen levee erosion from rainfall impact.

Hurricane winds can generate high waves, and the energy from the back-and-forth battering of an earthen levee can result in cutting the levee. Also, failure can occur around structures on the levee. According to newspaper reports, there were five or six eroded areas along the lake shore after Hurricane Wilma. If the wave setup exceeds the height of the levee, then washout could occur to the lake side, top, and outer side of the levee.

The wave run-up from Hurricane Wilma exceeded the maximum reading capacity of some of the water level recorders on the perimeters of Lake Okeechobee. Estimates of highest level of wave setup will be made from the watermark preserved at the S-2 pump station at the time by District staff. The initial estimate before surveying is 26 ft NGVD. Survey of the mark will provide accurate record. Hurricane Wilma's impact on Lake Okeechobee is not limited to the impact during the hurricane. Runoff associated with the hurricane rainfall has lingering impact on the lake. Lake Okeechobee water level rose following Hurricane Wilma. Rise in lake stage results in high rate discharge to manage the lake water level. All the hurricanes moved quickly through the area. Slow movement of the hurricanes might have had extensive hydrologic impact that would have included large-scale flooding.

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INTRODUCTION

Documenting hydrologic events such as hurricanes, storms, and droughts provides supporting information for water management decision making. The years 2004 and 2005 were very extreme hurricane seasons for South Florida. Based on a historical record of tropical systems, the combined impact of the 2004 and 2005 hurricane seasons on the District area was a series of rare events. This technical publication covers the hydrologic impact of Hurricanes Dennis, Katrina, Rita, and Wilma on the South Florida Water Management District (SFWMD or District) area during 2005. Based on available data, the spatial distribution and the magnitude of rainfall from the hurricanes are presented, along with an estimate for frequency of occurrence. Analysis of wind direction and magnitude and estimated wave run-up or surge on the Lake Okeechobee levee from Hurricane Wilma is provided. Water level changes at key water management system locations and surface water flows through major structures are also provided. Lastly, the path of the 2005 hurricanes that impacted the District area and estimates of radar rainfall are also shown. The 2004 hurricane season impact on South Florida is presented in Abtew and Huebner, 2006 and Abtew et al., 2006.

BACKGROUND

According to Chaston (1996), the hurricane is nature's way of transporting heat energy, moisture, and momentum from the tropics to the poles in order to decrease the temperature differential and preserve the current climate of the earth. Records indicate that Atlantic hurricanes have been observed since Christopher Columbus's voyage to the New World in the 1490s (Attaway, 1999). Based on published records, the average annual number of subtropical storms, tropical storms, and hurricanes in the North Atlantic Ocean between 1886 and 1994 is 9.4, of which 4.9 were hurricanes (Tait, 1995). Between 1871 and 1996, 1,000 tropical storms have occurred in the North Atlantic, Caribbean Sea, and Gulf of Mexico (Williams and Duedall, 1997). Annual distribution of tropical systems, excluding depressions, is shown in **Figure 1**. As shown in this figure, 79 percent of tropical storms and hurricanes occur from August through October (Neumann, et al., 1993).

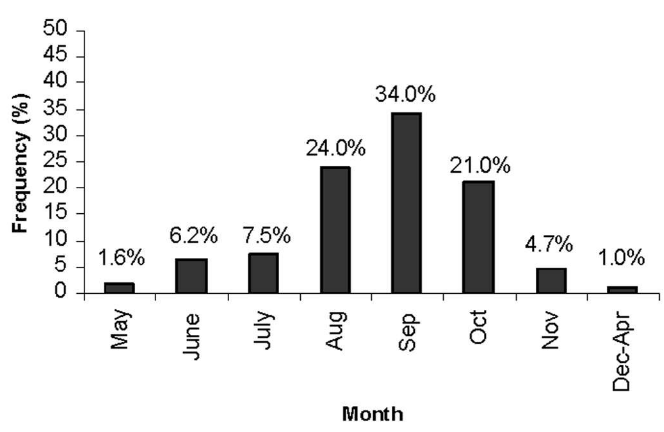

Figure 1. Distribution of North Atlantic hurricanes and tropical storms.

There were 114 hurricanes and tropical storms affecting peninsular Florida between 1871 and 1996, with about half as hurricanes (Attaway, 1999). The occurrence is about one named storm every year and one hurricane every two to three years. As the spatial area of interest decreases, the frequency of being affected by a hurricane decreases. The general area of the District has been affected by 48 hurricanes, 34 tropical storms, and 9 tropical cyclones (hurricanes or tropical storms) from 1871 to 2005 (**Table 1**). Since 1871, the Miami area was affected by hurricanes in 1888, 1891, 1904, 1906, 1909, 1926, 1935, 1941, 1945, 1948, 1950, 1964, 1965, 1966, 1972, 1992, and 1999 (Williams and Duedall, 1997). Between 1900 and 1996, Southeast Florida had 26 hurricanes directly hit (Herbert et al., 1997) and five additional hurricanes since 1997 (**Table 1**). Since 1997, Southeast Florida has had direct hits from Hurricanes Georges in 1998, Irene in 1999, Frances and Jeanne in 2004, and Katrina in 2005 (**Table 1**). **Table 2** depicts Southeast Florida hurricanes between 1900 and 2005 by category.

Table 1. Historical tropical cyclones, storms, and hurricanes affecting Central and South Florida from 1871–2005 (Attaway, 1999; Neumann et al., 1993; National Hurricane Center).

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1871	August 17-18	Tropical Cyclone	Indian River to Jacksonville	13.7	Rainfall observed in Jacksonville
1872					
1873	October 6-7	Tropical Cyclone	Fort Myers to Melbourne		
1874					
1875					
1876	September 12-19	Tropical Cyclone	Along eastern coast line	14.9	Hurricane did not make landfall in Florida; rainfall was observed in Dade County
	October 19-20	Tropical Cyclone	Naples to Vero Beach	15.3	Rainfall was observed in Dade County
1877					
1878	July 1-3	Tropical Cyclone	Port Charlotte to Vero Beach	9.58	Rainfall was observed at Punta Rassa in Lee County
	September 8-11	Tropical Cyclone	Arcadia to St. Augustine		Dade had 25.12 inches for September monthly rainfall
1879	September 21-22	Tropical Cyclone	Tampa to Titusville	12.77	Rainfall was observed at Daytona
1880					
1881	August 17-18	Tropical Cyclone	Tampa to Vero Beach		
1882					
1883					
1884					
1885	August 23-24	Tropical Cyclone	Along eastern coast line		
1886					Distinction was made between tropical storms and hurricanes (> 75 mph)
1887	October 29-30	Tropical Storm	Sarasota to Titusville	12.17	Rainfall was observed at Titusville
1888	August 16-17	Hurricane	Homestead to Naples		
1889	October 5-6	Tropical Storm	Cape Sable to Palm Beach		
1890					
1891	September 24-25	Hurricane	Homestead to Naples		
	October 6-7	Tropical Storm	Naples to Melbourne		
	October 9-10	Tropical Storm	Sarasota to Daytona Beach		
1892	June 10-11	Tropical Storm	Fort Myers to Vero Beach		Dade County received high rainfall
	October 24-25	Tropical Storm	Tampa Bay to Melbourne		

Table 1. Continued.

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1893					
1894	September 25-26	Hurricane	Tampa to Titusville	16.2	Rainfall was observed in Kissimmee
1895	October 16-17	Tropical Storm	Naples to West Palm Beach	24.39	Hypoluxo rainfall for the month
1896	October 8-9	Hurricane	Fort Myers to Melbourne		
1897	September 20-21	Tropical Storm	Fort Myers to Titusville		
	October 19-20	Tropical Storm	Tampa to St. Augustine		
1898	August 1-2	Hurricane	Fort Pierce to Clearwater		
	October 10-11	Tropical Storm	Naples to Melbourne		Rainfall from the storm was generally less than 1 inch
1899					
1900					
1901	August 10-11	Tropical Storm	West Palm Beach to Sarasota		
1902					
1903	September 11-12	Hurricane	Broward to Tampa		Heavy rain resulted from the hurricane
1904	October 17-18	Hurricane	Miami loop through Everglades	6.03	Rainfall was observed in Miami
1905					
1906	June 10-11	Tropical Storm	east of Panama City		
	June 16-18	Hurricane	Naples to West Palm Beach		
1907					
1908					
1909	October 11-12	Hurricane	Southern Dade to Atlantic Ocean	10.17	24-hour rainfall observed in Miami
1910	October 17-19	Hurricane	Cape Romano to Jacksonville		
1911					
1912					
1913					
1914					
1915					
1916					
1917					
1918					

Table 1. Continued.

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1919	September 10-11	Hurricane	Key West		hurricane went to Texas
1920					
1921	October 25-26	Hurricane	Tampa to north of Titusville		
1922					
1923					
1924	October 20-21	Hurricane	Naples to Fort Lauderdale	16.74	Rainfall observed in Fort Lauderdale
1925	November 30-December 1	Hurricane	Tampa to Titusville	15.1	Rainfall observed south of Miami
1926	July 27-28	Hurricane	Fort Pierce to Southern Georgia		
	September 18-19	Hurricane	Miami to Bonita Springs	8.02	Rainfall was observed in Fort Myers; high casualties in Moore Haven
1927					
1928	August 7-9	Hurricane	Vero Beach to N. W. Florida		
	September 16-17		Palm Beach to Jacksonville through Okeechobee		2000 died south of Lake Okeechobee
1929	September 28-29	Hurricane	Key West, southern tip of Florida	10.58	Rainfall was observed in Miami
1930					
1931					
1932	August 29-30	Tropical Storm	Key Largo to Fort Myers	10.24	Rainfall observed at Miami
1933	July 30-August 1	Tropical Storm	Stuart to Punta Gorda		
	September 3-5	Hurricane	Jupiter to Brooksville to Lake City		
1934	May 27-28	Tropical Storm	Fort Myers to Daytona Beach		
1935	September 2-4	Hurricane	Key West to North Florida along west coast of Florida	13.25	Narrow storm with high intensity, similar to Andrew of 1992 (rainfall observed at Punta Gorda)
	November 4-5	Hurricane	Miami to Cape Sable	11.8	Rainfall observed at Long Key
1936	June 15	Tropical Storm	Fort Myers to Miami	12.47	Rainfall observed at LaBelle
	July 28-29	Tropical Storm	Key Largo to Everglades City		
1937					
1938					
1939	August 11-12	Tropical Storm	Stuart to Tarpon Springs		
1940					

Table 1. Continued.

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1941	October 6-7	Hurricane	Miami to Fort Myers		
1942					
1943					
1944	October 18-19	Hurricane	Sarasota to Jacksonville	7.49	Rainfall observed in Orlando
1945	September 15-16	Hurricane	Key Largo to St. Augustine though central Florida		
1946	October 7-8	Hurricane	Sarasota to Lake City		
	November 1-2	Tropical Storm	Palm Beach to Lakeland		
1947	September 17 -18	Hurricane	Fort Lauderdale to Fort Myers	8.72	Rainfall observed in Fort Myers
	October 11-18	Hurricane	Cape Sable to Pompano		
1948	September 21-22	Hurricane	Everglades City to Stuart	11	Rainfall observed in Miami; path closely matched that of Hurricane Irene, October 1999
	October 4-5	Hurricane	Miami to Fort Lauderdale	9.95	Rainfall observed in Miami
1949	August 26-27	Hurricane	Palm Beach to Brooksville to Lake City	8.81	Rainfall observed at Belle Glade Expt. Station
1950	October 17-19	Hurricane "King"	Miami to Georgia through Central Florida	14.19	Rainfall observed in Orlando
1951	October 1-3	Tropical Storm	Fort Myers to Vero Beach	15.72	Rainfall observed in Bonita Springs
1952	February 1-3	Tropical Storm	Cape Sable to Miami		
1953	October 8-9	Tropical Storm "Hazel"	Fort Myers to Vero Beach		
1954					
1955					
1956					
1957					
1958					
1959	October 18-19	Tropical Storm "Judith"	Fort Myers to Fort Pierce		
1960	September 9-11	Hurricane "Donna"	Naples to Flagler Beach	8.48	Three days of rainfall in Miami
1961					
1962	August 26-27	Tropical Storm "Alma"	Miami to Titusville		
1963					
1964	August 27-28	Hurricane "Cleo"	Miami to Jacksonville along the coast	6.8	Rainfall as observed in Miami
	October 14-15	Hurricane "Isbell"	Cape Sable to Palm Beach	5.09	Rainfall observed at Everglades Expt. Station

Table 1. Continued.

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1965	September 8	Hurricane "Betsy"	Florida Keys and tip of Florida	10.89	Rainfall observed at HOMESTEADARB
1966	October 4-5	Tropical Storm "Inez"	Florida Keys and tip of Florida		
1967					
1968					
1969	September 6-7	Hurricane "Gerda"	Palm Beach to Vero Beach		Tropical storm while on land
1970					
1971					
1972	September 5	Tropical Storm "Dawn"	Southeast Florida Coast		
1973					
1974					
1975					
1976					
1977					
1978					
1979	September 3-4	Hurricane "David"	Palm Beach to Daytona Beach along the coast	8.92	Rainfall observed in Vero Beach
1980					
1981	August 17-19	Tropical Storm "Dennis"	Cape Sable to Cape Canaveral	20.38	Rainfall observed in Kendall
1982					
1983					
1984	September 26-28	Tropical Storm "Isidore"	Jupiter to Lakeland; turned north to Dade City	2.8	Rainfall observed in West Palm Beach
1985	July 23	Tropical Storm "Bob"	Naples to Vero Beach		
1986					
1987	October 12	Hurricane "Floyd"	Keys and tip of Florida	5.2	Rainfall observed in Naples
1988	November 23	Tropical Storm "Keith"	Sarasota to Melbourne	11	Rainfall observed in Largo
1989					
1990	October 11-12	Tropical Storm "Marco"	Keys to Cedar Key along the west coast	4.78	Rainfall observed at McDill AFB
1991					
1992	August 24	Hurricane "Andrew"	Homestead to Everglades City	6.9	Estimated at Homestead
1993					

Table 1. Continued.

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1994	November 16	Tropical Storm "Gordon"		16.0	Rainfall observed in Andytown
1995	August 1-3	Hurricane "Erin"	Vero Beach to north of Tampa	8.81	Rainfall observed in Melbourne
	August 23-26	Tropical Storm "Jerry"	Jupiter to Cedar Key	16.18	Rainfall observed in Naples
1996					
1997					
1998	September 25	Hurricane "Georges"	Florida Keys to Biloxi, Mississippi		
1999	October 13-17	Hurricane "Irene"	Flamingo to Jupiter	17.46	Rainfall observed in Boynton Beach
2000					
2001	August 2-7	Hurricane "Gabrielle"	Hillsboro to Volusia	5.96	Rainfall observed at Kissimmee
2002					
2003					
2004	August 12-16	Hurricane "Charley"	Charlotte to Volusia	5.07	Rainfall observed at Kissimmee
	September 4-8	Hurricane "Frances"	Palm Beach to Pasco	15.57	Rainfall observed at WPB Airport
	September 19-23	Extratropical "Ivan"	Palm Beach to Collier	2.03	Rainfall observed at WPB Airport
	September 24-28	Hurricane "Jeanne"	Palm Beach to Hernando	10.32	Rainfall observed at WPB Airport
2005	July 8-10	Hurricane "Dennis"	South of the Florida Keys	4.00	Areal rainfall over Southwest Florida; increased July rainfall on the Keys
	August 25-26	Hurricane "Katrina"	Broward/Miami-Dade line to Marco Island to Gulf of Mexico to Gulf Coast (New Orleans, Mobile, Gulf Port, etc.)	13.24	Rainfall observed at HOMESTEADARB on August 25
	September 20	Hurricane "Rita"	Florida Straits to Gulf of Mexico	6.27	Rainfall observed at S-18C, South Miami-Dade County
	October 23-24	Hurricane "Wilma"	Cape Romano to Atlantic Ocean through Palm Beach County	6.83 4.33	Areal rainfall over the Upper Kissimmee Rainfall Area District average areal rainfall

Table 2. Southeast Florida hurricanes between 1900 and 2005.

Category	Wind Speed (mph)	Number of Hurricanes
1	74-95	7
2	96-110	13
3	111-130	8
4	131-155	3
5	≥ 155	1

THE 2005 HURRICANE SEASON

During the 2005 hurricane season, the South Florida Water Management District area was hit by two hurricanes: Hurricane Katrina from the east and Hurricane Wilma from the west. A third hurricane, Hurricane Dennis, contributed rainfall to the Florida Keys and south-southwest Florida as it passed through western Cuba, Gulf of Mexico, and to the Florida Panhandle. A fourth hurricane (Hurricane Rita) passed through the Florida Straits from east to west, with impact on the Florida Keys and contributing rainfall to South Florida. A fifth tropical system, Tropical Storm Gamma, contributed significant rainfall on the District area while stationed in the Caribbean Sea. Based on the historical tropical systems record compiled in **Table 1**, the 2004 and 2005 hurricane seasons combined hurricane impact on the District area is a rare event. The path of the 2005 hurricanes that impacted the District area and estimates of radar rainfall are shown in **Figures 2a–d**.

Hurricane Dennis started as a tropical wave that moved westward from the coast of Africa in late June. It made landfall on southeastern Cuba as a category 4 hurricane. On July 9, 2005, it crossed over water and made landfall on western Cuba weakening to Category 3 (National hurricane Center (Beven, 2005)). As the hurricane crossed the Gulf of Mexico to the Florida Panhandle, it contributed rainfall to the Florida Keys and south-southwest Florida (**Figures 2a**).

According to the National Hurricane Center report (Knabb et al., 2006), Katrina developed as a tropical depression about 175 miles southeast of Nassau in the Bahamas on August 23, 2005. Katrina moved towards South Florida, making landfall on the Broward/Miami-Dade County line on the evening of August 25 as a Category 1 hurricane. The hurricane caused fatalities as well as damages to trees, power lines, homes, and businesses. As the hurricane moved west-southwestward through the southern tip of Florida (**Figure 2b**), it dumped over a foot of rainfall on some areas. It stayed six hours over land, mostly over the Everglades wetlands, and crossed to the Gulf of Mexico, just north of Cape Sable, on August 26. It made landfall on August 29 at the mouth of the Pearl River at the Louisiana/Mississippi border and caused unprecedented damage to Louisiana (particularly New Orleans), Mississippi, and Alabama. Most of the rainfall was on the south-east and south-west quadrants of the hurricane as it crossed South Florida. High-intensity rainfall, totaling 13.24 inches in a 24-hour period, was observed in Homestead (HOMESTEADARB rain gauge), which resulted in flooding. Such an amount of rainfall on the area in a 24-hour period is a rare frequency of 1-in-100-year return period. The intensity of rainfall was very high, as shown by the District gauge at Homestead Field Station (rain gauge HOMEFS+R). A rainfall intensity of close to 7 inches in two hours was observed on the evening of August 25. High-intensity rainfall results in high flooding.

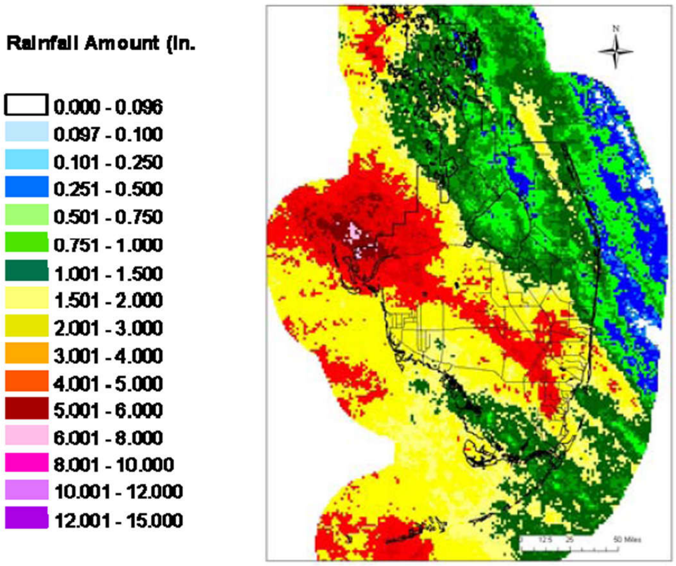

Figure 2a. Radar rainfall from Hurricane Dennis as it passed south of the Florida Keys (July 8-10, 2005).

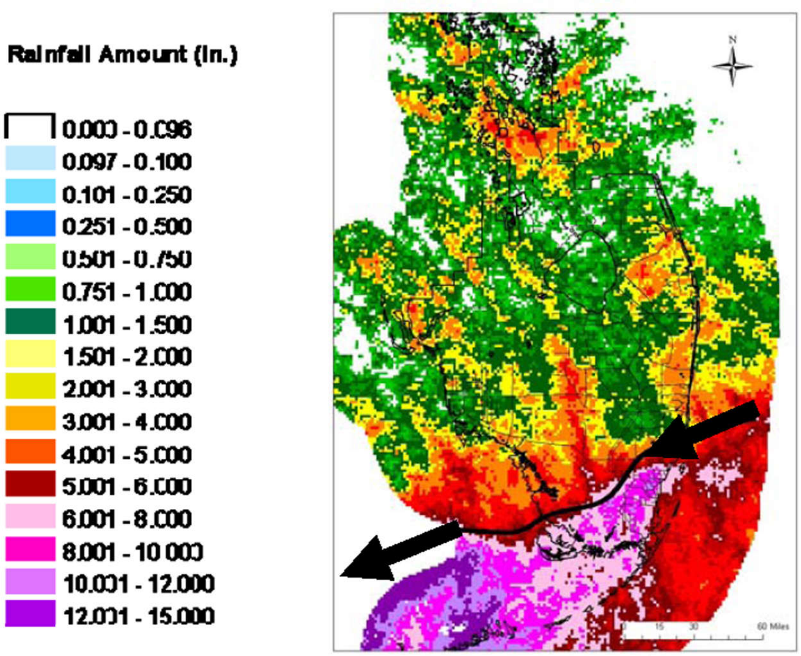

Figure 2b. Hurricane Katrina path and radar rainfall (August 24-27, 2005).

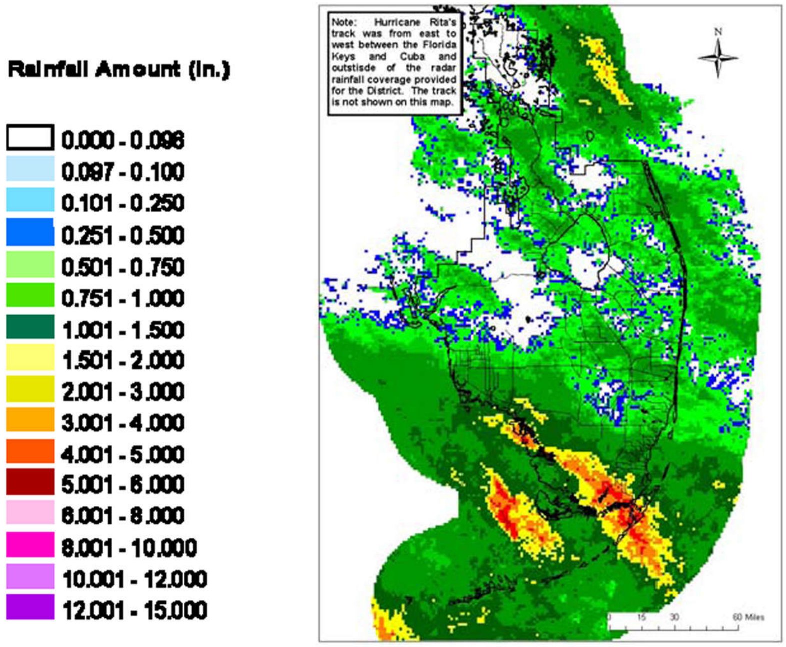

Figure 2c. Radar rainfall from Hurricane Rita as it passed through the Florida Straits (September 19-21, 2005).

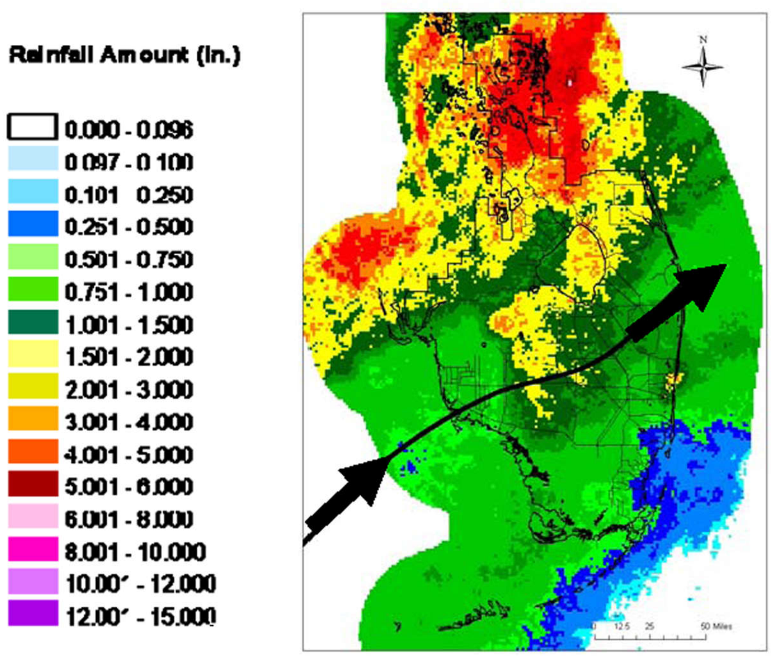

Figure 2d. Hurricane Wilma path and radar rainfall (October 22-25, 2005).

For the purpose of hydrologic impact of Hurricane Dennis on South Florida, rainfall associated with the hurricane from July 8-10, 2005, is totaled for each rainfall area (**Figure 3**) and presented in **Figure 4**. Key West rainfall in July 2005 was 6.37 inches compared to a historical average of 3.27 inches (http://www.srh.noaa.gov/eyw/HTML/climate/eywclimate.html).

For the purpose of hydrologic impact of Hurricane Katrina on South Florida, rainfall associated with the system from August 24-27, 2005, is totaled for each rainfall area (**Figure 3**) and presented in **Figure 4**. As seen from the radar rainfall estimates (**Figure 2a**), the highest areal rainfall was observed in Miami-Dade (6.27 inches), followed by the Everglades National Park (ENP) (6.1 inches). Areal rainfall is reported on the District's web site (http://iweb/iwebB501/omd/weather/opswthr.htm) as the Thiessen average of a network of rain gauges for each rainfall area. ENP area rainfall is computed from a simple average of eight gauge readings (S332, S174, S18C, HOMESTEADARB, JBTS, S331W, S334, S12D). It should be noted that the eastern section of the ENP got higher rainfall than the north and northwest sections (**Figure 2a**). Hurricane Katrina impacted Key West in storm surge and high rainfall. August rainfall for Key West was 13.49 inches compared to the average for the month, 5.40 inches (http://www.srh.noaa.gov/eyw/HTML/climate/eywclimate.html).

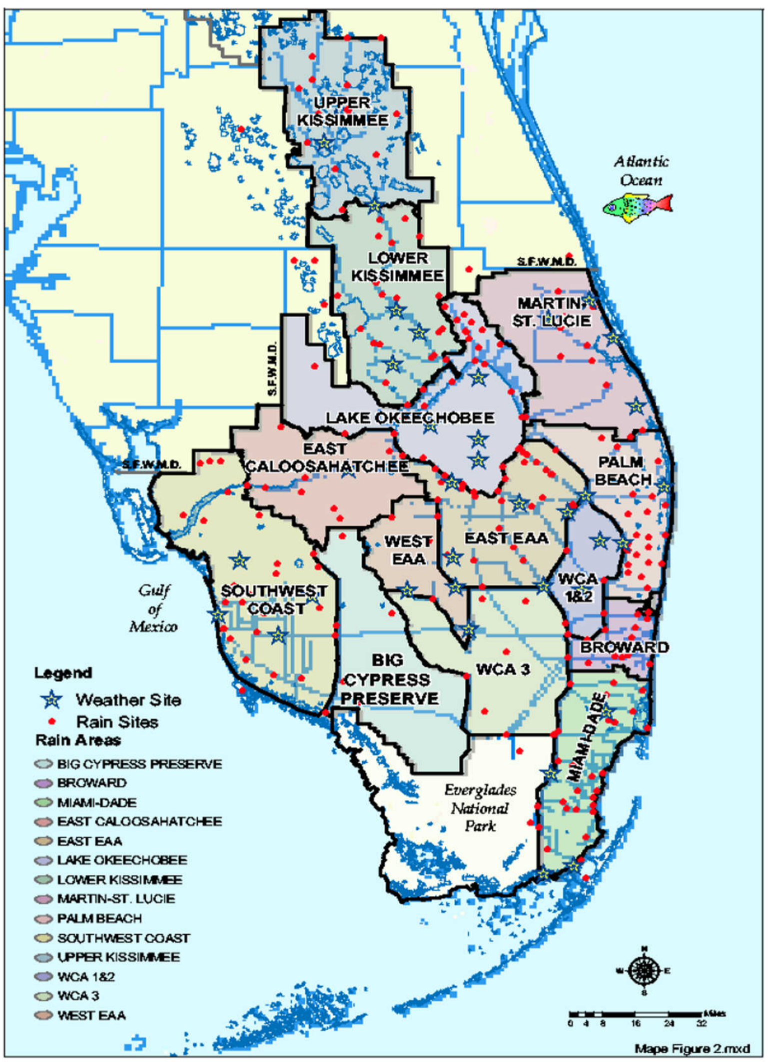

Figure 3. Rainfall areas of the South Florida Water Management District.

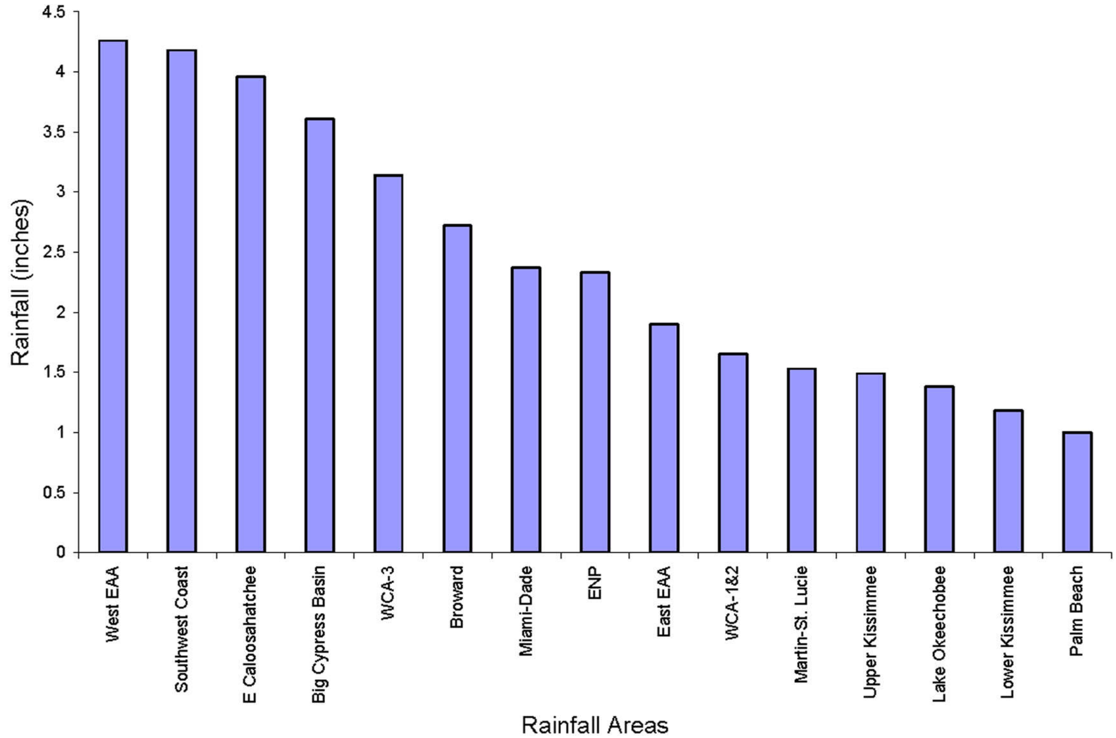

Figure 4. Hurricane Dennis areal average rainfall (July 8-10, 2005).

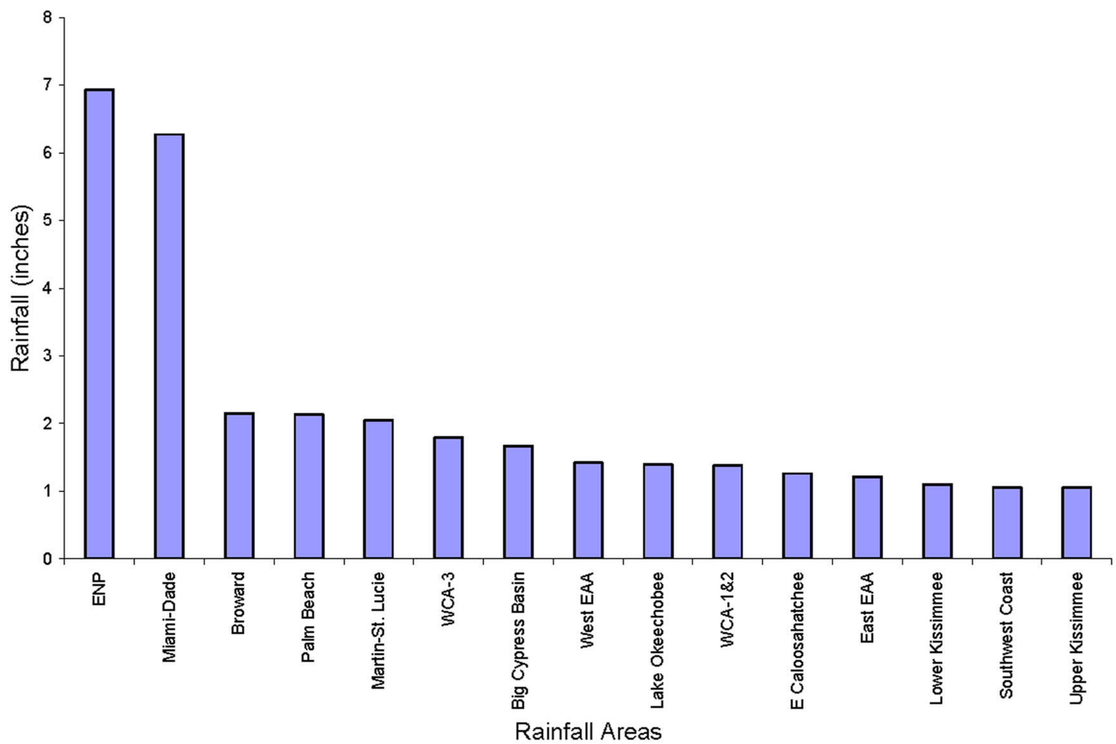

Figure 5. Hurricane Katrina areal average rainfall (August 24-27, 2005).

According to the National Hurricane Center (http://www.nhc.noaa.gov), Hurricane Rita developed as a tropical depression just east of the Turks and Caicos Islands on September 17, 2005. On September 19, it became a tropical storm and moved through the Central Bahamas. On September 20, Rita reached Category 2 hurricane status as it passed through the Florida Straits to the Gulf of Mexico and finally landed at the Texas/Louisiana line as a major hurricane. Even though the center of the hurricane did not pass through the Florida Keys, it impacted significantly with respect to downing trees, high surge, and flooding. As the hurricane moved southwest through the Florida Straits (**Figure 2c**), it contributed rainfall to the Keys and South Florida.

For the purpose of hydrologic impact of Hurricane Rita on South Florida, rainfall associated with the system from September 19-21, 2005, is totaled and presented in **Figure 6** for each rainfall area. As seen from the radar rainfall estimates (**Figure 2c**), the highest areal rainfall was observed in the ENP, followed by Miami-Dade, the Big Cypress Basin, Broward and Water Conservation Area 3. Areal rainfall is reported on the District's web site (http://iweb/iwebB501/omd/weather/opswthr.htm) as the Thiessen average of a network of rain gauges. ENP area rainfall is computed from a simple average of eight gauge readings (S332, S174, S18C, HOMESTEADARB, JBTS, S331W, S334, S12D). September rainfall for Key West was 7.35 inches compared to the average for the month, 5.45 inches (http://www.srh.noaa.gov/eyw/HTML/climate/eywclimate.html).

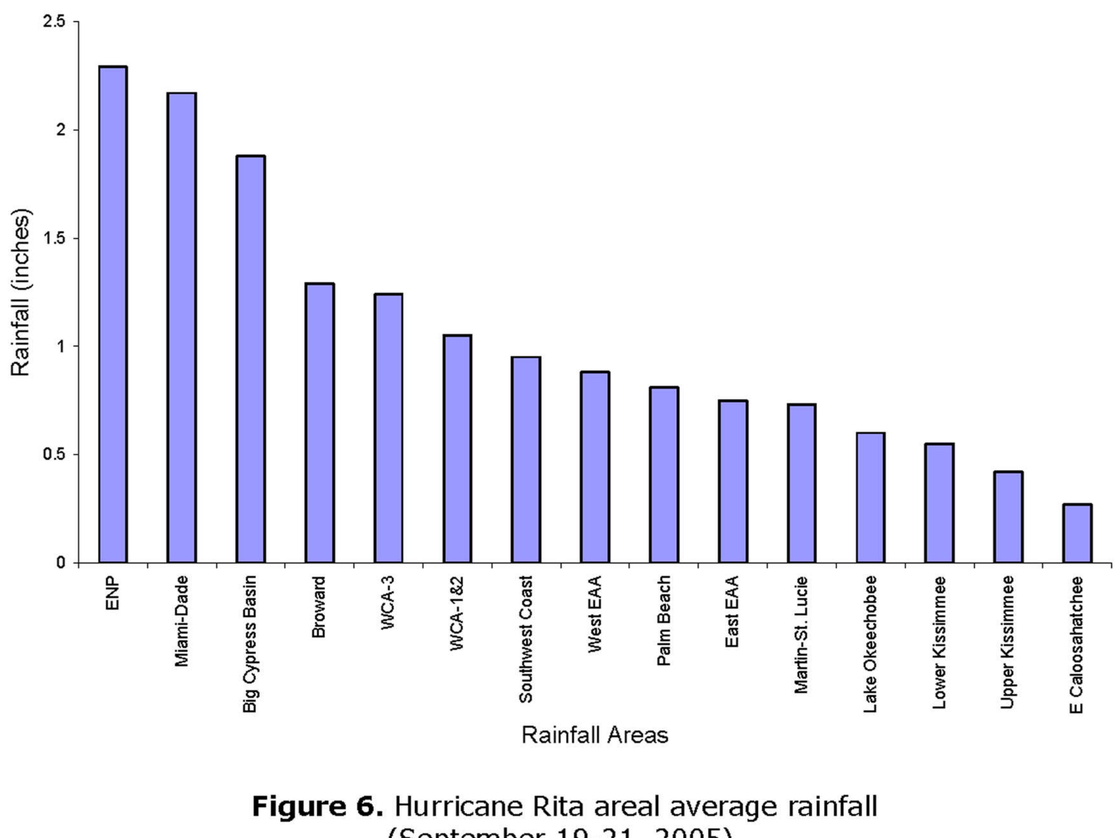

Figure 6. Hurricane Rita areal average rainfall (September 19-21, 2005).

According to the National Hurricane Center (Pasch et al., 2006), Hurricane Wilma formed as a tropical depression on October 15 east-southeast of Grand Cayman. On October 18, Wilma became a hurricane moving west-northwestward. On October 19, Wilma strengthened to a Category 5 hurricane with a record low pressure of 882 millibars (mb) for an Atlantic hurricane. On October 21, it made landfall on the island of Cozumel, Mexico, as a Category 4 hurricane. On October 22, Wilma crossed to the Yucatan Peninsula and after prolonged battering of the northeastern section, it emerged in the Gulf of Mexico in early morning of October 23. According to the National Hurricane Center, Wilma initially made landfall on southwest Florida near Cape Romano as a Category 3 hurricane on October 24. It then hit South Florida as a Category 2 hurricane. Subsequently, this hurricane crossed the Atlantic Ocean in four and a half hours (**Figure 2d**). The eye of Hurricane Wilma passed through South Florida inflicting extensive damage from the front end and back end of the hurricane. **Figure 7** depicts rainfall from Hurricane Wilma on each subregion (rainfall area). Areal rainfall is reported on the District's web site http://iweb/iwebB501/omd/weather/opswthr.htm as the Thiessen average of a network of rain gauges. ENP area rainfall is computed from a simple average of eight gauge readings (S332, S174, S18C, HOMESTEADARB, JBTS, S331W, S334, S12D). As shown in the radar rainfall estimates (**Figure 2d**) and gauge observations (**Figure 7**), most of the rainfall from the hurricane was on the headwaters of Lake Okeechobee and the southwest. Because the hurricane quickly crossed South Florida (less than five hours), the rainfall was not extreme. However, the location of the rainfall, the amount of runoff generated, and the high antecedent water levels in lakes and impoundments impacted the water management system hydraulically and environmentally. This is presented in the discussion on flows and water levels associated with the hurricanes.

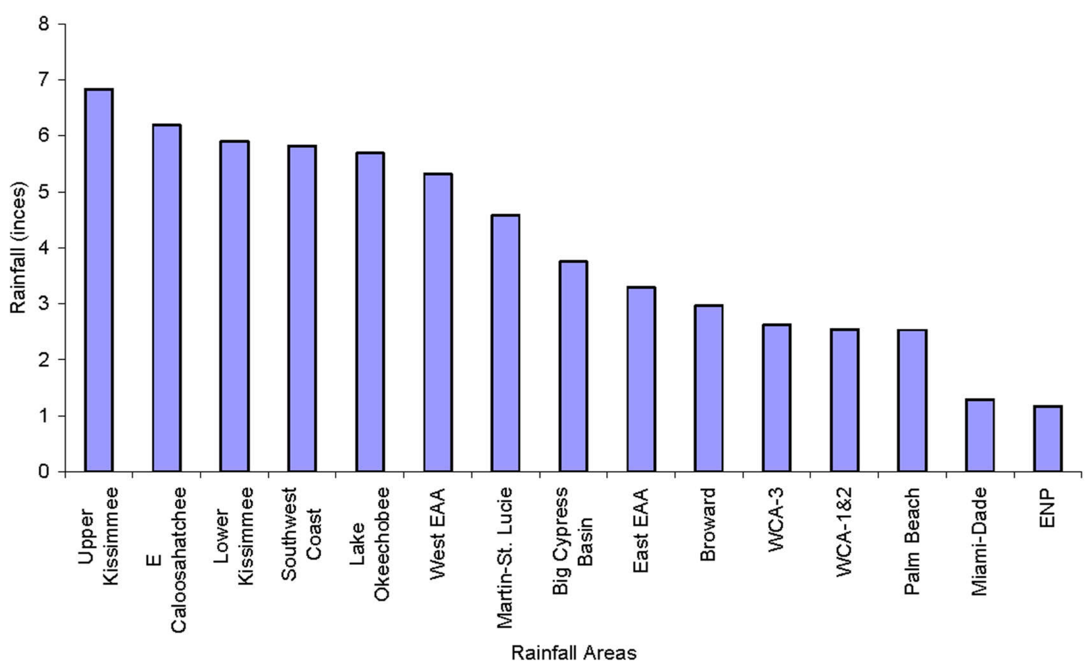

Figure 7. Hurricane Wilma areal average rainfall (October 22-25, 2005).

The following discussion is limited to the hydrologic impact of Hurricane Wilma and wind field over the water management system. Hurricane winds create wind setup on earth dams and have great potential for wash over the top of a levee, wind and water erosion of loose surfaces on embankments, and embankment erosion from back-and-forth sloshing of waves. Wind setup is a function of the speed of wind, the fetch or length of water over which the wind blows, the depth of water, and bottom roughness of reservoir or lake. Wind setup is generally larger in shallow reservoirs with a rough bottom (Linsley and Franzini, 1979).

Wind speed data from 15 District weather stations was available as 15-minute average wind speed and maximum gust wind speed in every 15-minute time interval. The sampling and averaging of wind speed and characterizing peak wind speed for these weather stations is different from the ASTM standard. The ASTM standard for characterizing surface wind is a 3-second continuous observation and outputs of peak 3-second, 10-minute mean, and peak 1-minute wind speed and other additional output options (ASTM, 1996). For District weather stations, maximum gust wind speed in every 15-minute interval is instantaneous wind speed sampled every minute (15 instantaneous samples) and the maximum of the fifteen samples registered as maximum gust wind speed. Fifteen-minute average wind speed is derived as average of 90 instantaneous observations at 10-second intervals within the 15-minute time period. While the 15-minute average wind speed dampens out peak wind speed, the maximum gust wind speed record relatively demonstrates how high instantaneous wind speed reached in 15-minute interval at the 1-minute interval sampling. However, the instantaneous 1-minute observations may be too far apart to capture the maximum instantaneous gust wind speed. Also, instantaneous wind speed has no sustained gust wind speed representation following most requirements. Nevertheless, the data can be used to estimate how high the hurricane wind reached instantaneously. Wind speed is measured at a height of 33 feet at the land-based weather stations. Wind speed on Lake Okeechobee (L006) is measured at about 23 feet above the average lake water level at the time. The height for wind speed sensors at the remaining three weather stations (L001, L005, and LZ40) is similar to L006. **Figure 8** depicts the L006 weather station on Lake Okeechobee. **Figure 9** depicts peak gust wind speeds at each weather station and time of peak. The weather stations report in Eastern Standard Time. The location of weather stations is shown in **Figure 10**. **Figures 11** through **25** depict 15-minute average wind speed and maximum gust wind speed at each 15-minute time interval on October 24, 2005 for each weather station where data was available. Weather stations in the eye of the hurricane distinctly reflect calmer conditions when the eye was passing over the area. The maximum gust wind speed observed from the 15 weather stations is 117 miles per hour (mph) at the BELL GL weather station in Belle Glade.

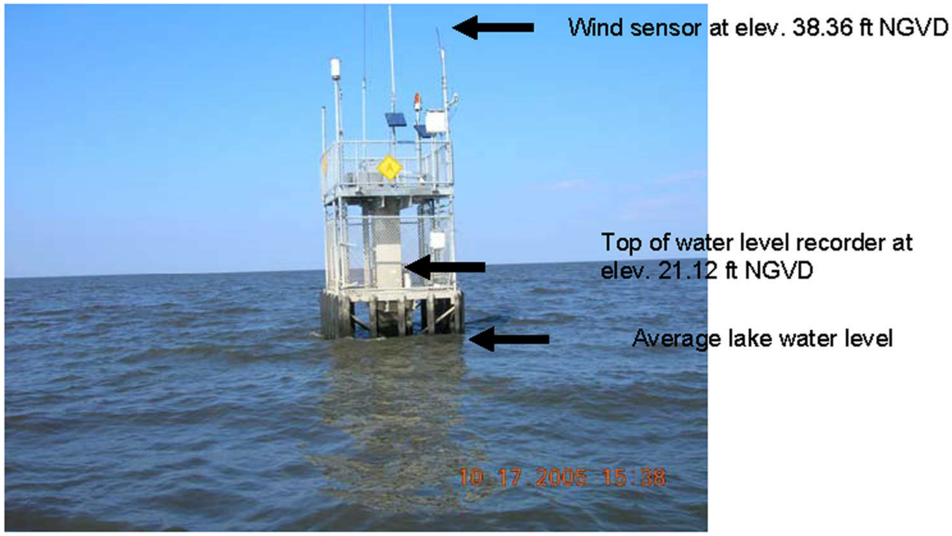

Figure 8. Weather station L006 in Lake Okeechobee (photo by SFWMD; October 17, 2005).

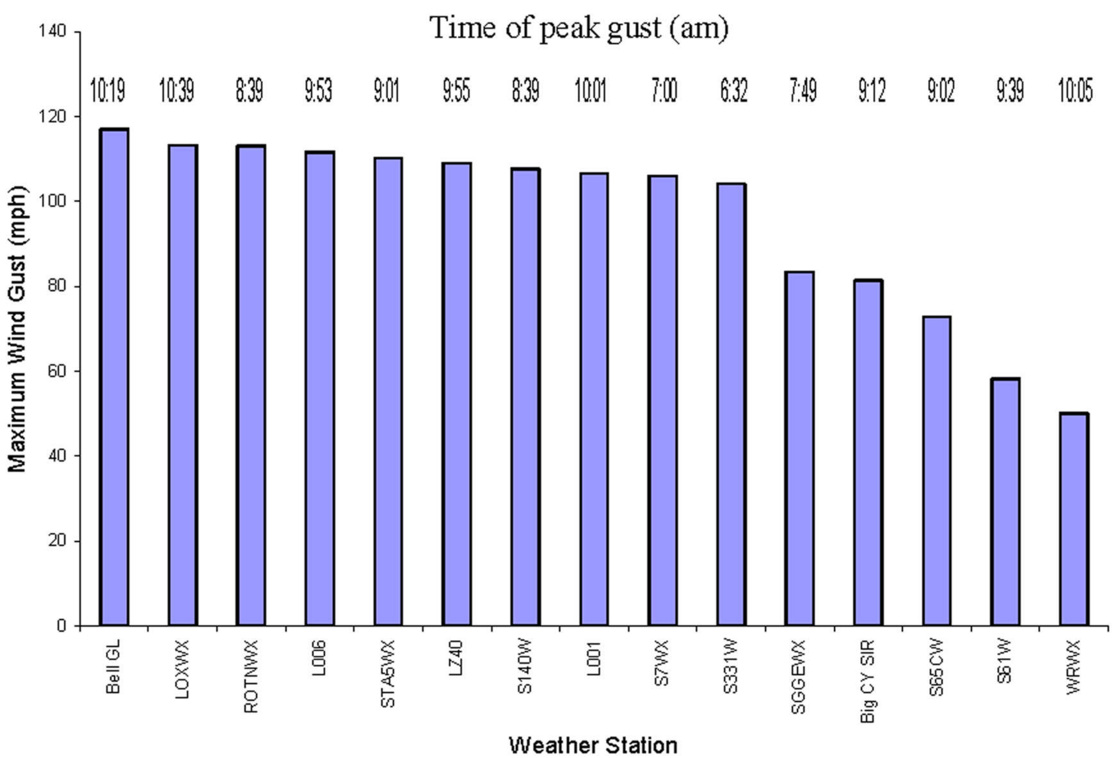

Figure 9. Instantaneous maximum gust wind speed (sampled at minute intervals) in 15-minute period at each weather station [Note: Big Cy SIR wind sensor readings were too low].

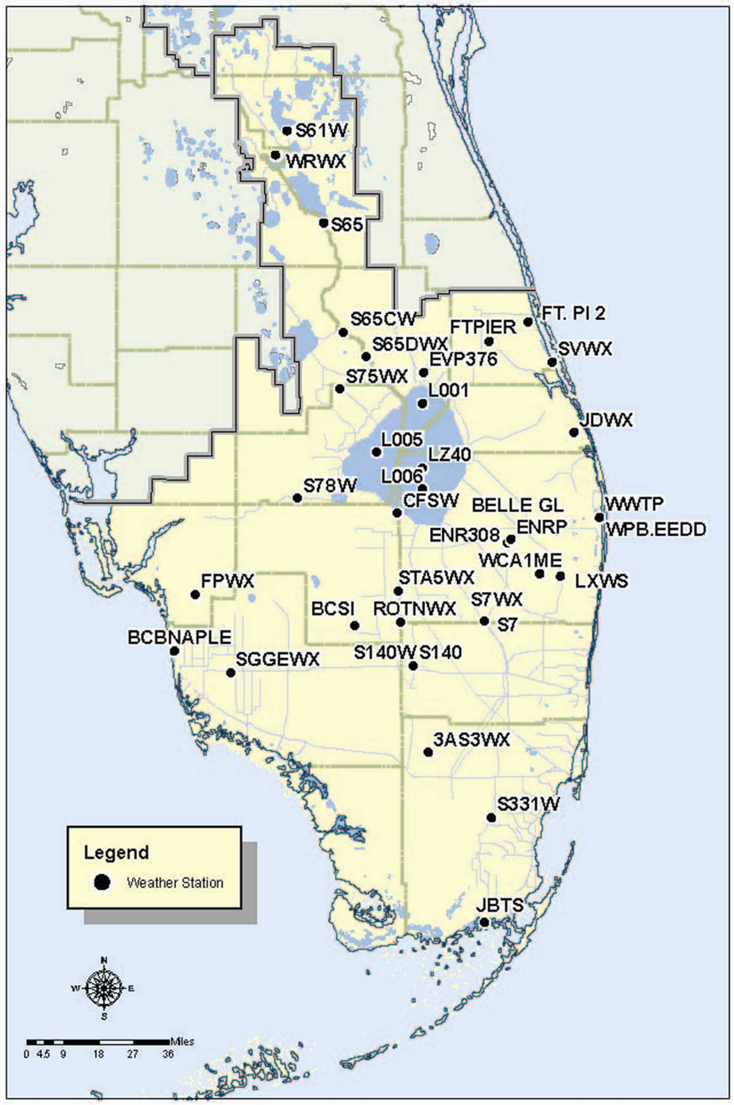

Figure 10. Location of weather stations.

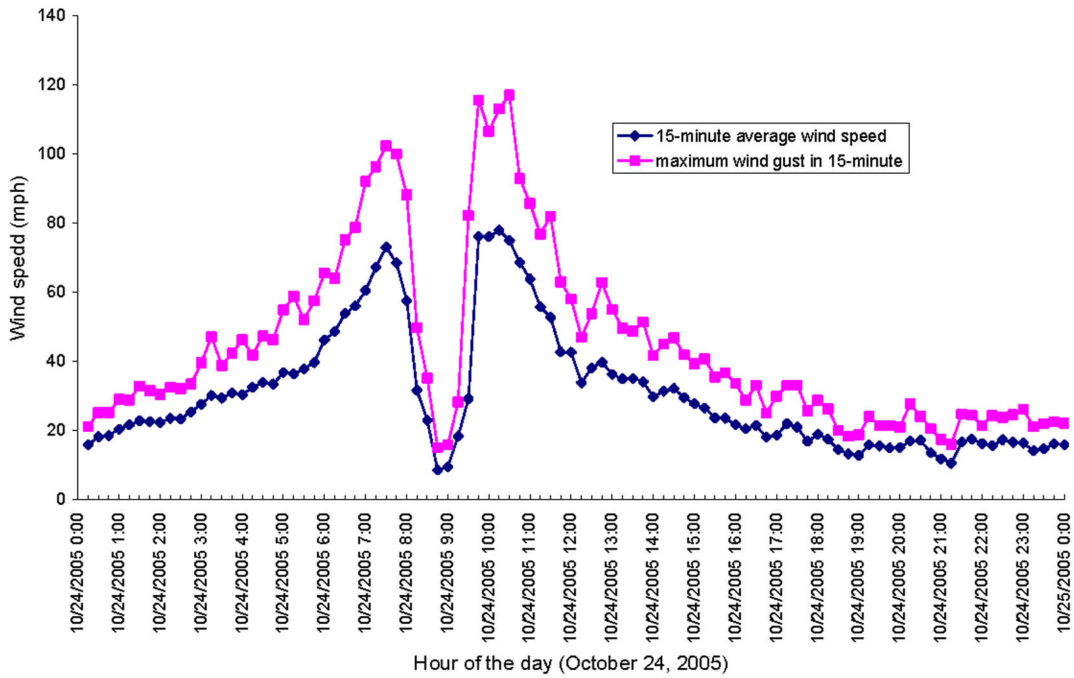

Figure 11. Wind speed at BELL GL weather station during Hurricane Wilma.

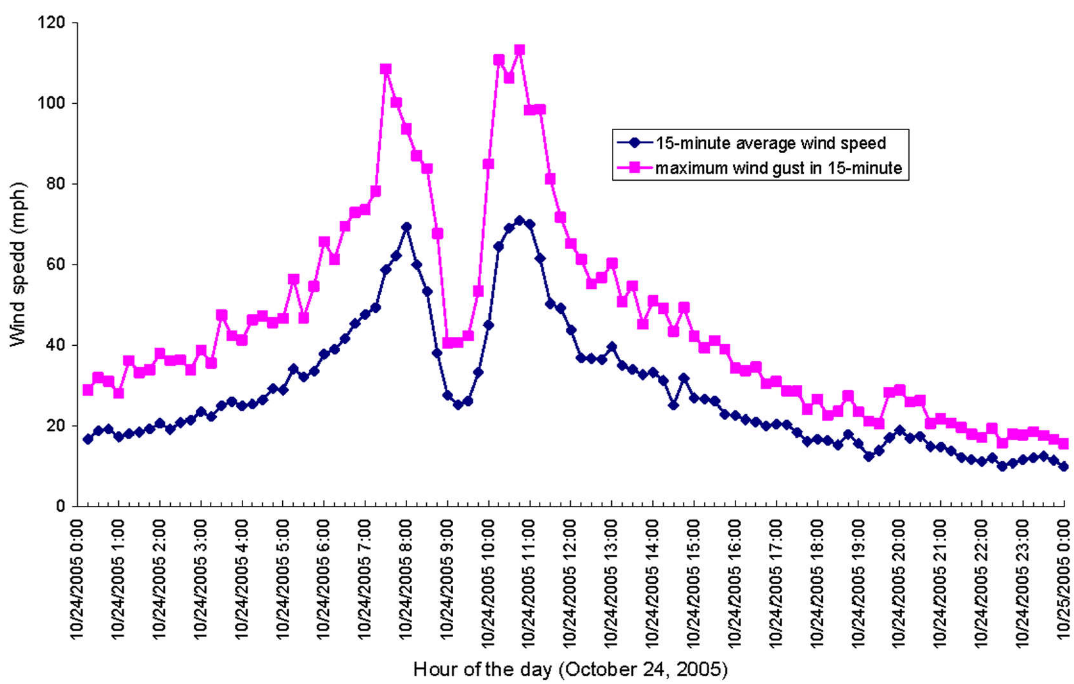

Figure 12. Wind speed at LOXWS weather station during Hurricane Wilma.

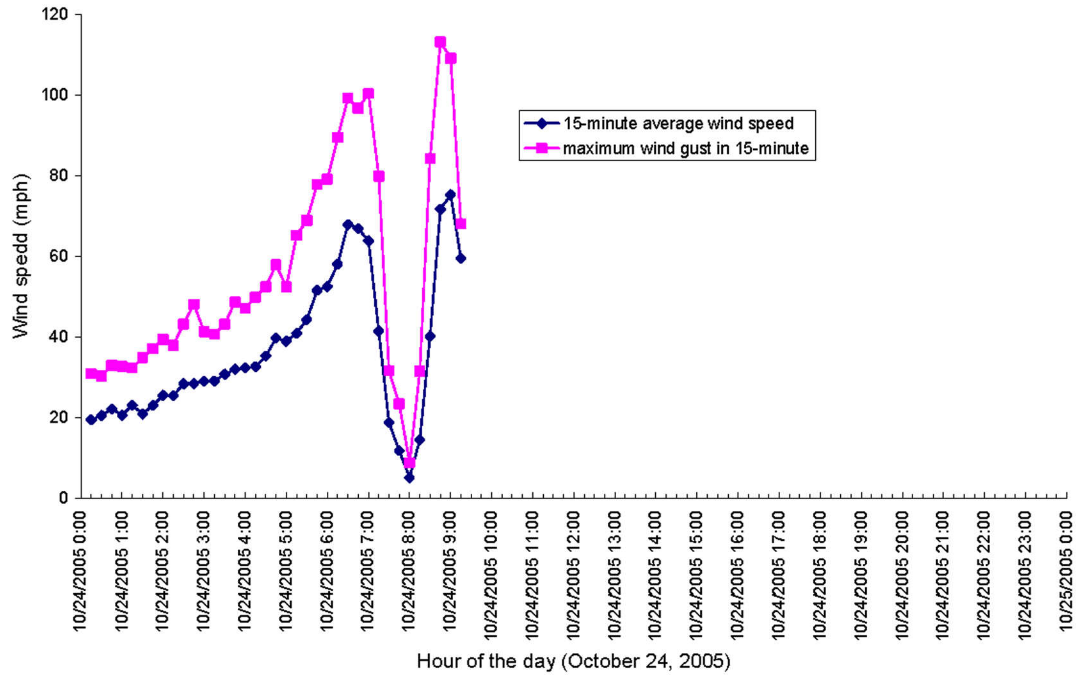

Figure 13. Wind speed at ROTNWX weather station during Hurricane Wilma [Note: sensor failed after the eye of the hurricane passed].

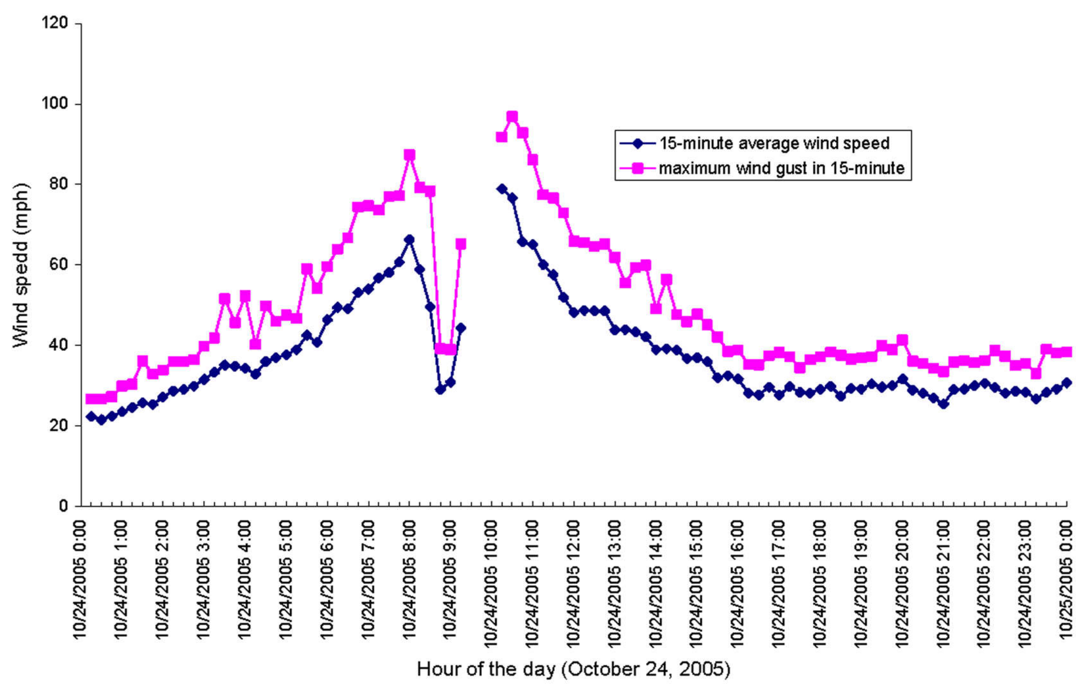

Figure 14. Wind speed at L006 weather station during Hurricane Wilma.

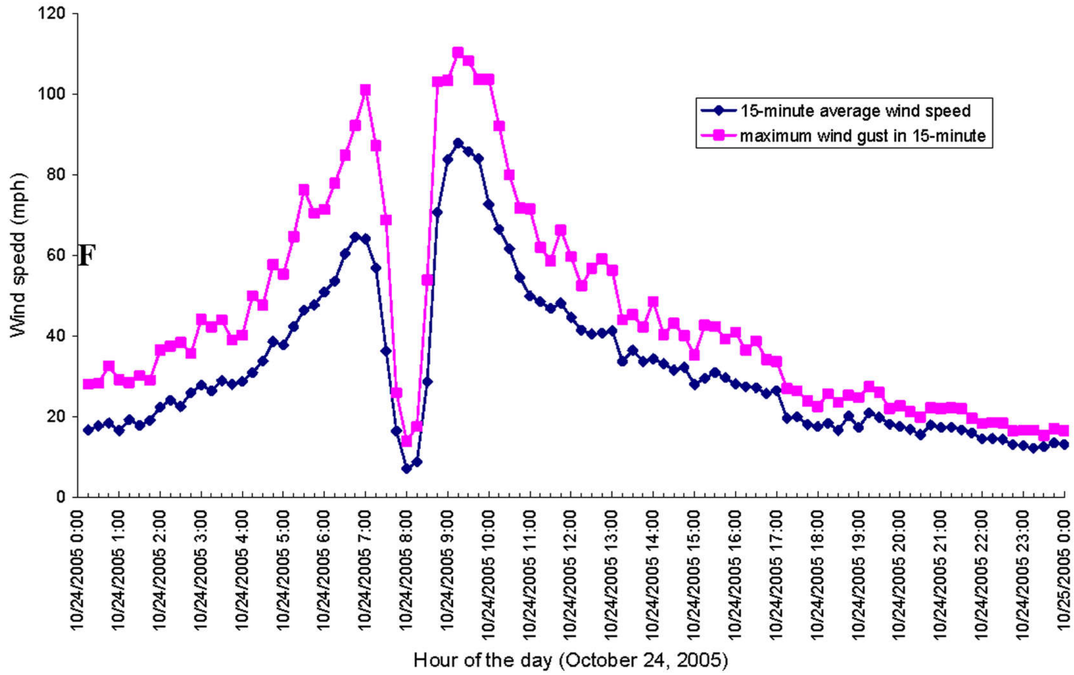

Figure 15. Wind speed at STA5WX weather station during Hurricane Wilma.

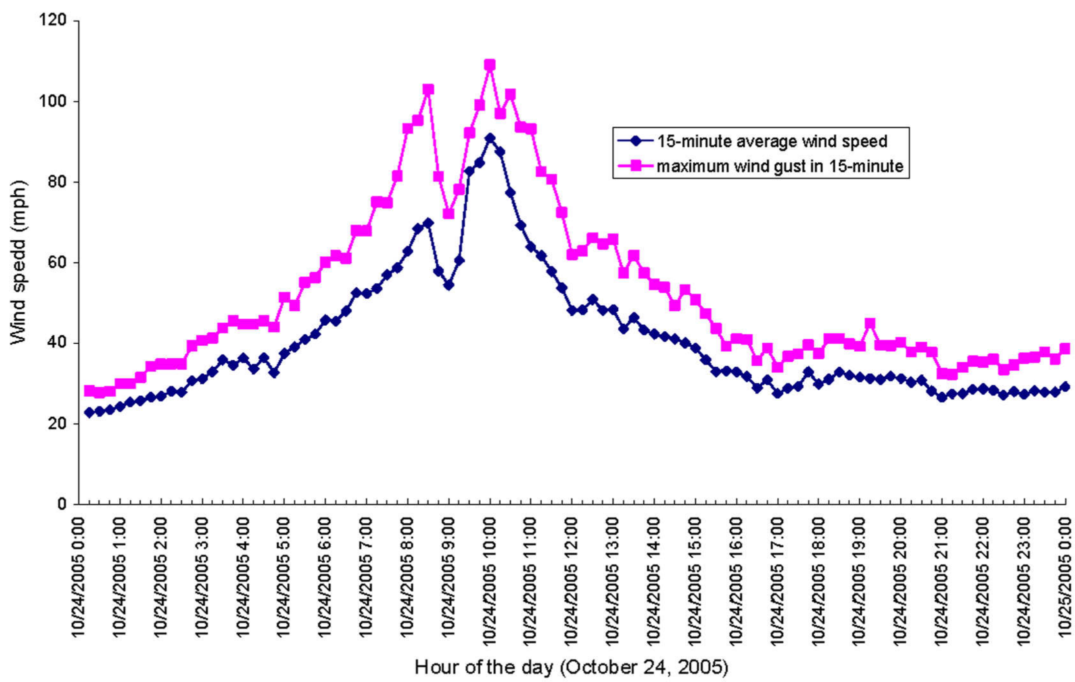

Figure 16. Wind speed at LZ40 weather station during Hurricane Wilma.

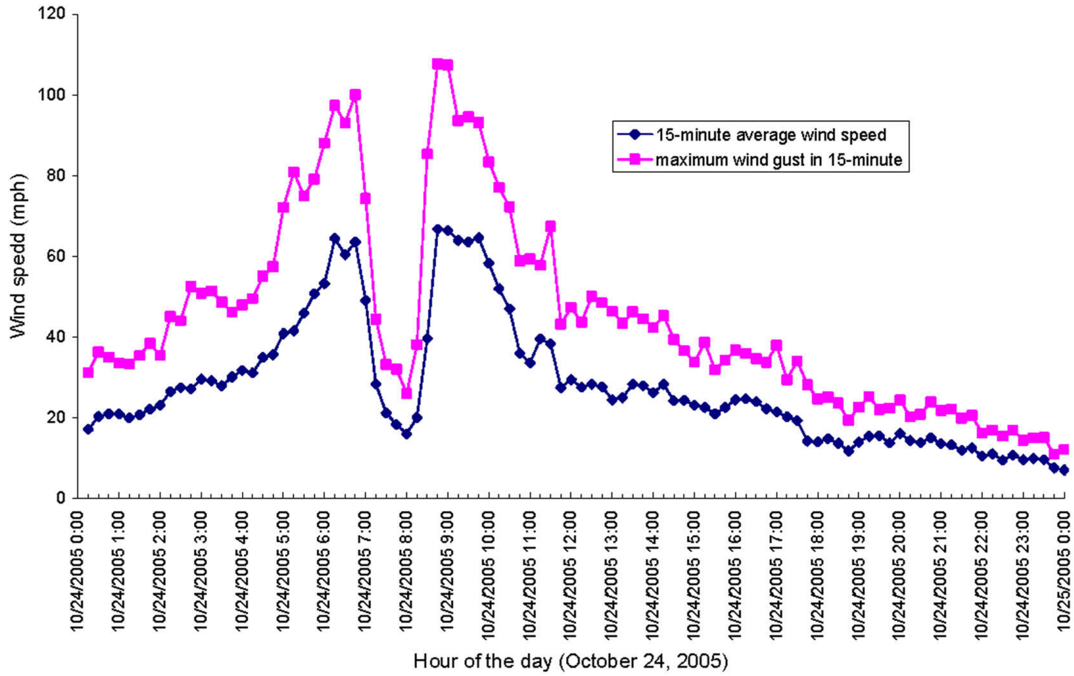

Figure 17. Wind speed at S140W weather station during Hurricane Wilma.

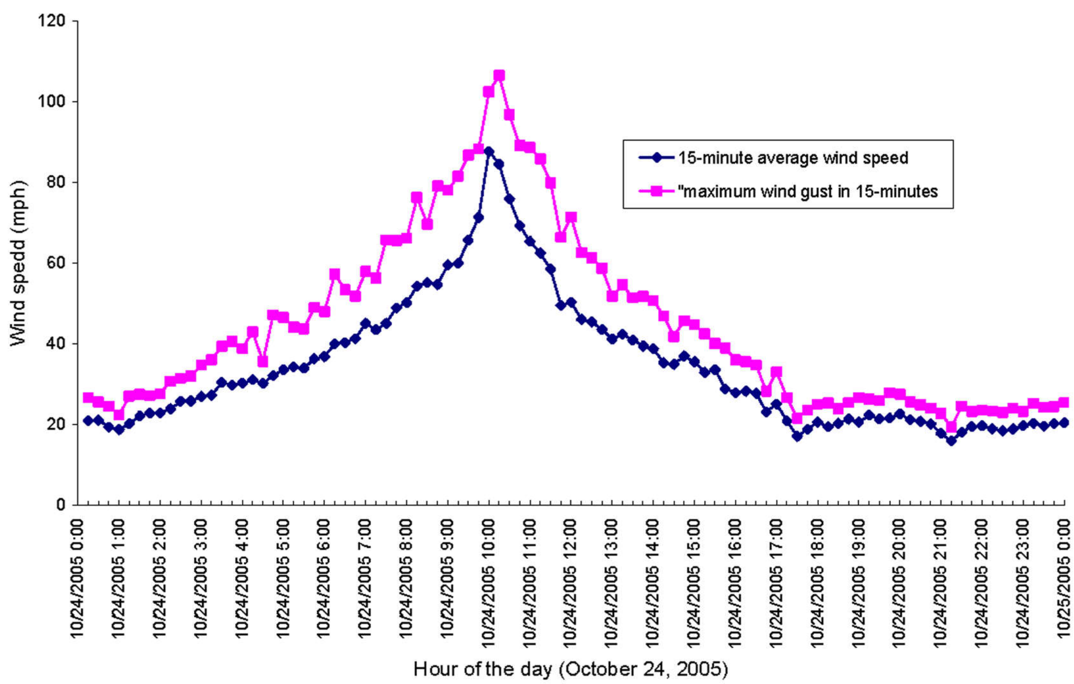

Figure 18. Wind speed at L001 weather station during Hurricane Wilma.

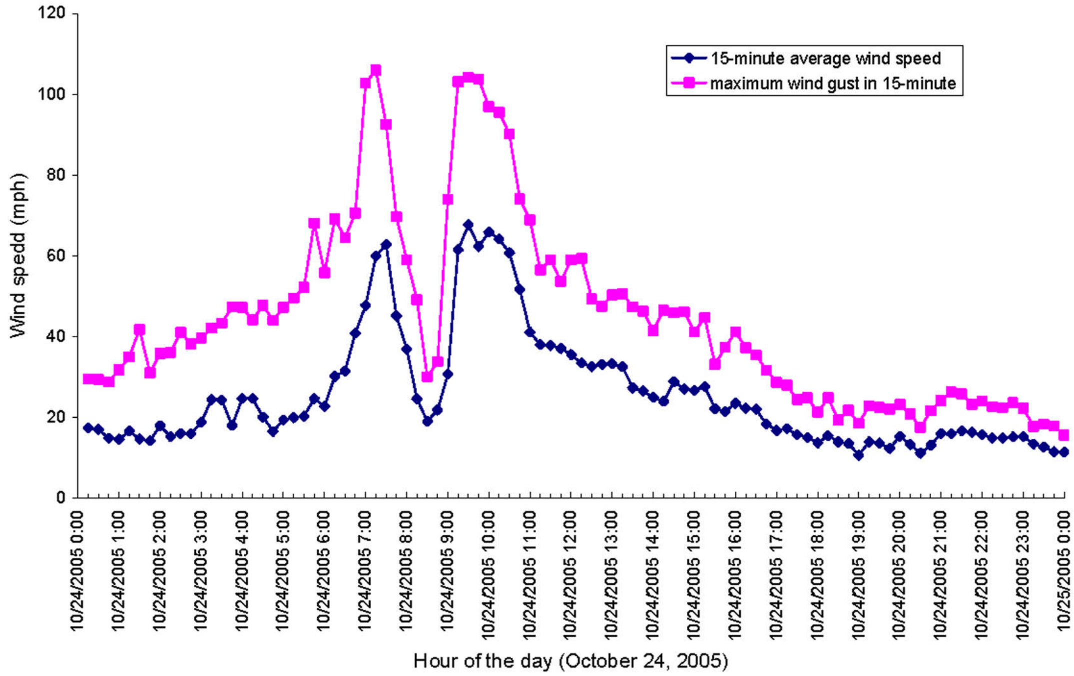

Figure 19. Wind speed at S7WX weather station during Hurricane Wilma.

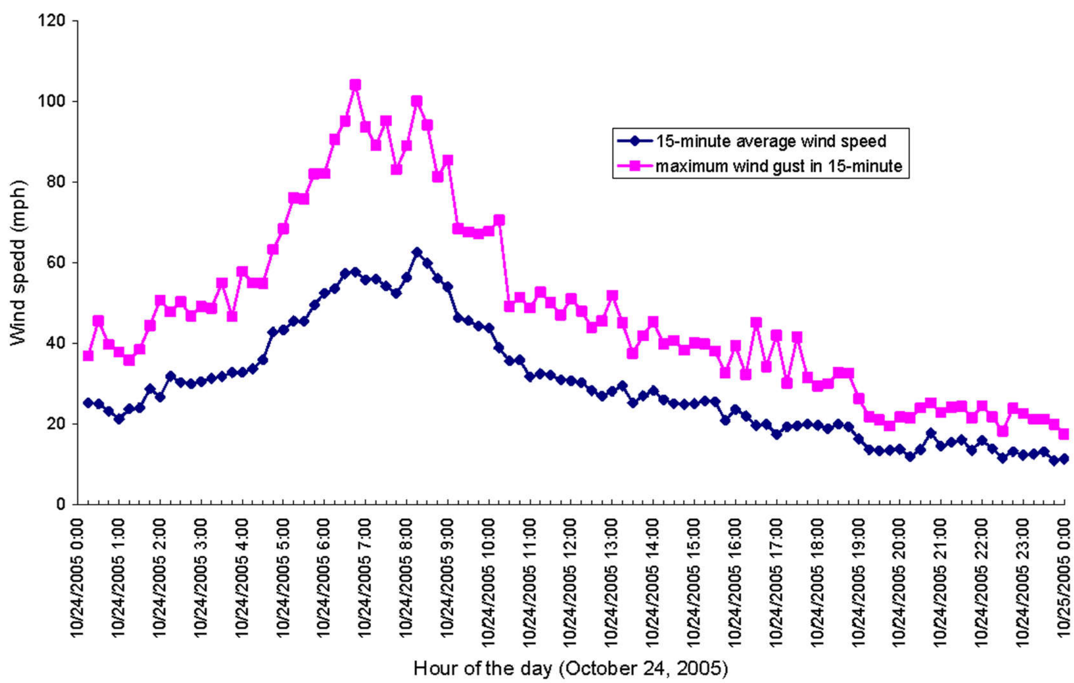

Figure 20. Wind speed at S331W weather station during Hurricane Wilma.

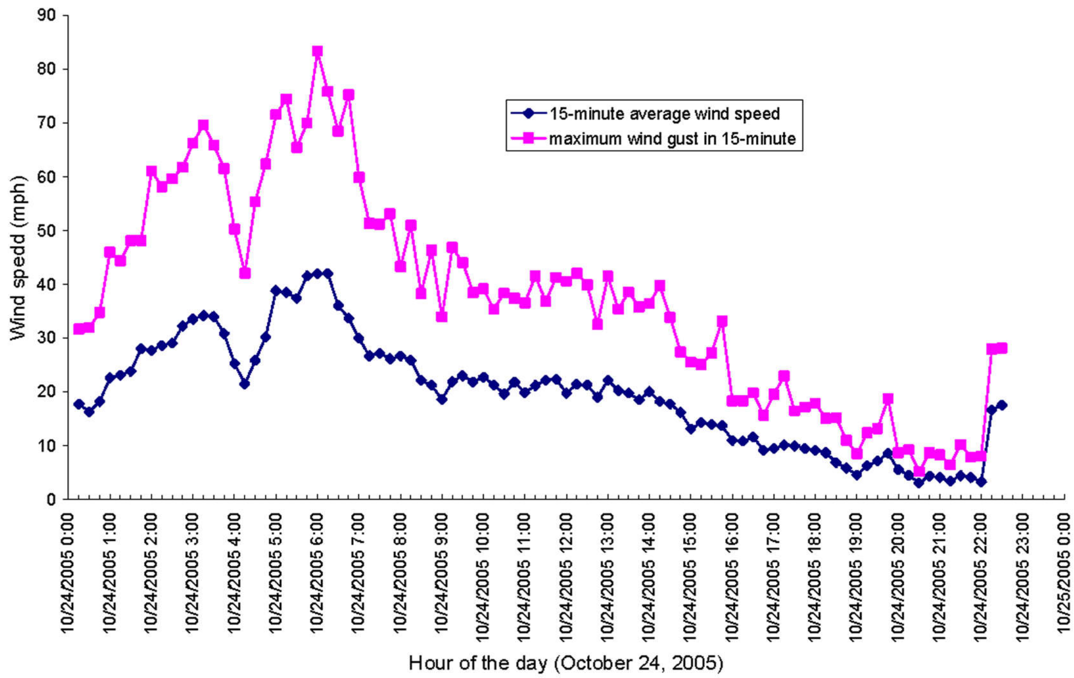

Figure 21. Wind speed at SGGEWX weather station during Hurricane Wilma.

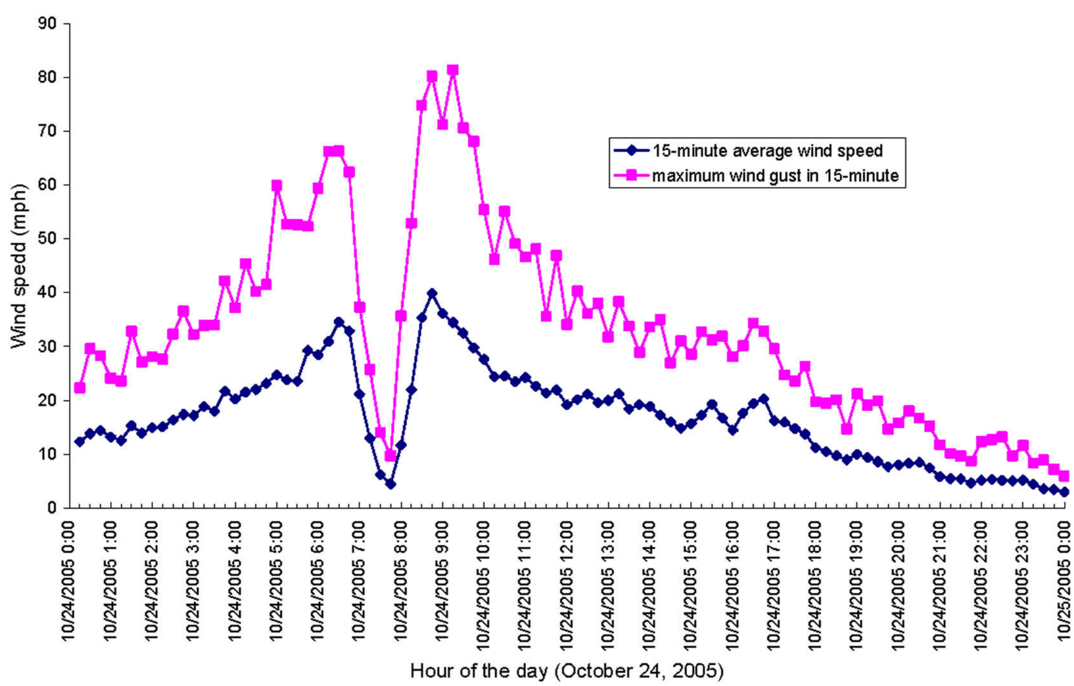

Figure 22. Wind speed at BIG CY SIR weather station during Hurricane Wilma (consistently recorded lower than neighboring stations).

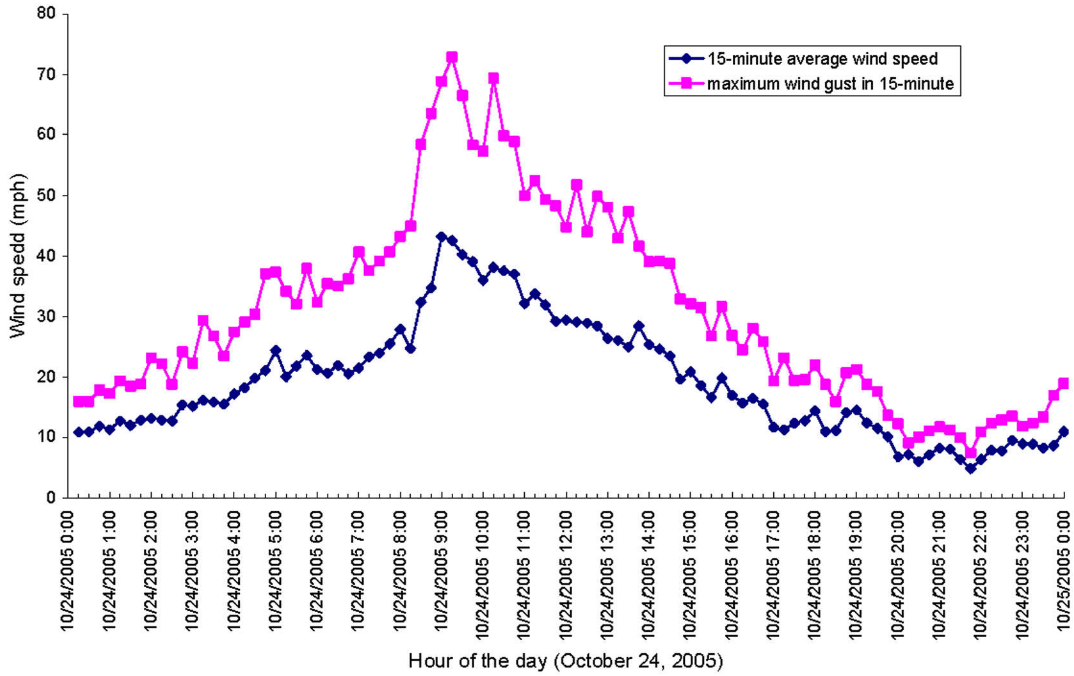

Figure 23. Wind speed at S65CW weather station during Hurricane Wilma.

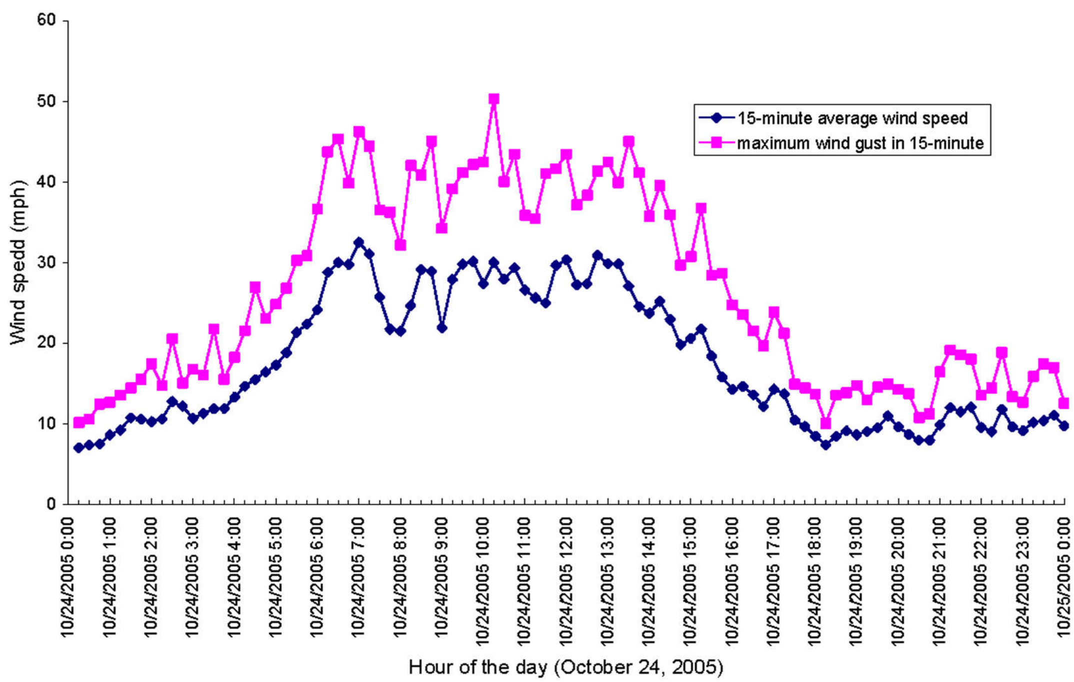

Figure 24. Wind speed at S61W weather station during Hurricane Wilma.

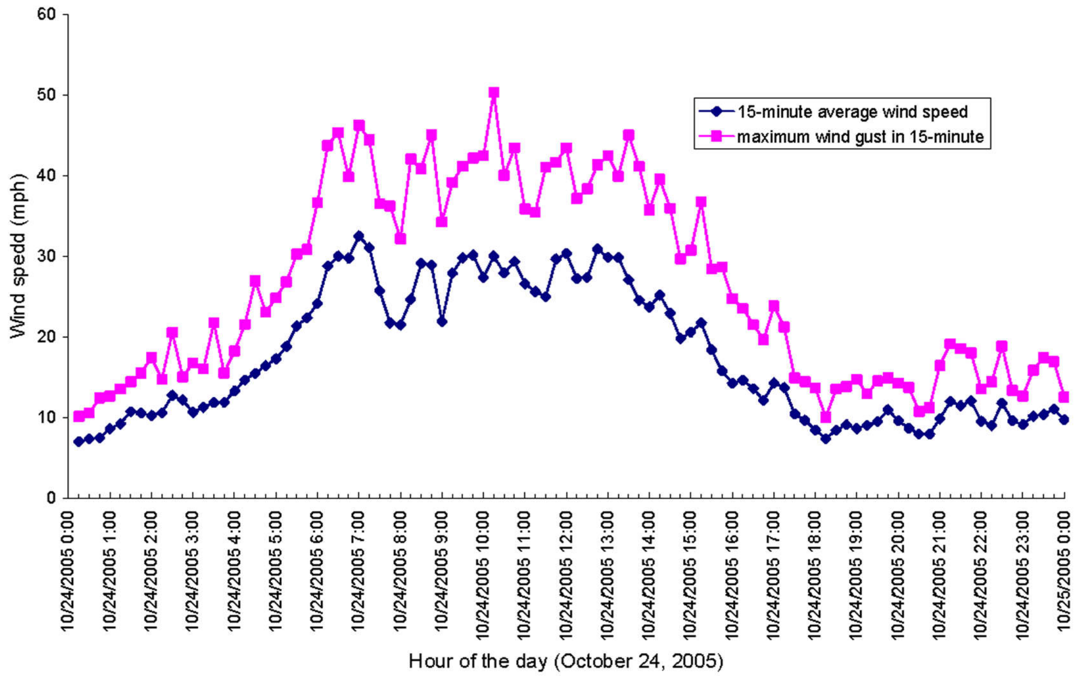

Figure 25. Wind speed at WRWX weather station during Hurricane Wilma.

HURRICANE IMPACTS ON THE SOUTH FLORIDA WATER MANAGEMENT SYSTEM

The South Florida Water Management System comprises lakes, earthen embankments, canals, water control structures, constructed wetlands, and a water management monitoring system. Hurricane-generated rainfall can create surface runoff above the local or regional capacity of storage and conveyance of the water management system resulting in flooding. The impact of the rainfall from a hurricane is dependent upon antecedent and precedent hydrologic conditions, the intensity of the rainfall, the amount of the rainfall, and the path of the hurricane. Winds from hurricanes generate waves that damage embankments and can result in levee failure. High water levels could cause levee failure through seepage and piping. Hurricane wind generated waves also erode embankments around water control structures with potential failure at a structure. Wind from hurricanes can deposit trees and vegetation on waterways and obstruct or limit the conveyance capacity of canals. Vegetation and other debris deposited on water control structures limit water management operations. Damage to water management monitoring facilities results in limited ability to make critical water management decisions, loss of power and control, and impaired operations. Hurricane winds affect vegetation in constructed wetlands by disturbing vegetation and pushing vegetation mass onto the levee banks. Strong hurricane winds resuspend settled sediments in the constructed wetlands (Stormwater Treatment Areas, or STAs) and impact phosphorus removal performance. Hurricane Rita impacted the Florida Keys as it passed through the Florida Straits. Hurricanes Katrina and Wilma had a major impact on the South Florida Water Management System.

Impact of Hurricane Katrina on the Management System

According to a District news release (August 26, 2005), Hurricane Katrina's impacts to Broward County were wind and some rainfall. **Figure 5** depicts that the areal rainfall on Broward County was about 2 inches. The news release also confirms that Miami-Dade County was impacted by wind and rainfall. The intensity of rainfall is presented in the previous section. Due to the high intensity of rainfall, flooding was reported in the Homestead area. Water level in western Miami-Dade was about 2 feet above ground level. Additionally, there was flooding in the L-31 and C-111 canal areas near the ENP, as well as the C-1 canal basin. In the C-111 basin, pump stations S-332 B, C, and D were in full operation. Structures S-174, S-175, S-176, S-177, and S-18C in South Miami-Dade also were operating. In the Florida Bay area, the S-197 structure was opened. In western Miami-Dade, the flood control detention basin on the C-4 canal was activated as a result of rising canal levels from the hurricane rainfall runoff. Due to the short duration of the hurricane and the size of the area affected, a shorter duration of hydrologic impact was anticipated where high water levels did not linger.

Impact of Hurricane Wilma on the Management System

In the 2005 hurricane season, Hurricane Wilma had the most impact on the water management system. Hurricane Wilma's wind filled canals with trees and backyard debris from residential sites along the canals. According to a District news release (November 7, 2005), C-2, C-7, and C-100 were strongly affected. Hurricane-related emergency debris removal from these waterways was required. **Figures 26** and **27** depict the maximum gust wind speed, 15-minute average wind speed, and wind direction on the southern region of the District. **Figure 28** depicts the removal operation in a vegetation- and debris-filled canal. Notably, there was no significant urban flooding reported due to Hurricane Wilma.

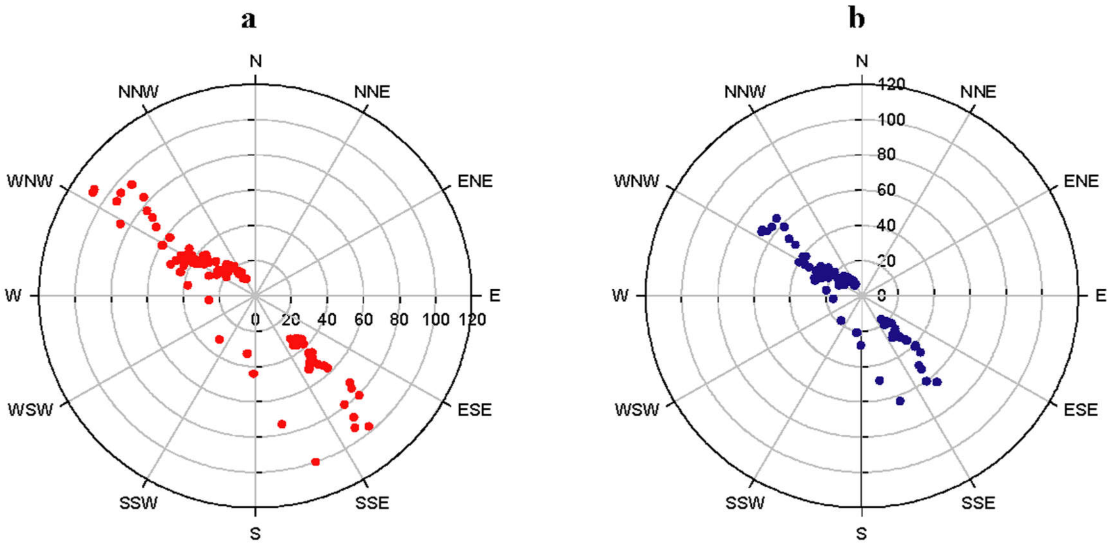

Figure 26. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at S140W weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

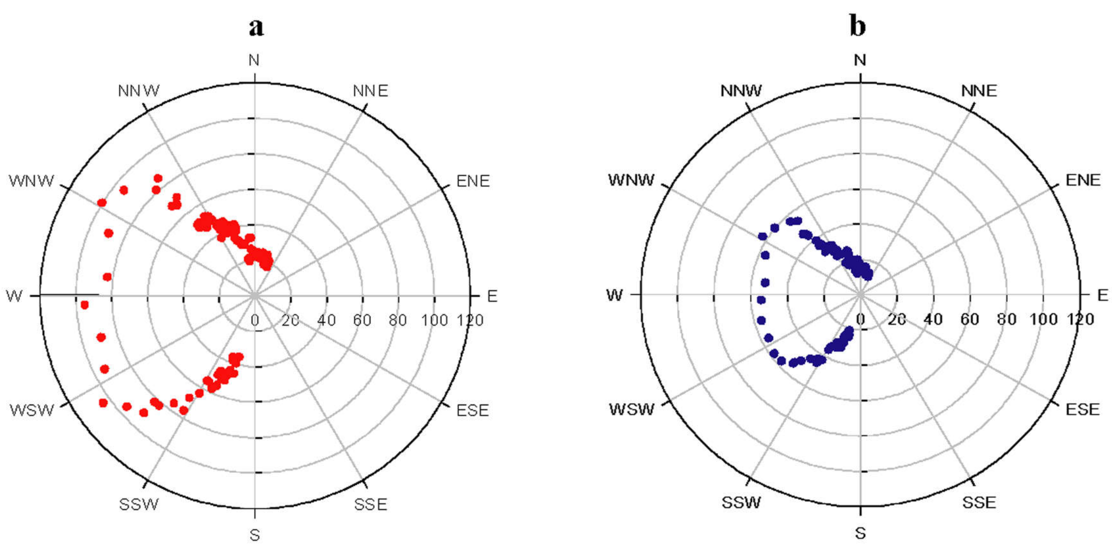

Figure 27. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at S331W weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

Figure 28. Removal operation of vegetation- and debris-filled canal after Hurricane Wilma (photo by SFWMD).

Hurricane Wilma passed over the six STAs at the south and southeastern edges of the Everglades Agricultural Area. According to a District news release (November 2, 2005), the STAs were impacted significantly. The impacts included resuspension of settled sediment, vegetation damage, and dislocation of wetland vegetation and pushing vegetation onto levee banks, lack of power, downed power lines on access roads, and levee and pump station damage reported. **Figures 29** through **34** depict maximum gust wind speed, 15-minute average wind speed, and wind direction from weather stations in the general area of the STAs. **Figure 35** depicts impacted vegetation in an STA, and **Figure 36** depicts downed power lines in an STA. Downed power lines on levees and roads of STAs limited access to facilities.

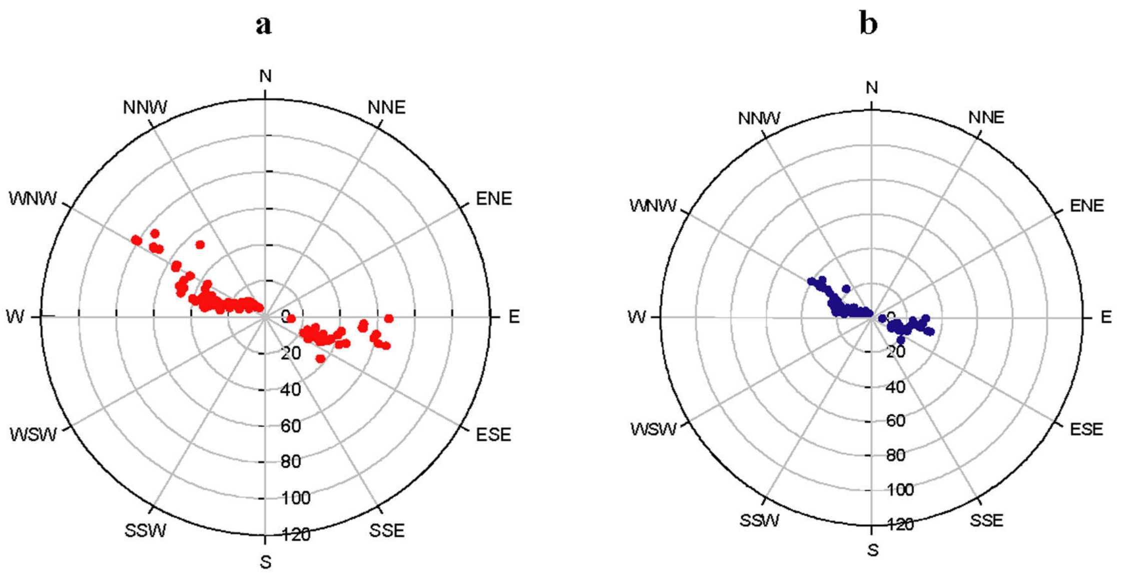

Figure 29. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at BIG CY SIR weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

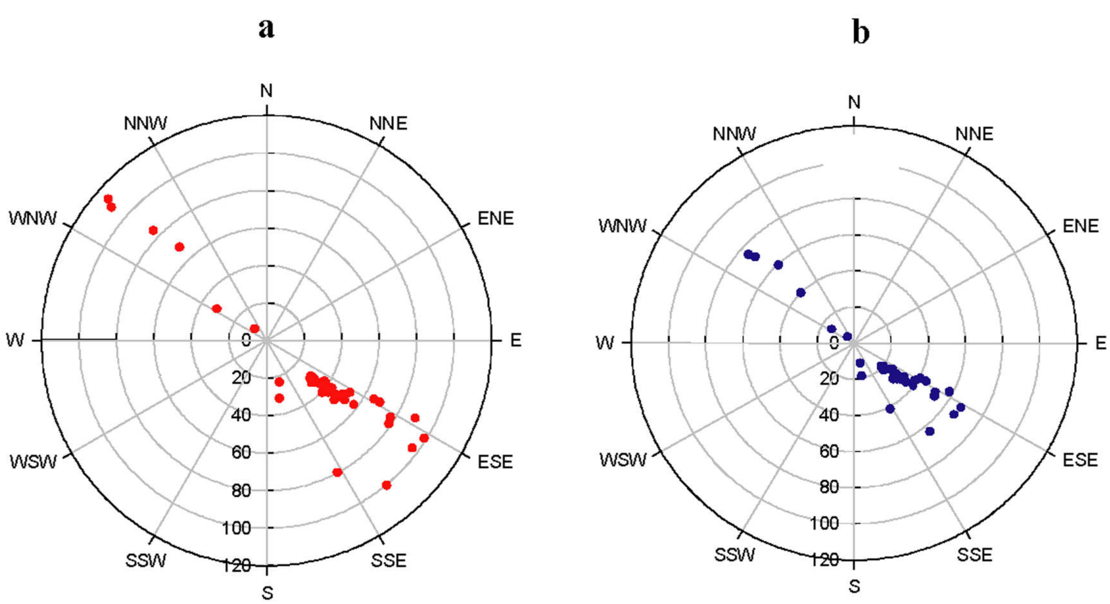

Figure 30. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at ROTNWX weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

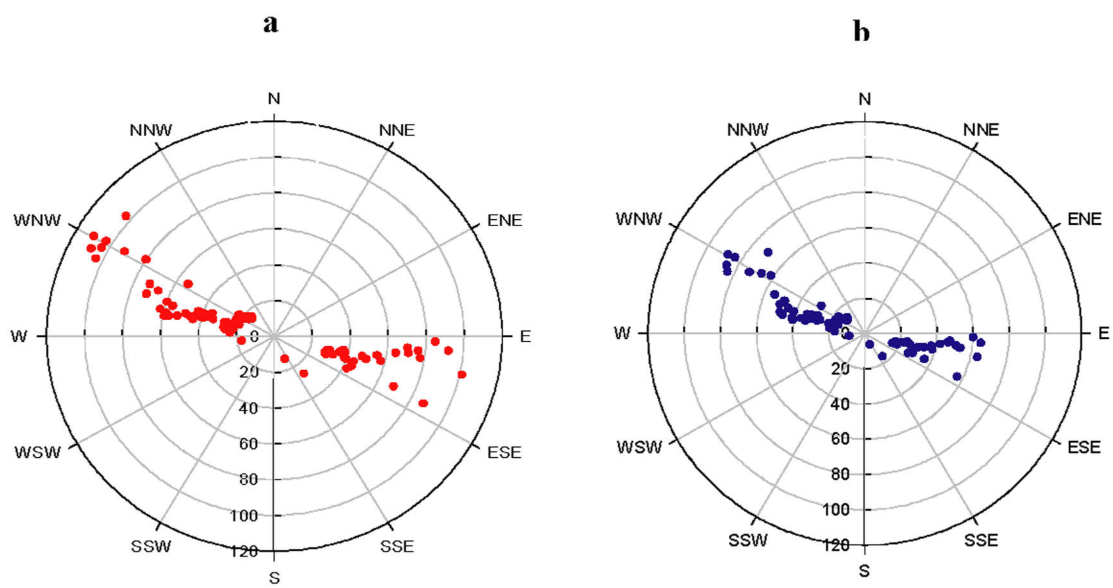

Figure 31. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at STA5WX weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

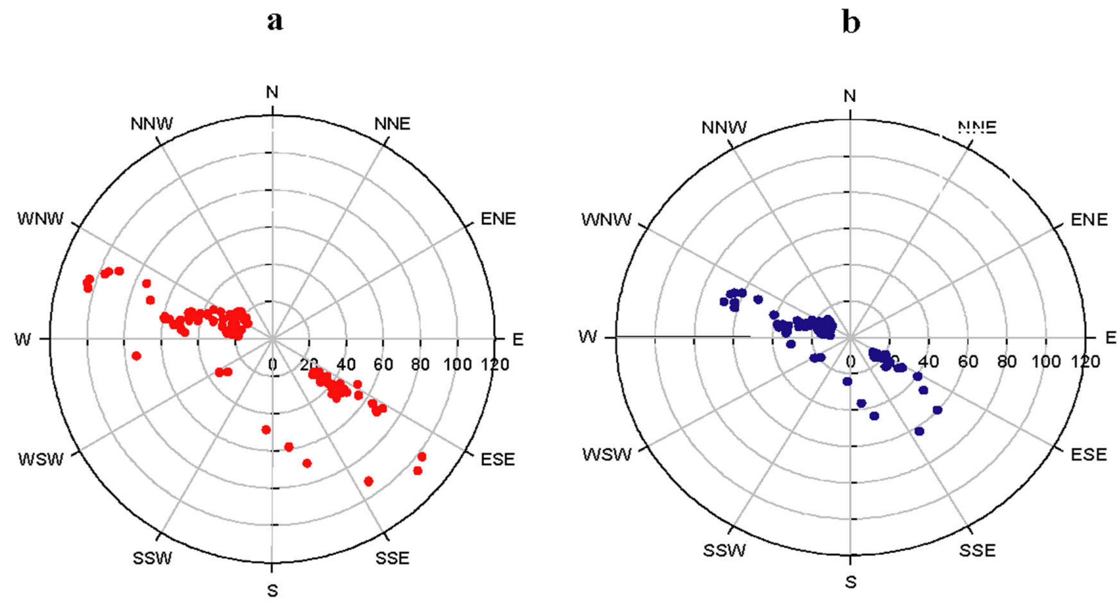

Figure 32. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at S7WX weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

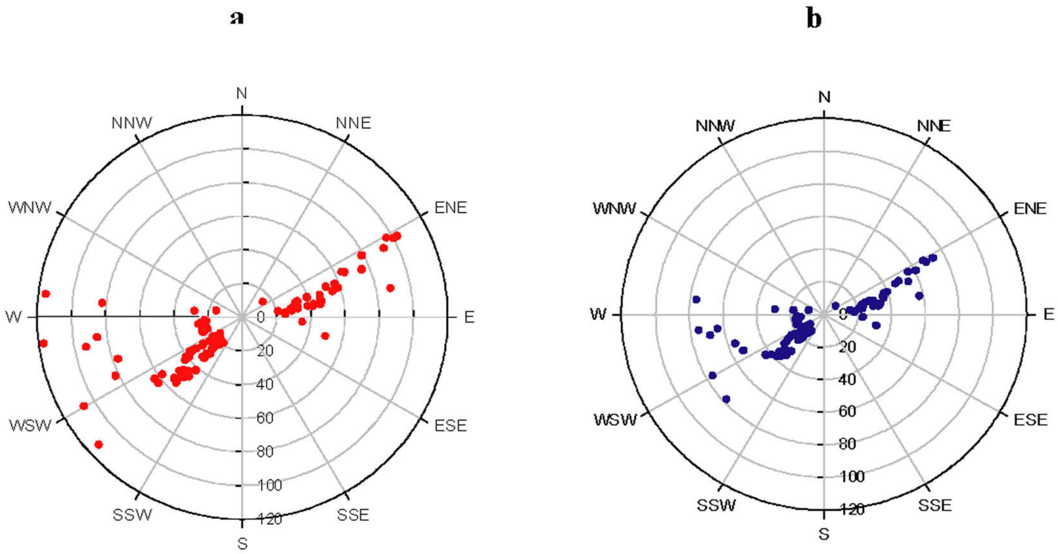

Figure 33. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at Belle GL weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

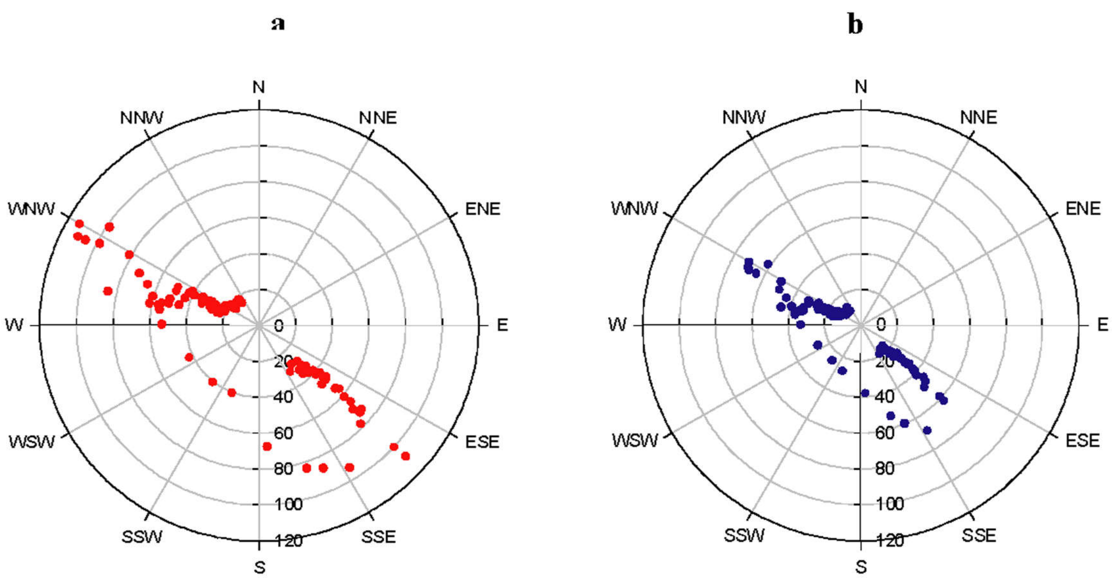

Figure 34. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at LOXWS weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

Figure 35. Vegetation pushed by Hurricane Wilma from the interior of the STA to the bank of a levee (photo by SFWMD).

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Figure 36. High-power transmission line damage by Hurricane Wilma in an STA (photo by SFWMD).

The Upper Kissimmee Basin, Lake Myrtle, Lake Mary Jane, Lake Gentry, Lake Tohopekaliga, and Lake Kissimmee were above regulation schedule following Hurricane Wilma, which generated more than 6 inches of areal average rainfall (**Figure 7**). A sharp increase in the water level of Lake Kissimmee depicts the rainfall impact of Hurricane Wilma on the Upper Kissimmee Chain of Lakes (**Figure 37**). Also, the sharp increase in surface water flow in the Kissimmee and surrounding basins is shown by the sharp increase in outflows from Lake Kissimmee (S-65), outflows from Lake Istokpoga (S-68), and inflows into Lake Okeechobee through the Kissimmee River (C-38 canal) through structure S-65E (**Figure 38**). Inflow into Lake Okeechobee through the Kissimmee River (S-65E) between the landfall of Hurricane Wilma and the end of 2005 was 525,369 ac-ft. There are many inflow points to the lake. Kissimmee River floodplain water levels at the restoration area climbed more than 7 feet due to surface water flow increases from the hurricane rainfall (**Figure 39**). The weather station with the lowest maximum gust wind speed from Hurricane Wilma is WRWX (50 mph), which is located in the Upper Kissimmee Basin at Disney Wilderness Preserve. Maximum wind gust speed and 15-minute average wind speed with wind direction are depicted in **Figure 40**. Wind speed during Hurricane Wilma was also relatively lower in the Lower Kissimmee Basin (**Figure 41**).

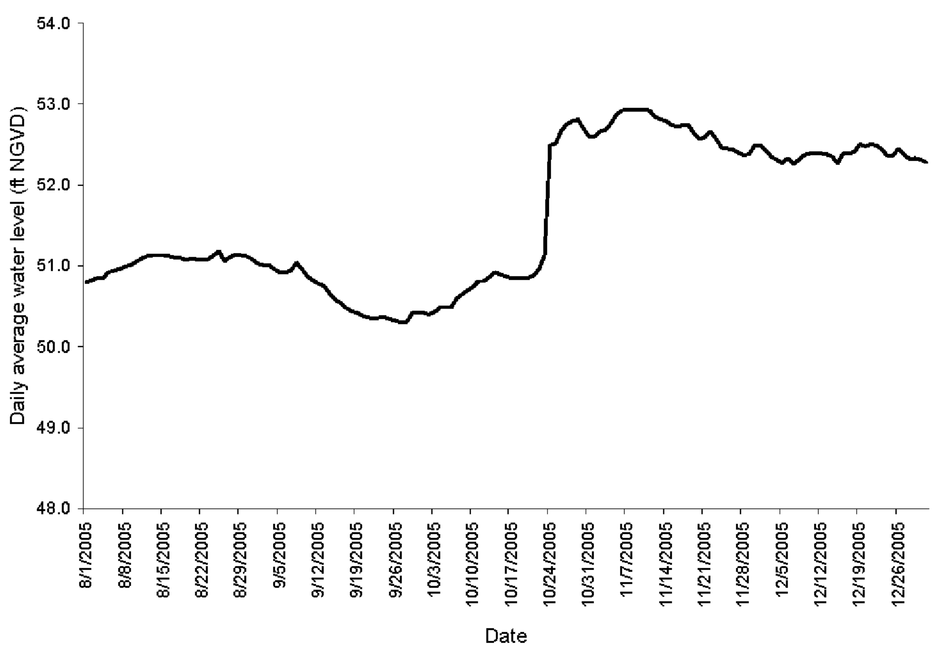

Figure 37. Water level changes in Lake Kissimmee during the 2005 hurricane season.

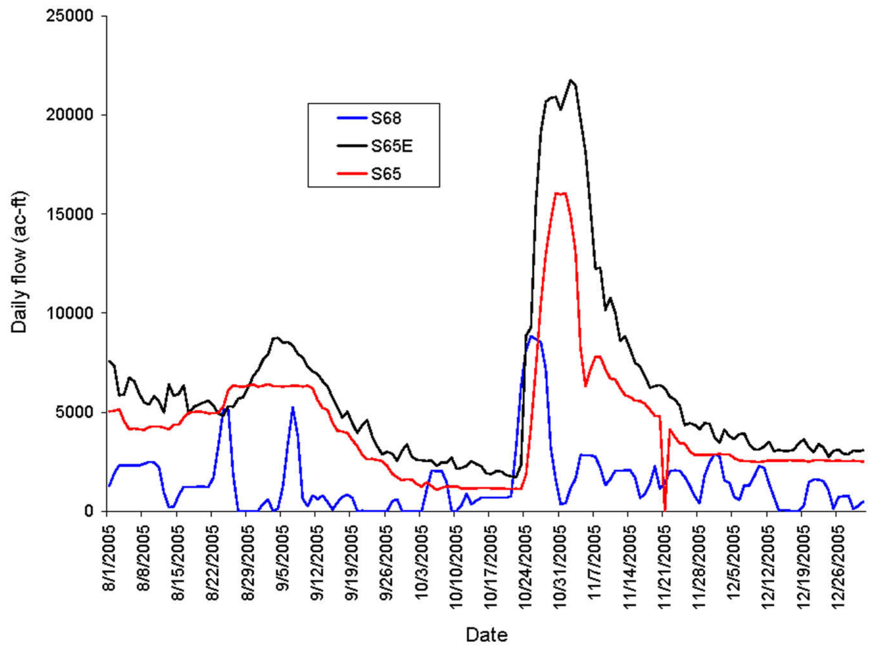

Figure 38. Lake Istokpoga outflows (S-68), inflows into Lake Okeechobee through S-65E, and outflows from Lake Kissimmee (S-65) during the 2005 hurricane season.

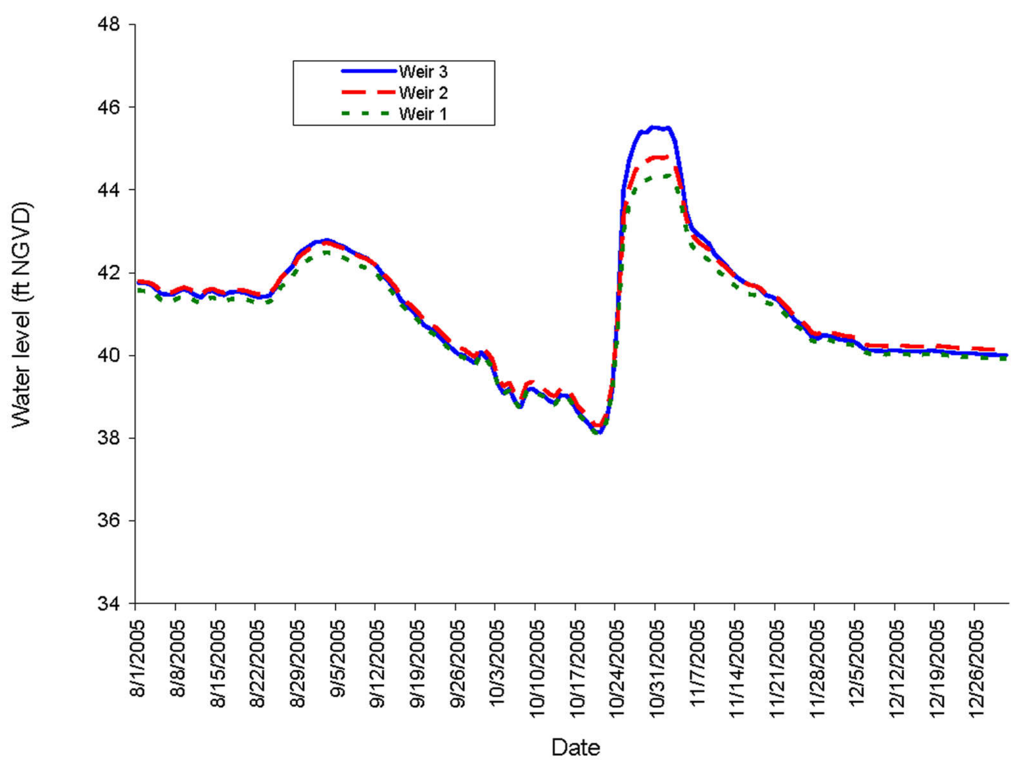

Figure 39. Kissimmee River floodplain water levels at the restoration area, weirs 1, 2, and 3, during the 2005 hurricane season.

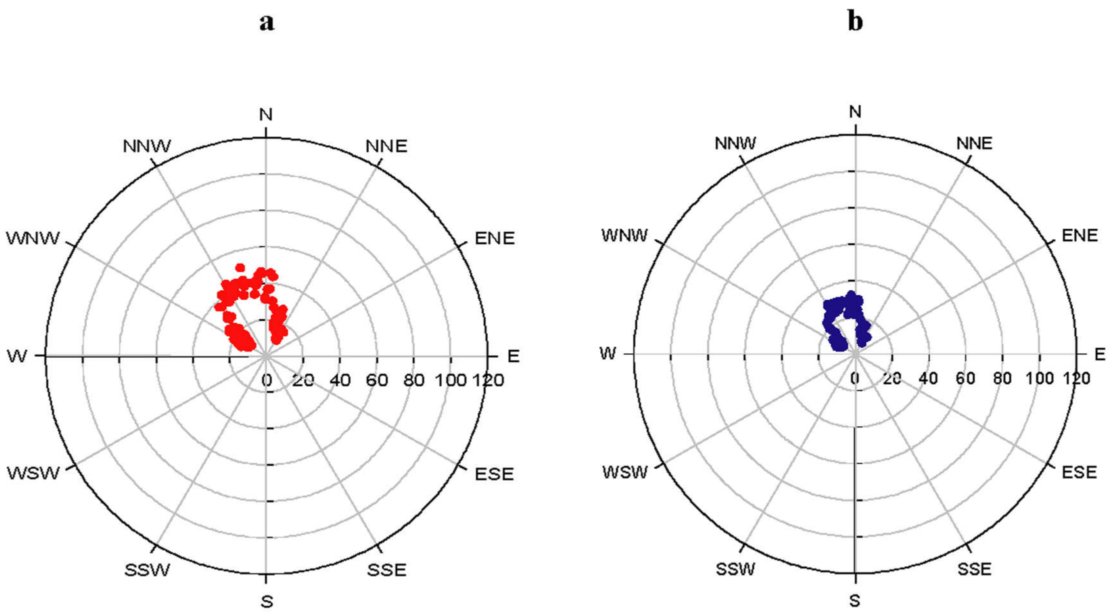

Figure 40. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at WRWX weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

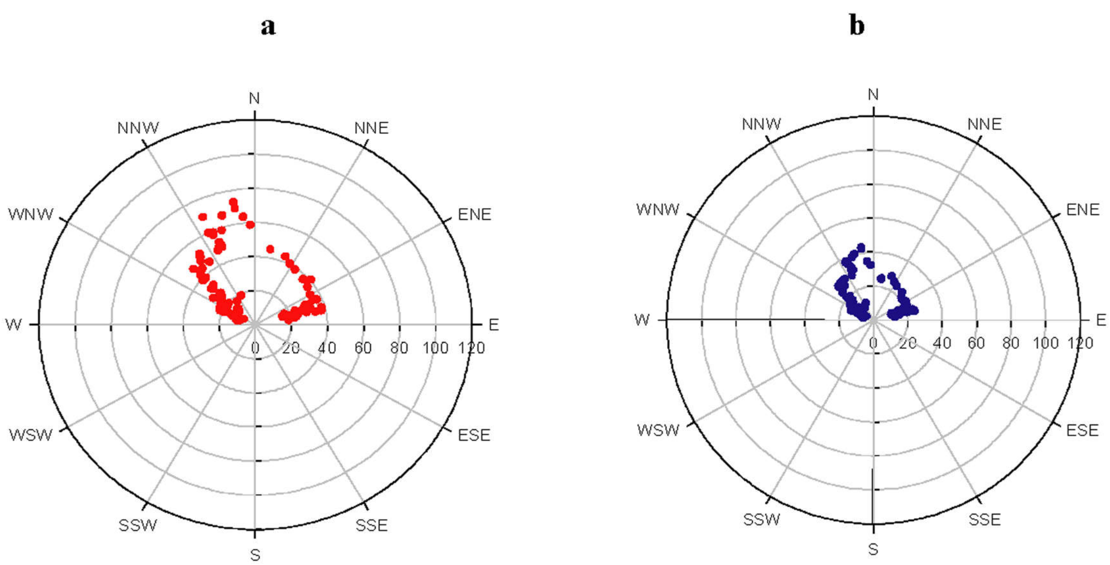

Figure 41. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at S65CW weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

Impact of Hurricane Wilma on Lake Okeechobee

Lake Okeechobee was fully impacted by Hurricane Wilma, as shown with the maximum wind gust speed (**Figure 9**), maximum wind gust speed, 15-minute average wind speed on the lake (**Figures 14**, **16**, and **18**) and the path of the hurricane (**Figure 2d**). Lake Okeechobee is impounded with an earthen levee, except at Fisheating Creek, where it is an open water connection, with numerous inflow and outflow water control structures. The impact zones of wind-generated high waves on Lake Okeechobee depend on the path of the hurricane, wind speed, wind direction, and duration of impact. There are four weather stations within Lake Okeechobee (L001, L005, L006 and LZ40), as shown in **Figures 10** and **49**. Three of the weather stations (except L005) had gust wind speed, average wind speed, and wind direction data collected during Hurricane Wilma. Weather station L001 is at the northern side of the lake; LZ40 and L006 are in the middle of the lake. Maximum gust wind speed (sampled at one-minute interval, maximum in 15 minutes) and 15-minute average wind speed and direction over the lake shown in **Figures 42** through **44** correspond with the area of levee erosion and high water levels. Wind direction over the lake is clearly shown as east-northeast (ENE) from the front side of the hurricane and NW from the back side of the hurricane. Both the gust and average wind speed data show that the back side of the hurricane had higher wind speed than the front side. Hurricane winds blow vegetation from the lake toward the levee banks. Water control structure built in the levees can get clogged with massive vegetation and debris, impeding emergency operations (**Figure 45**). The wind wave action stirs up the lake, resuspending settled sediment impacting water quality. High sediment concentration reduces the depth of light penetration into water, reducing the growth and maintenance of aquatic submerged vegetation. High sediment concentration is associated with increase in nutrient concentration. Due to the high water level in the lake, water has to be discharged. The quantity and quality of the discharge impact the receiving systems.

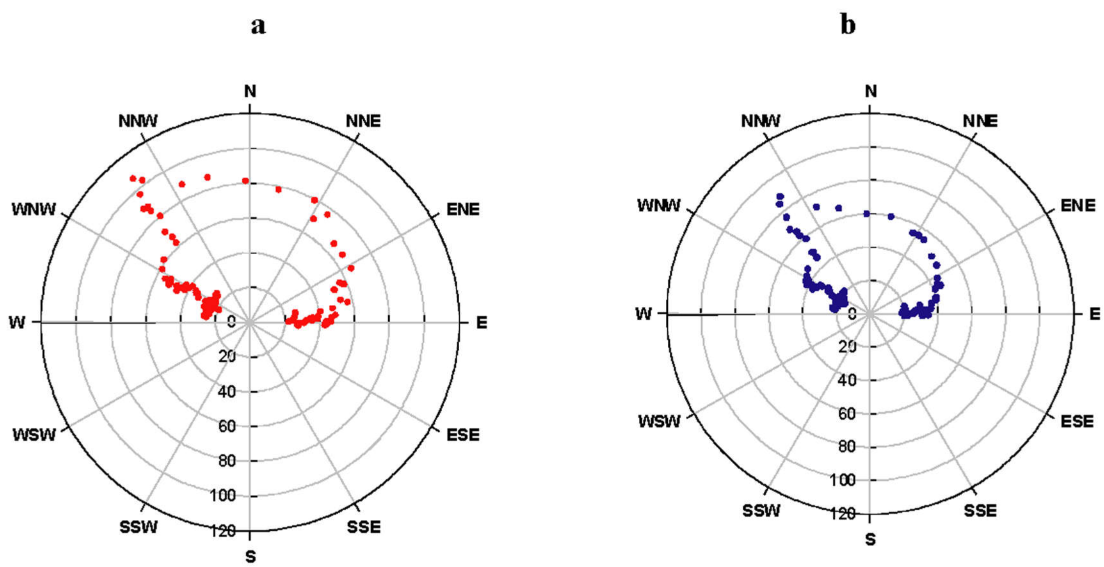

Figure 42. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at L001 weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

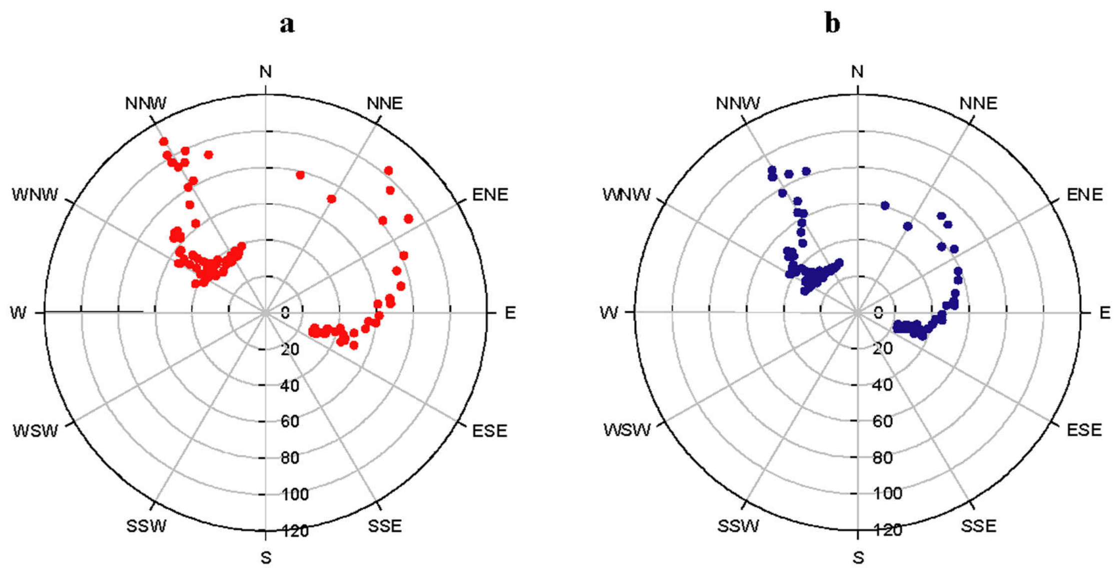

Figure 43. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at LZ40 weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

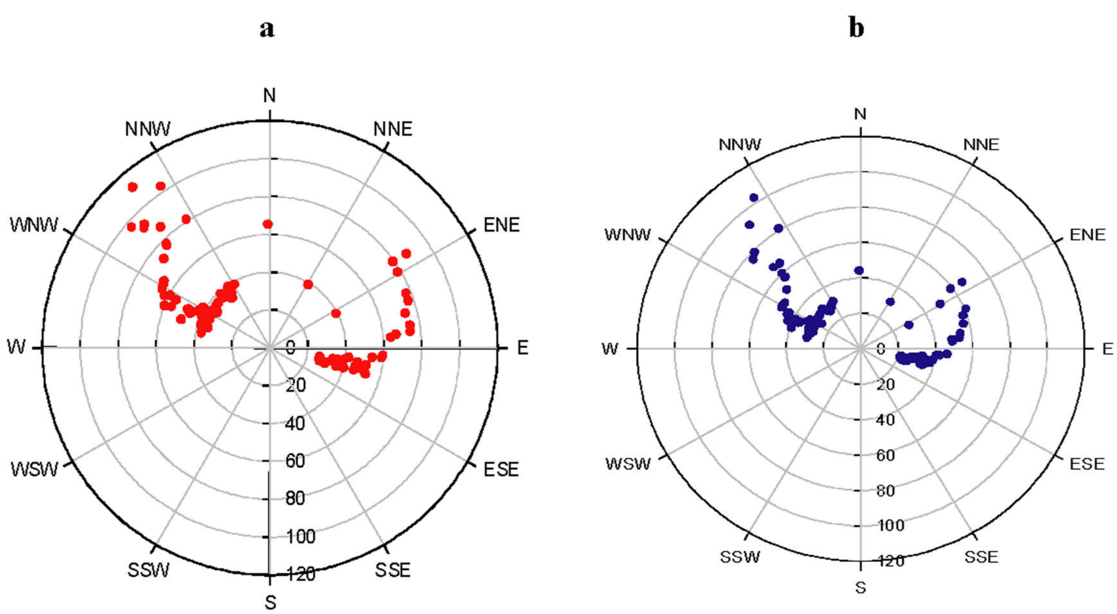

Figure 44. (a) Maximum wind gust speed (mph), (b) average wind speed (mph) and wind direction at L006 weather station during Hurricane Wilma at 15-minute interval (October 24, 2005).

Structural damage from hurricanes can occur in several ways. High rainfall on the lake's watershed from hurricanes results in high surface water inflows. This results in rising water level in the lake when outflow conveyance capacity is lower than inflow. High water level in the lake increases seepage through the levee, which could result in levee failure. Also, high water level creates the potential for high wind to generate high waves that could wash the lakeside of the levee or even overtop and erode the outside of the levee. According to a newspaper report (Suzanne Wentley, The Tribune, November 26, 2005), based on interviews with USACE staff, with lake stage at over 16.5 ft NGVD, a seepage problem occurs that warrants weekly inspection of the levee and repairs, when needed. Daily seepage inspection starts when lake stage reaches 17.5 ft NGVD. On the USACE web site (http://www.saj.usace.army.mil/h2o/), the Situation Report on Herbert Hoover Dike (Lake Okeechobee Dike) Emergency Action Plan states that lake normal operation occurs when the water level is below 16.5 ft; elevation range of 16.5–17.49 ft initiates levee inspection at intervals of 7 to 30 days, varying by reach; water levels of 17.5–18.49 ft initiates inspection at intervals of 1 to 7 days; and a water level greater than 18.5 ft initiates daily inspection. Seepage is the slow movement of water from the lake to outside through the levee due to the hydrostatic force created by high water level in the lake. Seepage is an inherent problem of earthen dams. Boiling, the actual movement of soil material through the levee along with the seepage water, occurs when the rate of seepage increases. Boiling starts with fine material movement followed by course material movement and results in a levee breach. The Tribune reported that there may be problems when the stage approaches 18.5 ft NGVD and levee breach is highly expected at 21 ft NGVD. Also, increased flow rates from high rainfall can create failure at a water control structure. High rainfall can create earthen levee erosion from rainfall impact.

Hurricane winds can generate high waves, and the energy from the back-and-forth battering of an earthen levee can result in cutting the levee. Also, failure can occur around structures on the levee. According to The Tribune, there were five or six eroded areas along the lakeshore after Hurricane Wilma. If the wave setup exceeds the height of the levee, then washout could occur to the lakeside, top, and outer side of the levee. It was also reported that a $19.7 million project is under way to reinforce the Lake Okeechobee levee. Initial work is on a 4.6-mile segment from Port Mayaca to Sand Cut. Lake Okeechobee impacts, especially levee damage, from Hurricane Wilma are depicted in **Figures 45** through **48**. The levee erosion - at least in some cases – is confirmed to be from wave action.

Instantaneous water level changes inside Lake Okeechobee and at the levee banks during Hurricane Wilma help demonstrate the impact of a hurricane on the lake. The District break-point water level data collection platforms provide this information. Unfortunately, three weather station-based water level recorders inside the lake (L005, L006, and LZ40) malfunctioned at the approach of the hurricane. As such, there is no record of temporal variation of water level inside the lake during the impact of the hurricane. Also, the recorders at the southern side of the lake, where there was the highest wave setup, were not able to record the maximum level of the wave because the maximum recording setting in the recorders was exceeded. Estimates of the highest level of wave setup can be made from water mark preserved at the S-2 pump station at the time by the District staff. The initial estimate before surveying is 26 ft NGVD (Walter Smelt, SFWMD, personal communication). A survey of the mark will provide accurate record. Based on data collected at the high resolution District water level recorders (**Figure 49**) on the perimeter of Lake Okeechobee, **Figures 50** through **59** depict water level changes at the lake's banks as Hurricane Wilma passed through the area. The figures are presented sequentially from north of the lake to the west, south, and southwest.

Figure 45. Vegetation pushed into hurricane gate S-351 and pump station S-2 along the south shore of Lake Okeechobee during Hurricane Wilma (photo by SFWMD.)

Figure 46. Lake Okeechobee levee damage from Hurricane Wilma (photo by SFWMD).

Figure 47. Lake Okeechobee levee damage from Hurricane Wilma (photo by SFWMD).

Figure 48. Lake Okeechobee levee damage from Hurricane Wilma (photo by SFWMD).

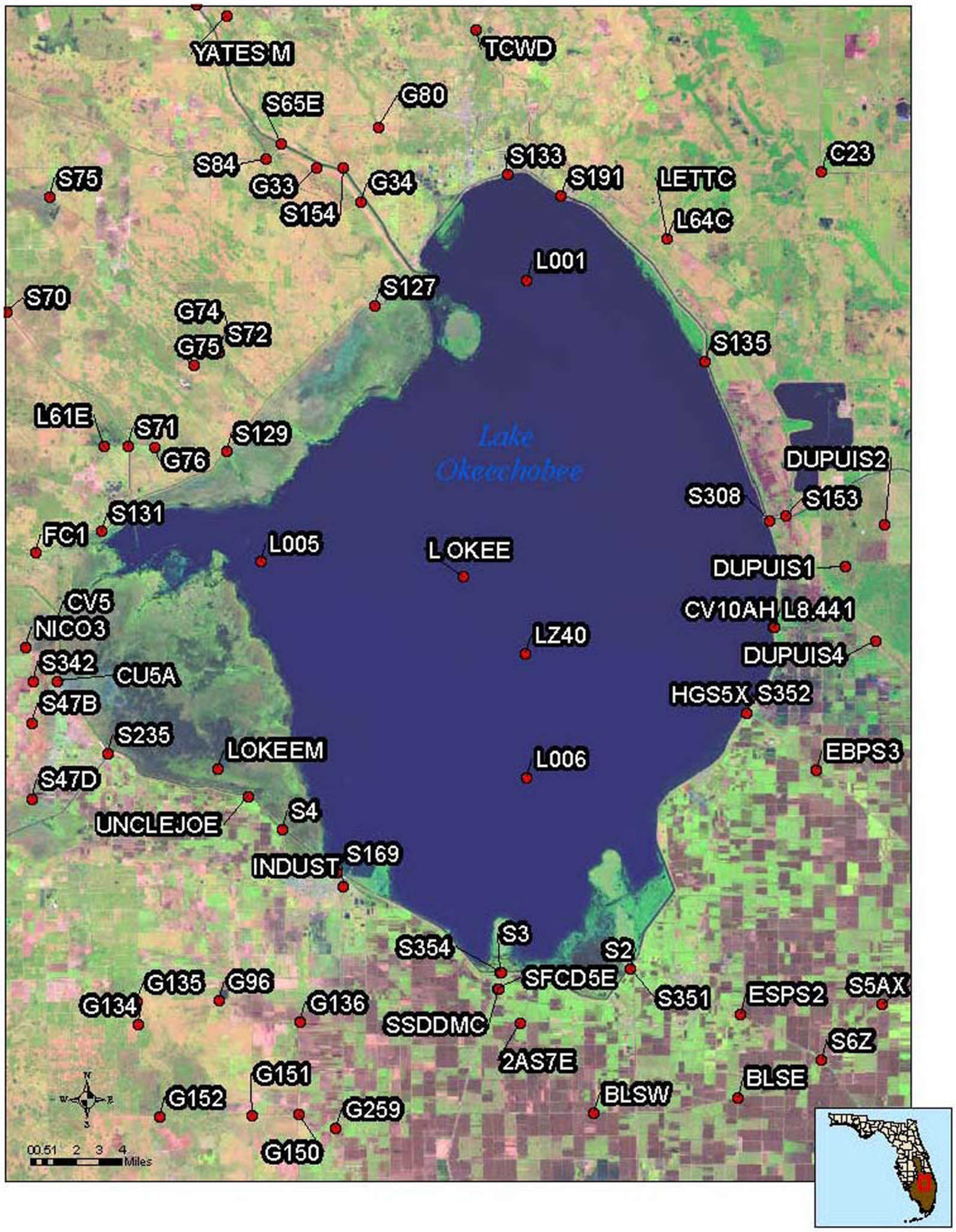

Figure 49. Water level recorders in Lake Okeechobee and the surrounding area.

Figure 50. Lake Okeechobee water level changes at the S-135 structure during Hurricane Wilma.

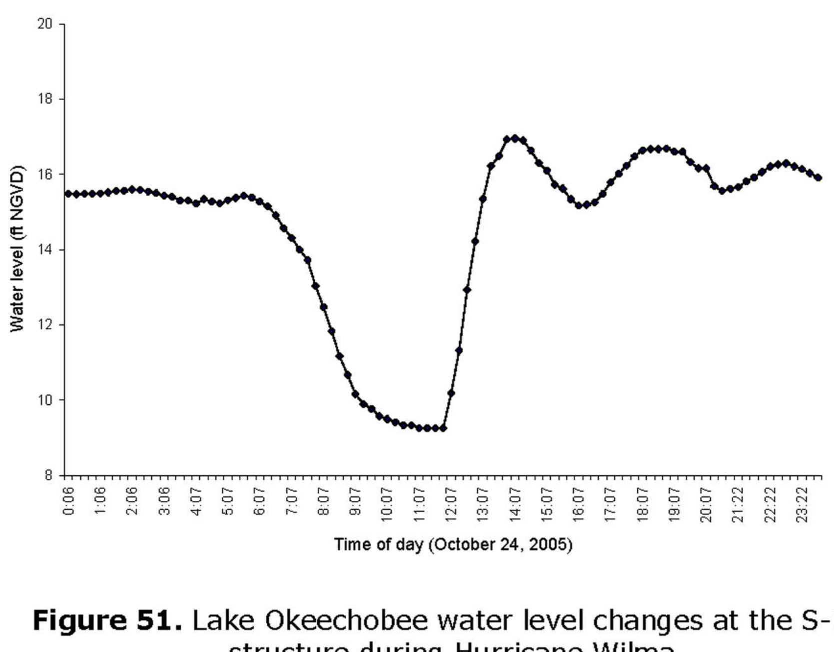

Figure 51. Lake Okeechobee water level changes at the S-191 structure during Hurricane Wilma.

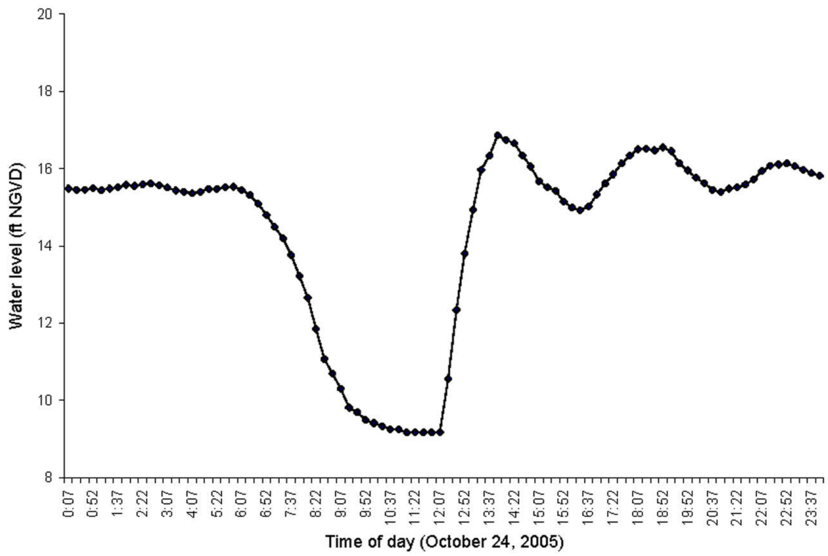

Figure 52. Lake Okeechobee water level changes at the S-133 structure during Hurricane Wilma.

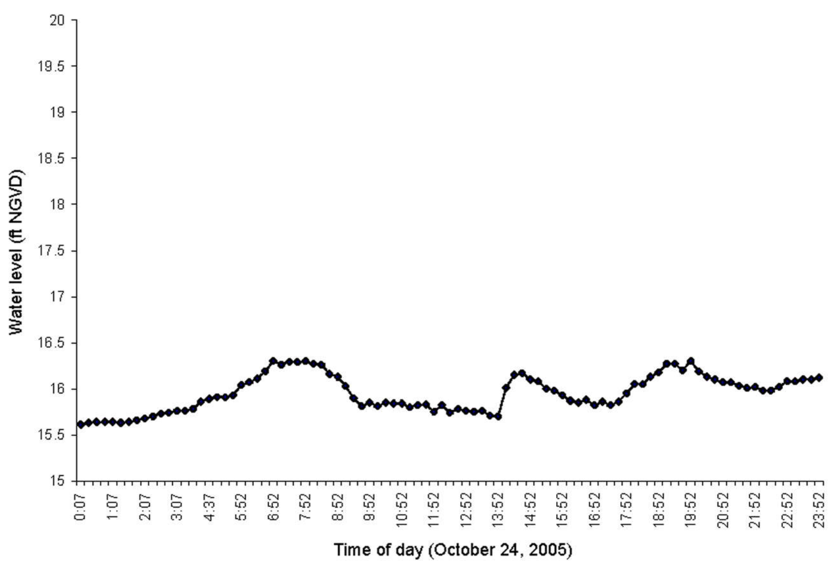

Figure 53. Lake Okeechobee water level changes at the S-127 structure during Hurricane Wilma.

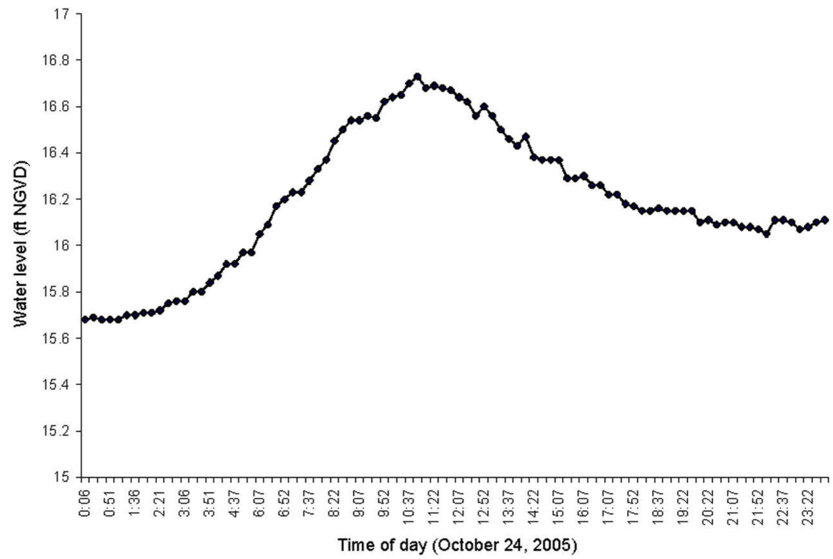

Figure 54. Lake Okeechobee water level changes at the S-129 structure during Hurricane Wilma.

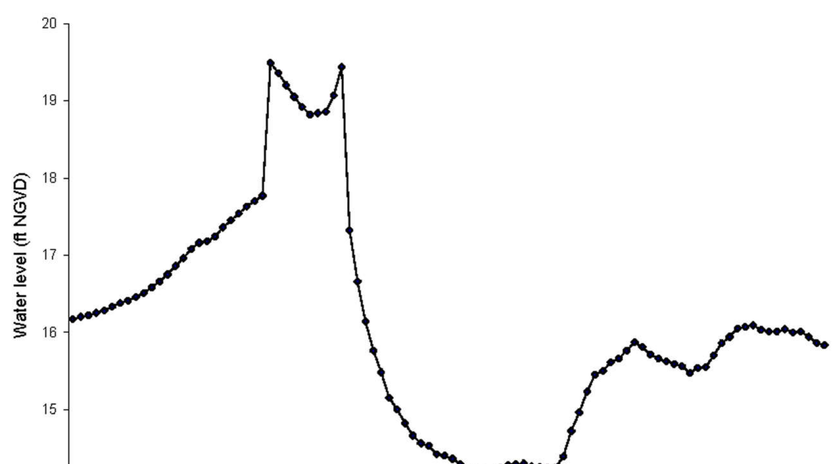

Figure 55. Lake Okeechobee water level changes at the S-131 structure during Hurricane Wilma.

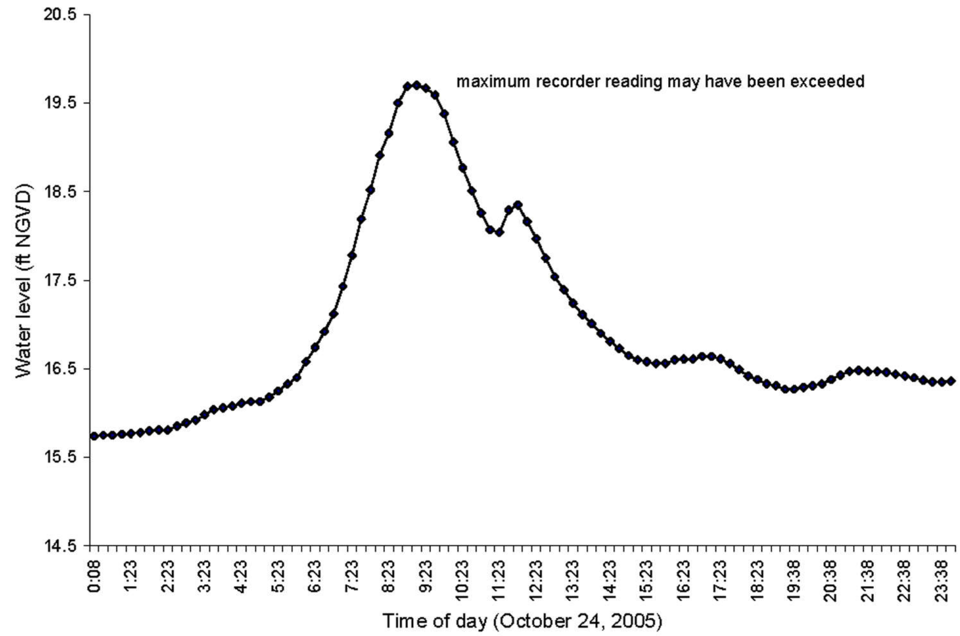

Figure 56. Lake Okeechobee water level changes at the S-4 structure during Hurricane Wilma.

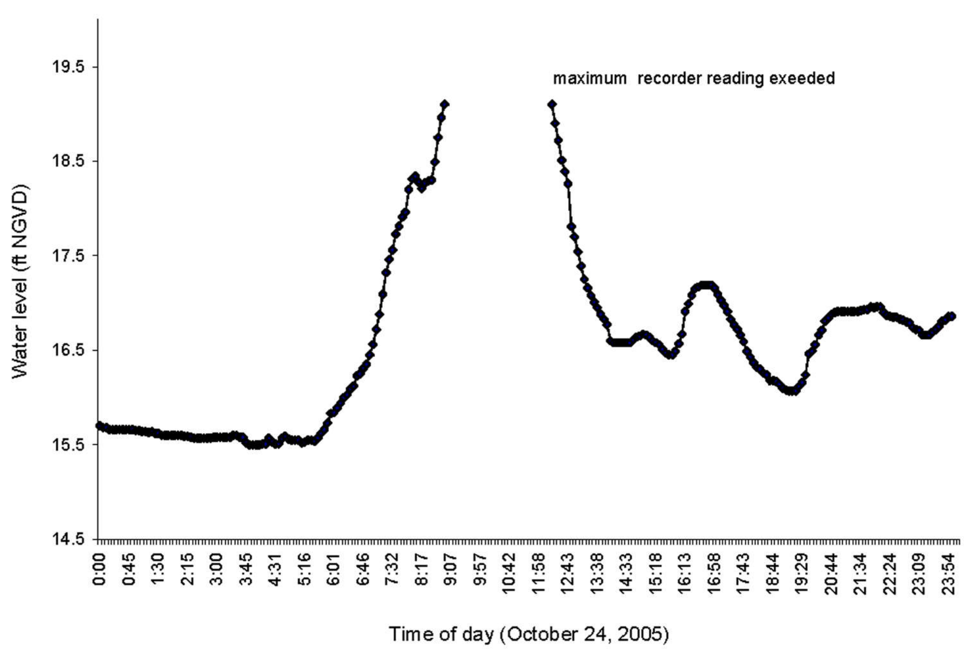

Figure 57. Lake Okeechobee water level changes at the S-3 structure Hurricane Wilma.

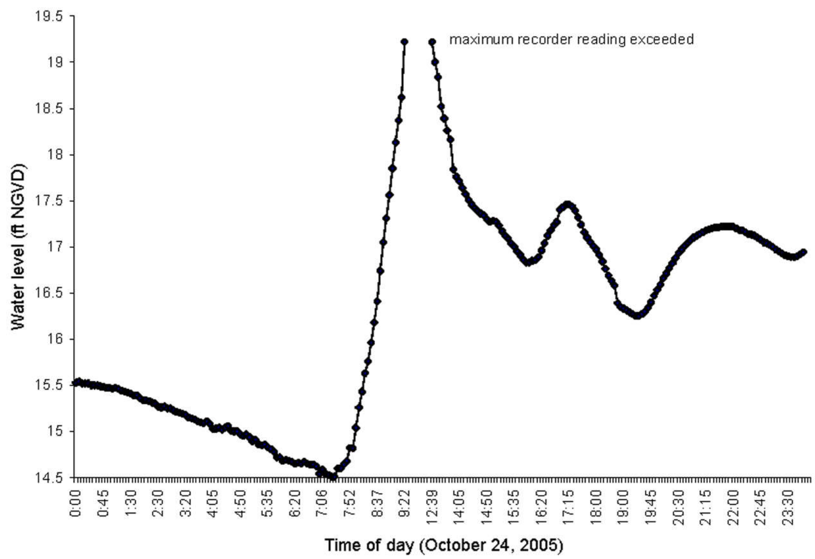

Figure 58. Lake Okeechobee water level changes at the S-2 structure during Hurricane Wilma.

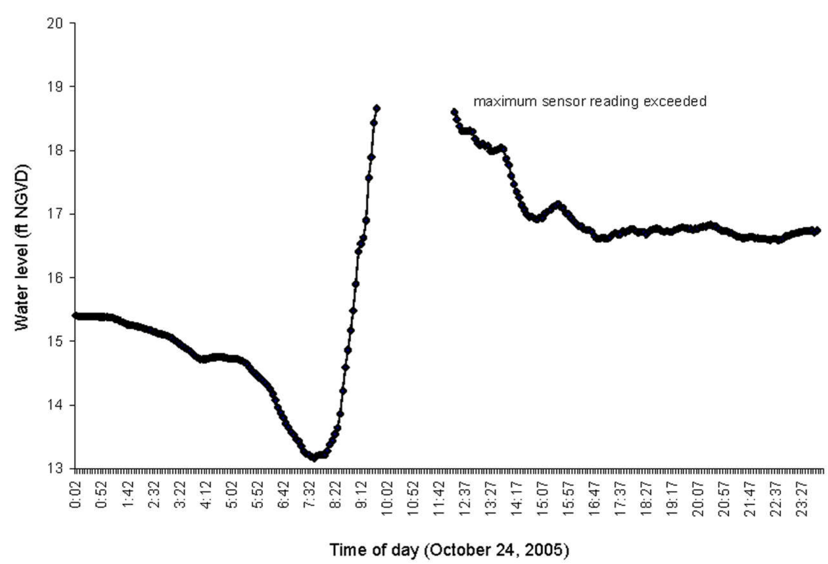

Figure 59. Lake Okeechobee water level changes at the S-352 structure during Hurricane Wilma.

Hurricane Wilma's impact on Lake Okeechobee is not limited to the impact during the hurricane. Runoff associated with the hurricane rainfall has lingering impact on the lake. Lake Okeechobee water level rise following Hurricane Wilma is depicted in **Figure 60**. **Figure 38** depicts the increase in inflow to Lake Okeechobee through the Kissimmee River outlet (S-65E). Rise in lake stage results in high rate discharge to manage the lake water level. The impact of high water levels in the lake was discussed previously. **Figure 61** depicts discharge from Lake Okeechobee into the Caloosahatchee River (S-77) and the St. Lucie River (S-308). Approximately 1 million ac-ft of water had been discharged through the two outlets following Hurricane Wilma (on October 24, 2005) and through the end of the year.

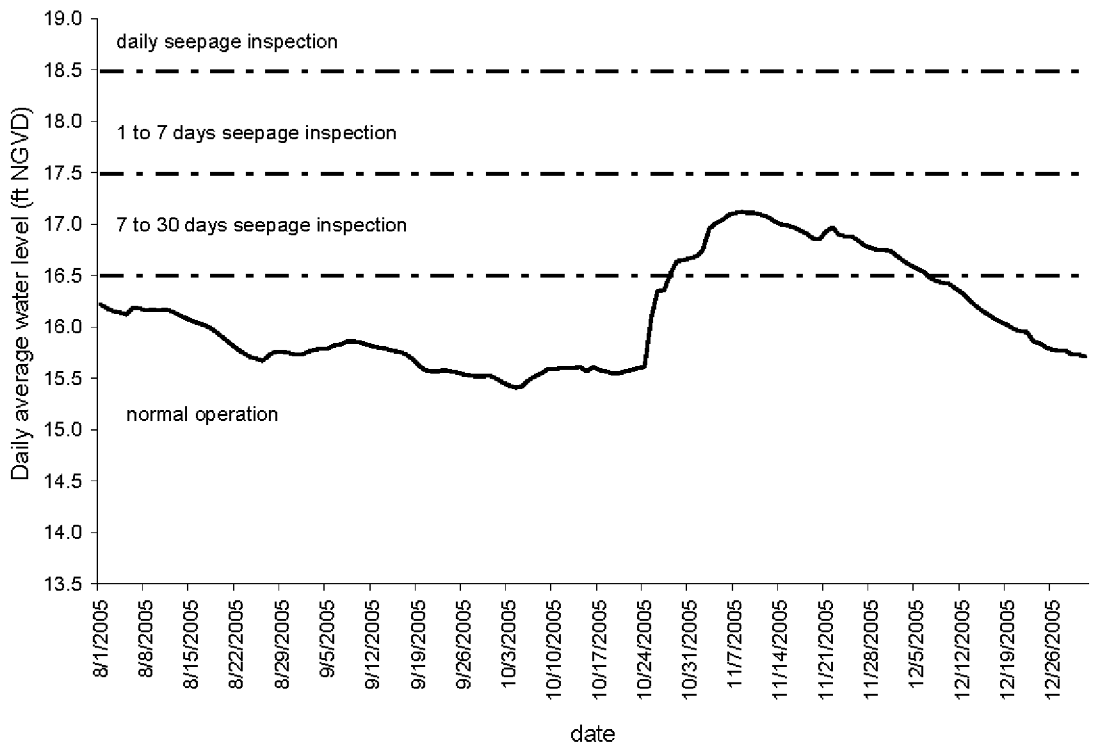

Figure 60. Lake Okeechobee daily average water level rise due to Hurricane Wilma.

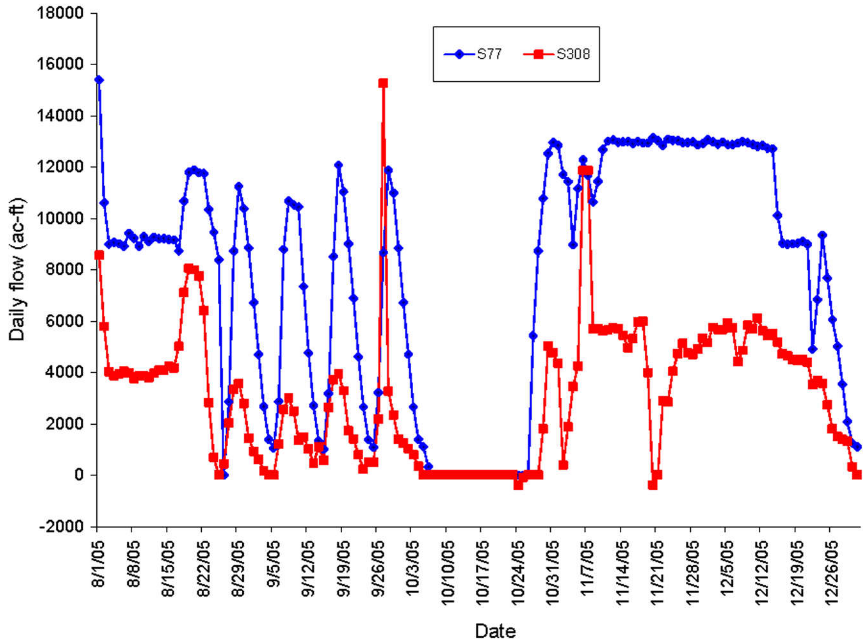

Figure 61. Lake Okeechobee daily discharge through S-77 (Caloosahatchee River) and S-308 (St. Lucie River).

CONCLUSIONS

Tropical systems are part of the hydrometeorology of South Florida. Although tropical systems can break long-term drought and replenish surface and subsurface storage, there is a potential of flooding due to the high intensity, long duration, and large areal coverage of rainfall. The impact of rainfall from tropical systems on South Florida is higher when the event occurs with soils saturated and available surface water storage is limited. There is a potential for tropical systems to generate rainfall and runoff that could overcome the region's storage and conveyance system. The 2005 hurricane events in South Florida combined with the 2004 intensive hurricane season was a rare sequence of events.

Hurricane Katrina mainly impacted the southern-most region of the District and the hydrologic impact was limited to the area as the drainage is generally to the south. High rainfall and flooding occurred. The Homestead area received 13.24 inches of rainfall over 24 hours, a rare frequency of a 1-in-100-year return period. The Florida Keys also received high rainfall and storm surge. Hurricane Rita also impacted the southern region of the District as the hurricane passed through the Florida Straits. It contributed significant rainfall to the southern region including the Florida Keys.

Hurricane Wilma was the strongest of the four hurricanes that impacted South Florida in 2005. It also passed through the central section of South Florida and widely affected the area. Apart from the extensive and costly wind damage, rainfall from Wilma has impacted the South Florida Water Management System. Rainfall north of Lake Okeechobee has a longer-lasting impact on the water management system, as the area is the headwater of Lake Okeechobee. Lake Okeechobee water level, water quality, vegetation, and levees were impacted by Hurricane Wilma. The STAs water quality, vegetation, levee and other infrastructures were also impacted by this hurricane. All of the hurricanes moved quickly through the region. Slower movement of these hurricanes would have had extensive hydrologic impact on the water management system, particularly large-scale flooding.

LITERATURE CITED

Abtew, W. and R.S. Huebner. 2006. Hydrologic Impact of the 2004 Hurricane Season on South Florida. Paper accepted for presentation at the World Environment and Water Resources Congress 2006, ASCE. May 21-25, 2006, Omaha, NE.

Abtew, W., R.S. Huebner and V. Ciuca. 2006. Chapter 5: Hydrology of the South Florida Environment. Redfield, G., ed. In: *2005 South Florida Environmental Report*. South Florida Water Management District, West Palm Beach, FL.

ASTM. 1996. Standard Practice for Characterizing Surface Wind Using a Wind Vane and Rotating Anemometer. Annual Book of ASTM Stanadards. Vol. 11.03.

Attaway, J.A. 1999. Hurricanes and Florida Agriculture. Florida Science Source, Inc., Lake Alfred, FL.

Beven, J. 2005. Tropical Cyclone Report Hurricane Dennis 4-13 July 2005. National Weather Service. National Hurricane Center. Tropical Prediction Center. Online at http://www.nhc.noaa.gov/.

Herbert, P.J., J.D. Jarrel and M. Mayfield. 1997. The Dedliest, Costliest, and Most Intense United States Hurricanes of this Century (and other frequently requested hurricane facts). NOAA Technical Memorandum NWS TPC-1. U.S. Department of Commerce.

Knabb, R.D., J.R. Rhome and D.P. Brown. 2006. Tropical Cyclone Report Hurricane Katrina 23-30 August 2005. National Weather Service. National Hurricane Center. Tropical Prediction Center. Online at http://www.nhc.noaa.gov/.

Linsley, R.K. and J.B. Franzini. 1979. *Water-Resources Engineering*. McGraw-Hill, New York, NY.

Neumann, C.J., B.R. Jarvine, C.J. McAdie and J.D. Elms. 1993. Tropical Cyclone of the North Atlantic Ocean, 1971–1992. Historical Climatology Series 6-2, U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Pasch, J.R., E.S. Blake, H.D. Cobb III and D.P. Roberts. 2006. Tropical Cyclone Report Hurricane Wilma 15-25 October 2005. National Weather Service. National Hurricane Center. Tropical Prediction Center. Online at http://www.nhc.noaa.gov/.

Tait, L.S. (ed.). 1995. Hurricanes…Different Faces in Different Places. The 17th Annual National Hurricane Conference. April 11–14, 1995. Trump Taj Mahal, Atlantic City, NJ.

Williams, J.M. and I.W. Duedall. 1997. *Florida Hurricanes and Tropical Storms*. University Press of Florida, Gainesville, FL.