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Hurricane Effects on South Florida Water Management System: A Case Study of Hurricane Wilma of October 2005

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ABSTRACT

An unprecedented eight hurricanes (Charley, Frances, Ivan, Jeanne, Dennis, Katrina, Rita and Wilma) affected South Florida in 2004 and 2005. These storms resulted in high property losses, high rainfall, high surface water flows, rise in lake water levels and damage to water management infrastructure. The last storm to hit was Hurricane Wilma which passed through the central section of South Florida from the west to the east as a Category 2 hurricane with gust wind speed as high as 180 km h^{-1} and widely affected the area. Apart from the extensive costly wind damage, rainfall from Wilma affected the South Florida Water Management System. One of the risks associated with hurricanes in South Florida is the potential for wave erosion damage to the Herbert Hoover Dike on Lake Okeechobee and consequences of a breach. The Herbert Hoover Dike was damaged by Hurricane Wilma. Analysis of wind direction and speed over the region and estimated storm surge and wave setup of 4.68 m on the Lake Okeechobee levee corresponds with water mark and levee damage observations. Water level data is presented showing the lake drawdown at upwind and the wave setup downwind. Atmospheric pressure change over the region during the hurricane is presented. Water quality of the lake was affected due to settled sediment re-suspension and increase in phosphorus in the water column. Spatial monthly mean total suspended solids concentration increased from 19 mg L^{-1} to 131 mg L^{-1} (689 percent), while spatial monthly mean total phosphorus concentration increased from 201 µg L^{-1} to 305 µg L^{-1} (152 percent). The hurricane uprooted and dislocated vegetation from wetlands and littoral zones of lakes. Canals and water control structures were filled with uprooted vegetation and other debris resulting in limited flood conveyance.

Keywords: Hurricanes, Tropical Systems, Hurricane Wilma, Hurricane Wind, Hurricane Pressure, Hurricane Rainfall, South Florida, Lake Okeechobee, Water Quality

INTRODUCTION

According to Chaston (1996), hurricanes are 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. Historical records indicate that Atlantic hurricanes have been observed since Christopher Columbus' voyages 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 was 9.4, of which 4.9 were hurricanes (Tait, 1995).

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Between 1871 and 1996, 1,000 tropical storms have occurred in the North Atlantic, Caribbean Sea, and Gulf of Mexico (Williams and Duedall, 1997).

The distribution of tropical systems, excluding depressions, from 1906 through 2006 is shown in Figure 1. Eighty-two percent of tropical storms and hurricanes occurred from the beginning of August through the end of October. Between 1871 and 1996, 114 tropical systems affected the Florida peninsula with approximately 50 percent of the systems being hurricanes (Attaway, 1999). A tropical system is classified as tropical storm when maximum sustained wind speeds reach 63 km h^{-1} and as hurricane when wind speeds are at least 119 km h^{-1}. Hurricanes strengths are further categorized based on wind speed (in km h^{-1}) as follows: Category 1 (119-153), Category 2 (154-177), Category 3 (178-209), Category 4 (210-250) and Category 5 (> 250).

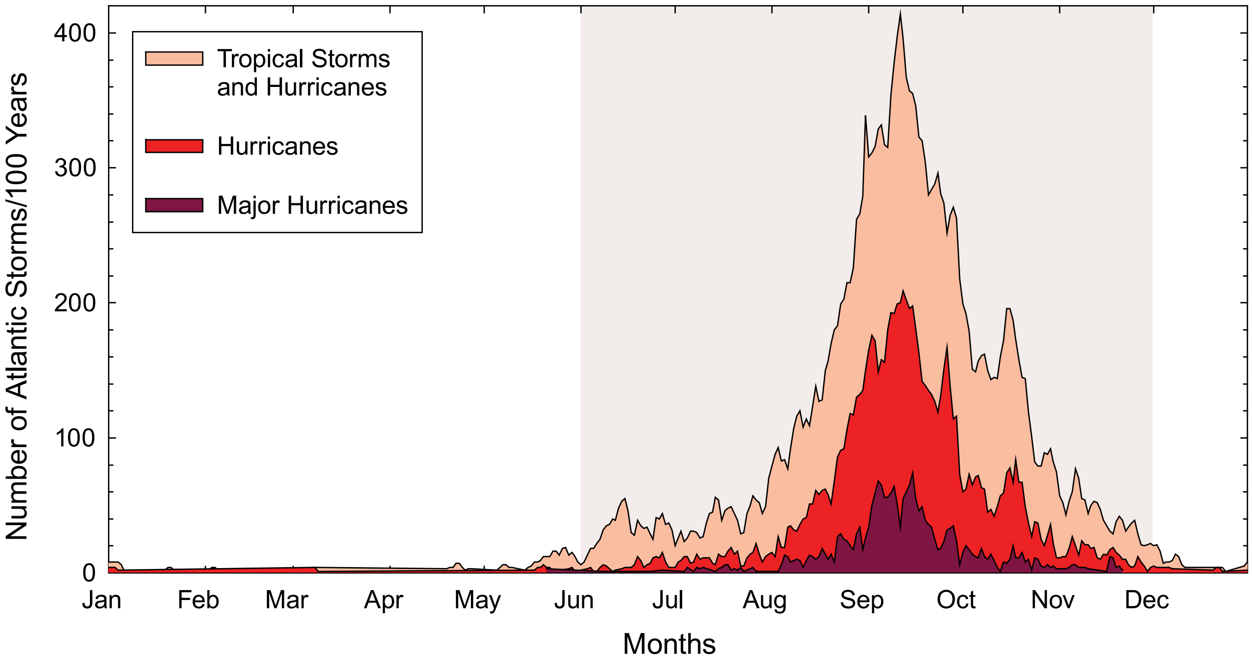


Figure 1. Distribution of North Atlantic tropical storms from 1906 through 2006. Data source (http://weather.unisys.com/hurricane/atlantic/index.html accessed on November 15, 2007). Shaded area denotes hurricane season (June through November).

The general area of the South Florida Water Management District (SFWMD, Figure 2**)** has been affected by 48 hurricanes, 36 tropical storms, and 9 tropical cyclones (hurricanes or tropical storms) from 1871 to 2007. As the spatial area of interest decreases, the frequency of hurricane effect also decreases. 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, (Williams and Duedall, 1997); and later in 1999, 2004 and 2005. Since 1998, South Florida has been affected directly or indirectly from Hurricanes Georges in 1998, Irene in 1999; Hurricanes Charley, Frances and Jeanne in 2004; and Dennis, Rita, Katrina and Wilma in 2005 (Abtew and Huebner, 2006; Abtew et al., 2006). Historically, South Florida experiences a tropical system every two to three years.

Figure 2. The South Florida Water Management District with water management infrastructure (canals, lakes and impoundments).

It is estimated that tropical systems contribute 15 to 20 percent of South Florida rainfall (Abtew et al., 2007). Additionally, rainfall from these systems had ended severe regional droughts. For example, a tropical storm dropped more than 25 cm of rainfall over the Miami area at the end of August during the 1932 drought. Passage of Tropical Storm Dawn in September 1972 brought much needed rainfall to South Florida during the 1971 to 1972 drought. Similarly, Hurricane Dennis passed through South Florida in 1981 as a tropical storm and contributed over 51 cm of needed rainfall. In July 1985, Hurricane Bob also contributed to South Florida rainfall as a tropical storm. Hurricane Keith made landfall as a tropical storm in the upper portion of South Florida in November 1988 and deposited over 27 cm of rainfall. The 2000-2001 drought effect was minimized due to 15 cm of rainfall from Hurricane Gabrielle in the Kissimmee area when landed as a tropical storm. Large spatial coverage and high runoff volumes are typical characteristics of rainfall associated with tropical systems. These characteristics will result in flooding and high water levels in lakes and reservoirs. High volumes of surface water and intense runoff can damage water management infrastructure throughout South Florida (Figure 2).

Hurricanes generate high velocity winds, which can also affect water management infrastructure in many ways. Waves generated in impoundments can damage earthen levees through wave erosion and over topping. Levee breach or over topping may result in loss of human life and property damage downstream. In South Florida, hurricane-generated waves in Lake Okeechobee resulted in 392 and 2,700 fatalities in

1926 and 1928, respectively (Bromwell et al., 2006). In 1947 and 2005, the dike around Lake Okeechobee experienced significant levee erosion from hurricane-generated wave setup and storm surge. Water control structure and canal performance is decreased due to vegetation and other debris accumulation from hurricane activity. Of all the hurricanes that affected South Florida during the 2004 and 2005 hurricane seasons, Hurricane Wilma (October 24th, 2005) produced the most damage to the Herbert Hoover Dike of Lake Okeechobee. The effects of Hurricane Wilma on South Florida, specifically Lake Okeechobee, are discussed in this paper.

The South Florida Water Management System

The South Florida Water Management System extends from Orlando to the north to the Florida Keys to the south (Figure 2). It covers an area of 46,400 km^2 extending across 16 counties. The SFWMD manages the region's water resources for flood control, water supply, water quality and natural systems needs. The region's water management system consists of lakes, impoundments, wetlands, and canals that are managed under a water management schedule based on flood control, water supply, and environmental restoration. The general surface water flow direction is from the north to the south, but there are also water supply and coastal discharges to the east and the west. The major hydrologic components are the Upper Kissimmee Chain of Lakes, Lake Okeechobee, Lake Istokpoga, the Everglades Agricultural Area (EAA), the Caloosahatchee Basin, St. Lucie Basin, the Lower East Coast and the Everglades Protection Area (EPA). The Upper Kissimmee Chain of Lakes is a principal source of inflow to Lake Okeechobee. The primary source of inflow into Lake Okeechobee is the Kissimmee River (C-38 Canal) which drains the Upper Kissimmee (4,194 km^2), Lower Kissimmee (1,882 km^2) and part of the Istokpoga water management basins. Other inflows into Lake Okeechobee include flows from Lake Istokpoga and Lake Istokpoga Surface Water Management Basin, 1,082 km^2 (through C-40, C-41 and C-41A canals), Fisheating Creek, the Taylor Creek-Nubbin Slough Basin and reverse flows from the Caloosahatchee River, the St. Lucie Canal, and the EAA (Abtew et al., 2007).

Generally, South Florida has low relief and the hydraulics of the system requires a large storage capacity, a network of canals, numerous hydraulic structures and a complex water management system to keep lands dry during wet periods and to supply water during dry periods. The general hydraulic gradient is from the north to the south. From Lake Tohopekaliga in the Upper Kissimmee in the north to Florida Bay in the south, the elevation drop is 16.5 m over 400 km. The elevation drop from Lake Tohopekaliga to Lake Okeechobee is 13.4 m in about 130 km. On average, the water level drop from Lake Okeechobee to the Caloosahatchee Estuary, 113 km to the west, and to the St. Lucie Estuary, 56 km to the east, is 4.4 m. The topography of South Florida requires a complex drainage system.

The drainage system is a three-layer system: primary, secondary and tertiary. The tertiary system is mainly composed of residential and business area retention ponds, drainage canals and water control structures. These systems are maintained privately by entities such as homeowner associations. The secondary system is operated primarily by local drainage districts. This system drains excess water from the tertiary system and discharges into the primary system. The primary system is managed by the SFWMD. The primary system comprise of vast surface water storage areas as lakes, impoundments and wetlands, 3,000 km of canals and more than 400 water control structures. Water is moved throughout the water management system by gravity and pumps. In addition, SFWMD has an extensive hydrometeorology and hydraulics monitoring network that supports a real-time water management decision making.

Lake Okeechobee

Lake Okeechobee is the largest lake in the southeastern United States (26° 58'N, 80° 50'W). It is the center of the South Florida hydrologic system, with an area of 1,732 km^2. It is a relatively shallow lake with an average depth of 2.7 m. A bathymetric map of Lake Okeechobee is shown in Figure 3 with locations of weather stations, water level recording sites and location of 1levee damage from hurricane generated waves. In its natural state, the lake received runoff from over a 7,000 km^2 drainage area to the north and, when full, it overflowed to the south. After agricultural practices and settlement started south of the lake, the need for flood protection resulted in levee construction at various stages. In 1926, a hurricane storm surge overtopped the levee that was there at the time and resulted in 392 fatalities. Again in 1928, a hurricane storm surge resulted in 2,700 fatalities. As a result, the construction of a bigger levee, the Herbert Hoover Dike, around Lake Okeechobee began in 1932. In its current state, the Herbert Hoover Dike is 225 km long with height varying between 9.8 m and 14 m (Bromwell et al., 2006). The lake is impounded with an earthen levee except at its confluence with the Fisheating Creek, where there is an open water connection. Water levels are regulated through numerous water control structures in the levee. As mentioned previously, the lake serves the region with flood control, water supply, fishing and recreation. Lake Okeechobee was directly affected by Hurricanes in 1947, 1999, 2004 and 2005 since the current dike was built. 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. The 1947 hurricane and Hurricane Wilma of 2005 caused significant levee erosion. Wind setup on Lake Okeechobee and levee damage from Hurricane Frances and Jeanne in 2004 is well documented in Chimney (2005).

Structural damage from hurricanes can occur in several ways. High rainfall on the lake's watershed results in high surface water inflows. These inflows result in a rising water level in the lake when outflow conveyance capacity is lower than inflow conveyance capacity. Further, high water level in the lake increases seepage through the levee, which can result in levee failure. Hurricane winds can generate high waves, and the energy from the back-and-forth battering of an earthen levee by these waves can breach the levee. Additional failure can occur around structures on the levee. The higher the water levels are in an impounded body of water or lake, the greater the potential for levee erosion from high waves caused by high winds. These high waves could wash the lake-side of the levee, or even overtop and erode the outside of the levee. Based on daily situation report posted on the U.S. Army Corps of Engineers web site, normal Lake Okeechobee operation water level at the time was below 5.03 m National Geodetic Vertical Datum (m NGVD 1929); 5.03 to 5.33 m NGVD elevation initiates levee inspection at intervals of 7 to 30 days, varying by reach. Water levels of 5.34 to 5.64 m NGVD initiate inspection at intervals of 1 to 7 days, and levels greater than 5.64 m NGVD initiate daily inspection (Abtew et al., 2006). Currently, regulation of lake water level is influenced by the potential risk of levee failure from seepage and hurricane winds.

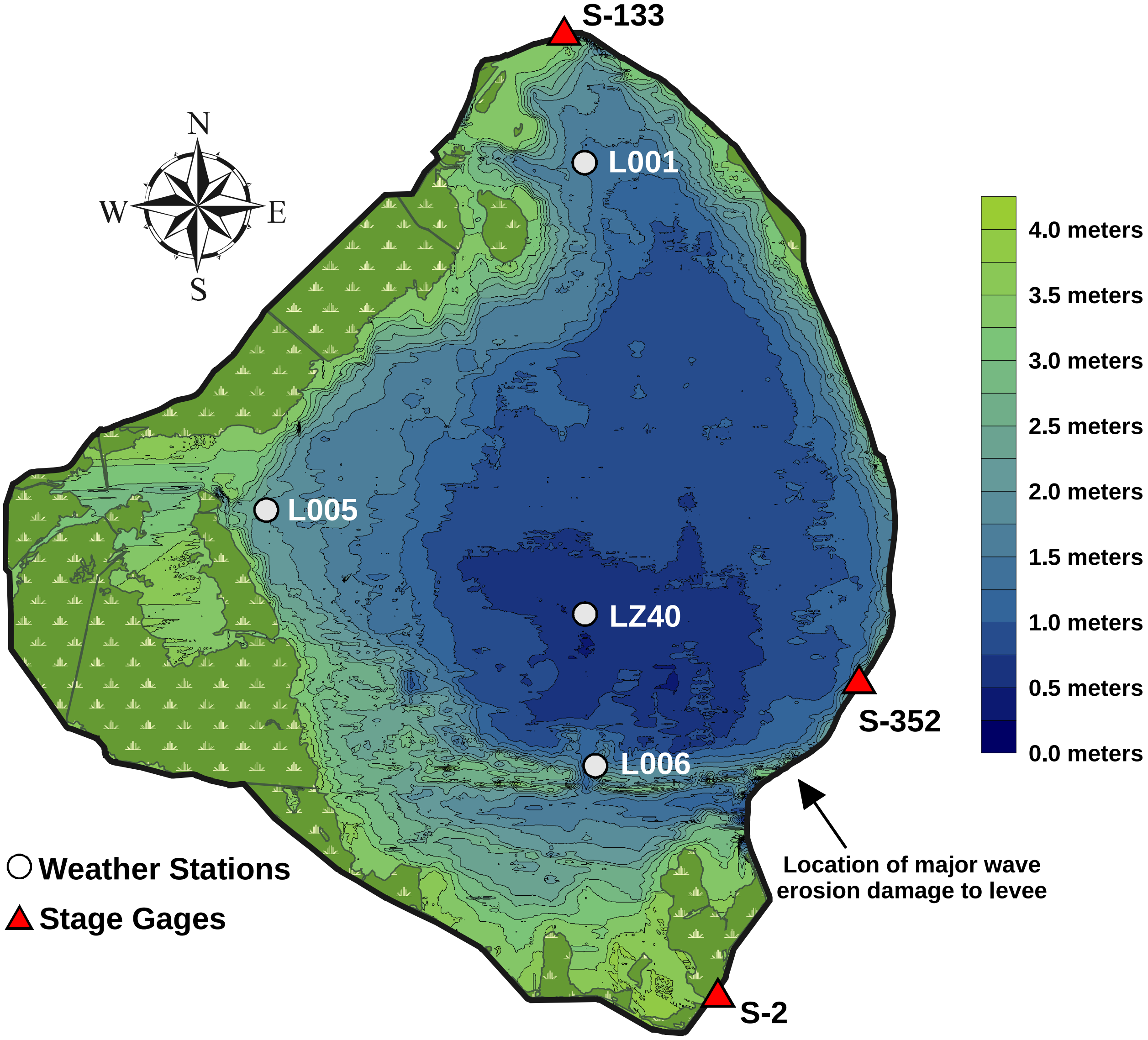


Figure 3. Map of Lake Okeechobee bottom elevations with locations for weather stations (circles), water level measurement sites (triangles), and location of levee erosion.

Seepage is the slow movement of water from the lake through the levee due to the hydrostatic force created by the 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 coarse material movement and can result in levee breach. Internal erosion incidents at multiple sites occurred at 5.5 m NGVD and breach of tieback dike occurred at 6.25 m NGVD (Bromwell, et al., 2006). Increased flow rates from high rainfall could also create failure at a water control structure or create earthen levee erosion.

Hurricanes can also affect the water quality of a shallow lake. It has been speculated that Lake Apopka (located in Central Florida) may have changed from a clear and macrophyte-dominated lake to a nutrient-rich and turbid lake dominated by phytoplankton due to a hurricane in late 1947 (Clugston, 1963;

Bachmann et al., 2000; Havens et al., 2001). More recently, the passage of Hurricane Irene in 1999 to the east of Lake Okeechobee resulted in lake churning with a maximum wind speed of 90 km h^{-1}. These wind speeds and changing wind directions increased suspended sediment concentrations in the lake (Havens et al., 2001). Further, hurricane activity induced vertical mixing of the lake water and resulted in increased nutrient concentrations. Following the hurricane, the mean total phosphorus (TP) concentration for the lake increased and was attributed to re-suspension of phosphorus-rich sediments from the lake bottom and increased phosphorus (P) input from tributaries (Havens et al., 2001). Chimney (2005) presented observed and modeled wind effects of Hurricane Francis and Hurricane Jeanne of 2004 on Lake Okeechobee. He reported water level differences in the lake between the north and south perimeters were 2.6 m and 3.5 m during Hurricane Francis and Hurricane Jeanne, respectively.

HURRICANE WILMA

According to the National Hurricane Center (Pasch et al., 2006), Hurricane Wilma formed as a tropical depression on October 15, 2005, east-southeast of the Grand Cayman Island. On October 18th, Wilma became a hurricane moving west-northwestward towards the Yucatan Peninsula. Wilma strengthened to a Category 5 hurricane on October 19th, with a record low pressure of 882 mb (661.7 mm mercury), a record for an Atlantic hurricane. The hurricane made landfall on the island of Cozumel, Mexico, as a Category 4 hurricane. A day later, Wilma crossed the Yucatan Peninsula after prolonged battering of the northeastern section and re-emerged in the Gulf of Mexico on October 23rd as a Category 1 storm. While being steered toward the west coast of South Florida, Wilma strengthened further and made landfall as a Category 3 hurricane near Cape Romano at the southwest corner of South Florida on October 24th. During its swift crossing of South Florida to the Atlantic (4.5 hours), Wilma weakened to a Category 2 hurricane. The path taken by Hurricane Wilma across South Florida and the rainfall coverage are depicted in Figure 4.

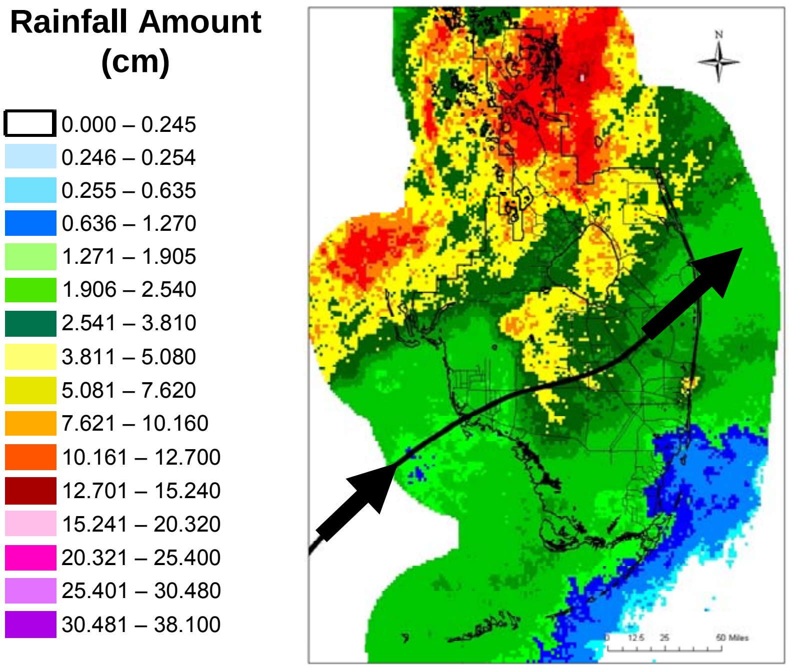
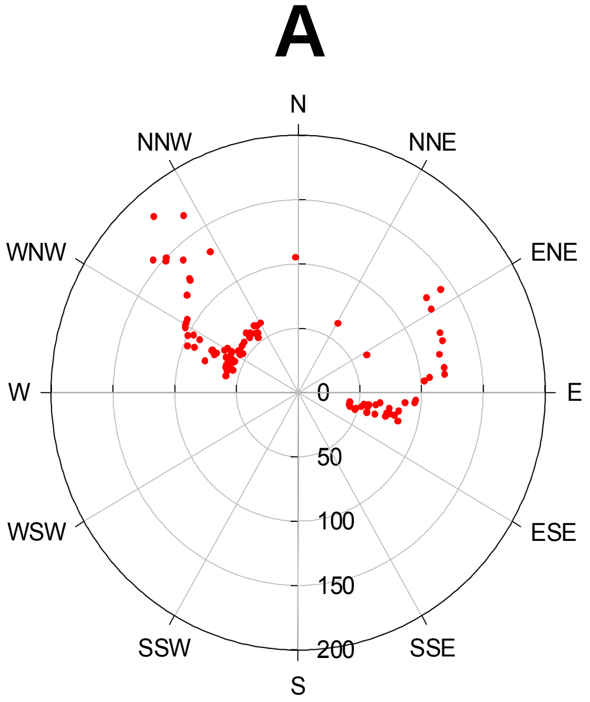


Figure 4. Path of Hurricane Wilma across South Florida on October 24, 2005 and cumulative rainfall amounts generated by the hurricane (October 22-25, 2005).

As the eye of Hurricane Wilma passed through South Florida, it inflicted extensive damage on the area from the front and back ends of the hurricane. Most of the rainfall generated by the hurricane fell over the headwaters of Lake Okeechobee and the southwestern portion of Florida (Figure 4). Since the hurricane crossed South Florida quickly, the rainfall was not extensive; but the location of the rainfall, the intensity of the rainfall, the amount of runoff generated, and the high antecedent water levels in lakes and impoundments affected the water management system both hydraulically and environmentally.

Wind Speed and Direction Observations

Four weather stations are located within Lake Okeechobee. Gust wind speed, average wind speed, and wind direction data were collected during Hurricane Wilma at three of the weather stations (L001, LZ40, L006). Weather station L001 (located at the northern side of the lake) registered instantaneous maximum gust wind speed of 172 km h^{-1}, while weather station L006 (located in the south-side of the lake) registered instantaneous maximum gust wind speed of 180 km h^{-1} (Figure 3). 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 depicted as east-northeast (ENE) from the front side of the hurricane and northwest (NW) from the backside of the hurricane (Figures 5A and 5B). Both the gust and average wind-speed data show that the back side of the hurricane had higher wind speeds than the front side. The elevation at which wind speed was measured was 11.7 m NGVD as verified at station LZ40.



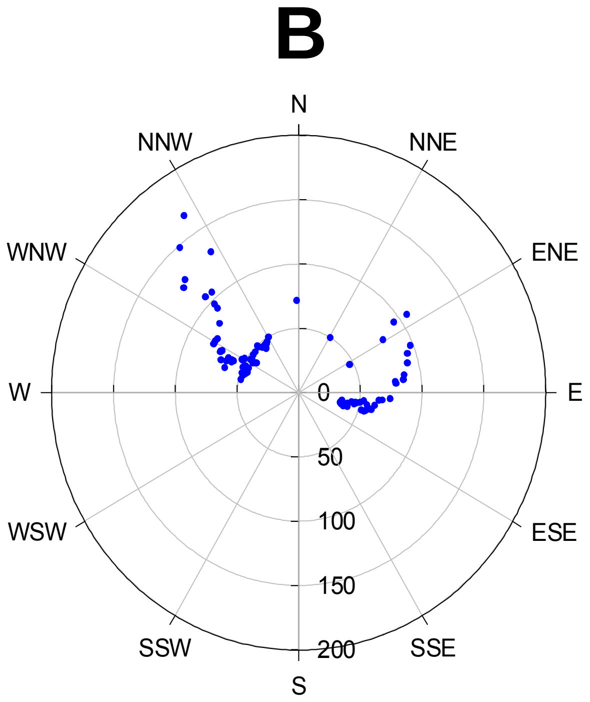


Figure 5. (A) Maximum gust wind speed (km h^{-1}), (B) Average wind speed (km h^{-1}) and wind direction at L006 weather station in Lake Okeechobee during Hurricane Wilma at 15-minute intervals (October 24th, 2005).

Wind Setup Analysis

Hurricane winds can generate high waves and storm surge, 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. Several areas were eroded along the lake levee as Hurricane Wilma passed through the area. If the wave setup and storm surge exceed the height of the levee, then washout could occur to the lake side, top, and outer side of the levee. The wave setup and storm surge from Hurricane Wilma exceeded the maximum reading capacity of water level recorders on the perimeter of Lake Okeechobee. Survey from the watermark preserved by District staff at the S-2 pump station, at the southern levee, indicated the wave setup and storm surge had reached 9.34 m NGVD. The lake water level at the time was 4.76 m NGVD, resulting in a wave setup of 4.58 m at the southern end of Lake Okeechobee. The maximum gust wind speed over the lake occurred at 10:30 am on October 24th, 2005 from the back winds of the hurricane. Figures 6A and B depict the spatial pattern and magnitude of the hurricane gust and 15-minute average wind speed at the time of peak and wind directions. Part of the levee was eroded from waves generated by Hurricane Wilma (Figure 7). The maximum wind speed and the direction correspond to this segment of the lake levee that was severely eroded (Figure 3, 6A, 6B and 7). Gust wind speed at the farthest north area of the District was 60 km h^{-1} and 40 km h^{-1} at the southern tip of the District.

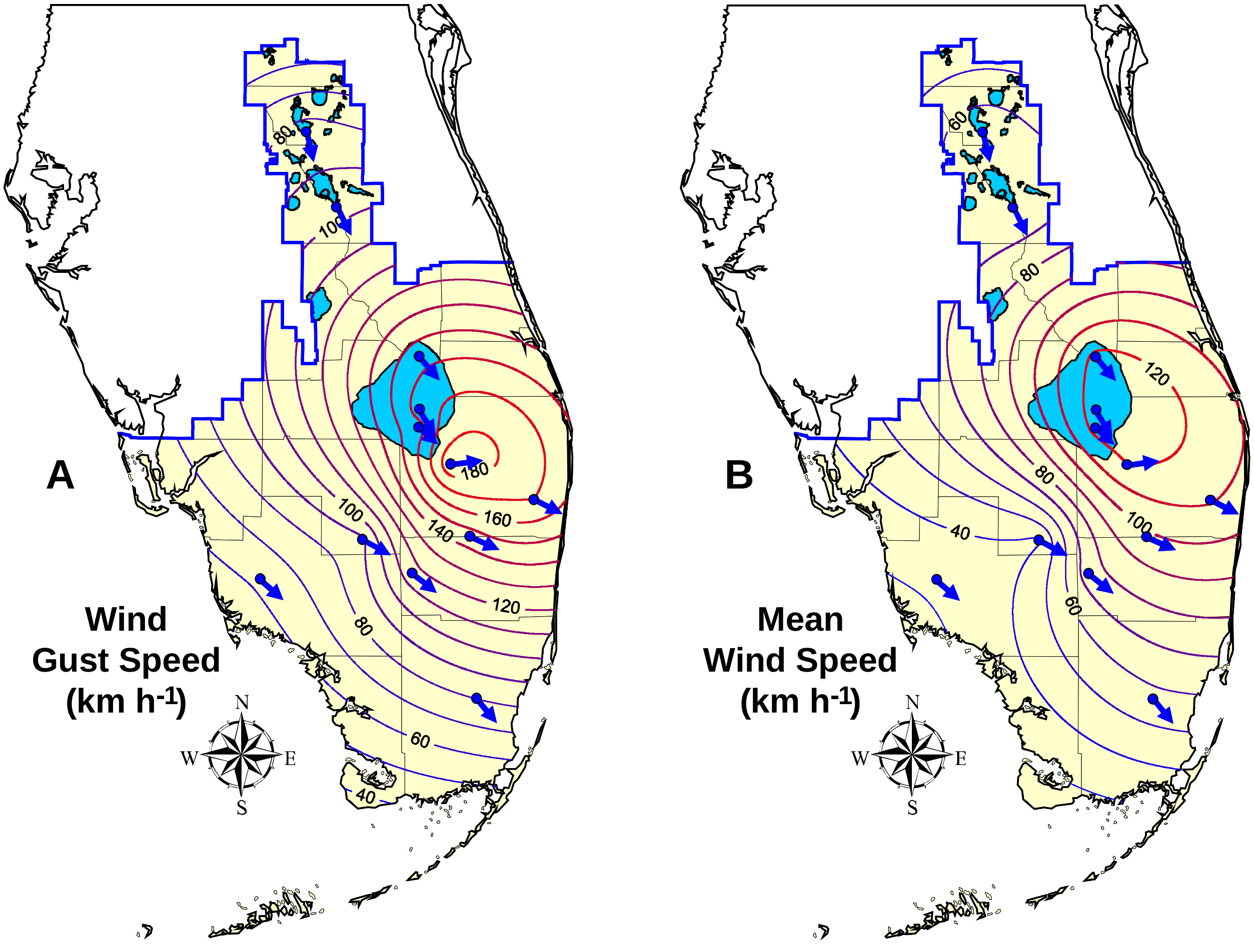


Figure 6. (A) Maximum gust wind speed (km h^{-1}) and (B) 15-minute average wind speed and directions from Hurricane Wilma over South Florida at 10:30 am on October 24th, 2005.

Figure 7. Wave erosion damage to the Herbert Hoover Dike of Lake Okeechobee from Hurricane Wilma (Bromwell et al., 2006).

Wind setup is the tilting of the reservoir water surface caused as a result of water movement toward the leeward shore as pushed by the wind. Wind setup is generally larger in shallow reservoirs and can be estimated by the following equation (Linsley and Franzini, 1979):

$$Z_w = 0.005V^{1.06}F^{0.47} \tag{1}$$

Where Z_w is the average height (meters) of the highest one-third of the waves and is called significant wave height; V is wind speed in km h^{-1} above the water surface; and F is the fetch in km. With average wind speed over the middle of the lake of 120 km h^{-1} for two hours (9:15 am-11:15 am) and 43 km of fetch, the estimated wave height is 4.68 m. This value is comparable to the measured wave setup of 4.58 m. Chimney (2005) applied steady-state models to estimate wind setup on Lake Okeechobee during Hurricanes Frances and Jeanne in 2004.

Hurricane winds blowing over a water body cause tilt to water levels due to tangential stress on the water surface and low pressure. For large shallow water bodies such as Lake Okeechobee, the upwind side can be blown dry as anecdotally reported for Lake Okeechobee (Bromwell et al., 2006). Continuous water level recorders are available around the shores of Lake Okeechobee and four water level gauges are in the middle of the lake. The gauges at the middle of the lake malfunctioned during the critical hours of Hurricane Wilma. The gauges around the shores were not fitted to record a storm surge maximum water level as it is out of the range of normal operations. Two gauges, one from the north, upwind, (S133) and one from the south, downwind, (S352) depict the water level tilt in a limited way (Figure 8).

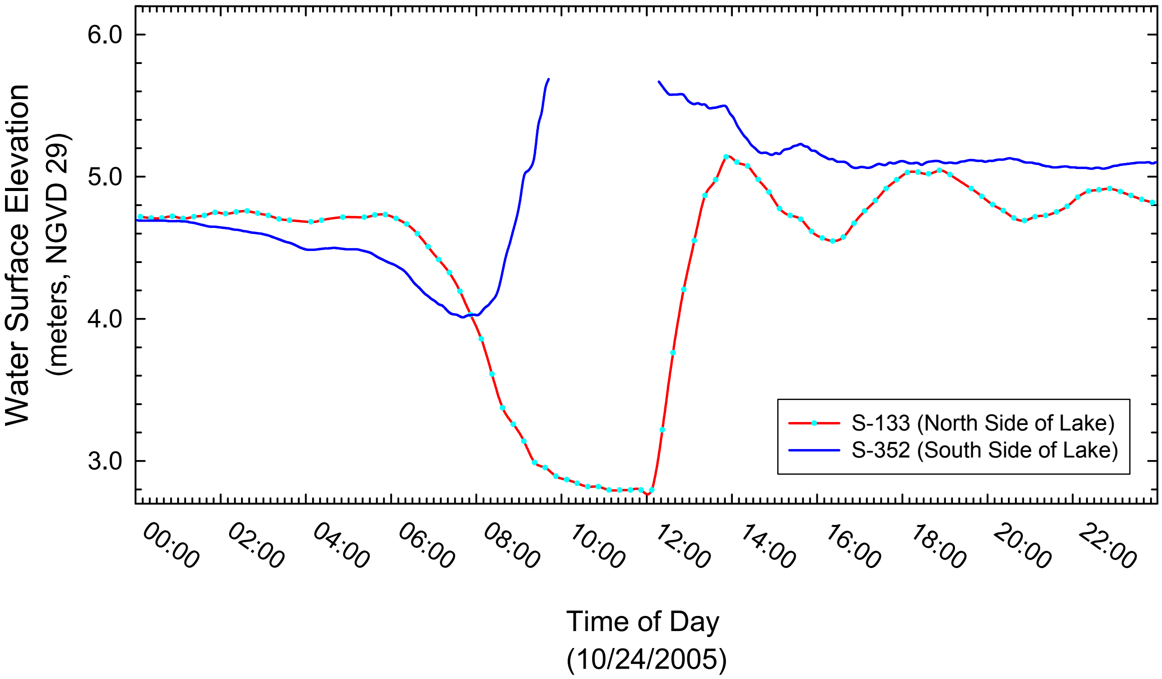


Figure 8. Water surface elevation changes in Lake Okeechobee during the passage of Hurricane Wilma over South Florida at gauge S-133 (upwind) and S-352 (downwind). The break in elevation for the S-352 gauge resulted in wave height exceeding water level sensor maximum reading.

Hurricane Wilma passed over the six large-scale constructed wetlands known as Stormwater Treatment Areas (STAs) at the south and south-eastern edges of the EAA. The STAs were affected significantly. The effects included re-suspension of settled sediment and increased phosphorus concentration in the water column, vegetation damage, dislocation of wetland vegetation, loss of power, levee and pump station damages. The downed power lines on levees and roads also limited access to facilities. Major rehabilitation of the treatment wetlands was needed to restore the treatment performance (Pietro et al., 2007). In the region, canals and water control structures were clogged with hurricane dislocated vegetation and other debris resulting in reduction of conveyance capacity.

Atmospheric Pressure Spatial and Temporal Distribution

At peak wind speed over Lake Okeechobee (10:30 am on October 24th, 2005), the minimum 15-minute average atmospheric pressure registered by the LOXWS weather station, southeast of Lake Okeechobee, was 726 mm mercury (968 mb). Concurrently, maximum pressure was located on the northern and southern ends of the District (748 mm mercury, 997 mb). Conversion for atmospheric units is shown in the Appendix. The center of the hurricane had moved forward on a path southeast of the lake when the maximum gust wind speed affected the lake (Figures 9A, 4). Energy from the wind is a function of the difference in pressure from the center of the hurricane to the outer boundary where the wind profile is asymptotic, the radius of maximum wind, and radius of the point of interest (Myers, 1954). The pattern of the pressure spatial distribution has a similar pattern to the wind speed spatial distribution with low pressure corresponding to high wind speed as expected (Figures 6A, B and 9A). The minimum 15-minute average pressure through the duration of the hurricane over South Florida was 713 mm mercury (950 mb) measured at STA5WX weather station (7:45 am on October 24, 2005) southwest of the lake. Minimum pressure over the lake occurred earlier than the maximum wind speed over the lake (Figure 10).

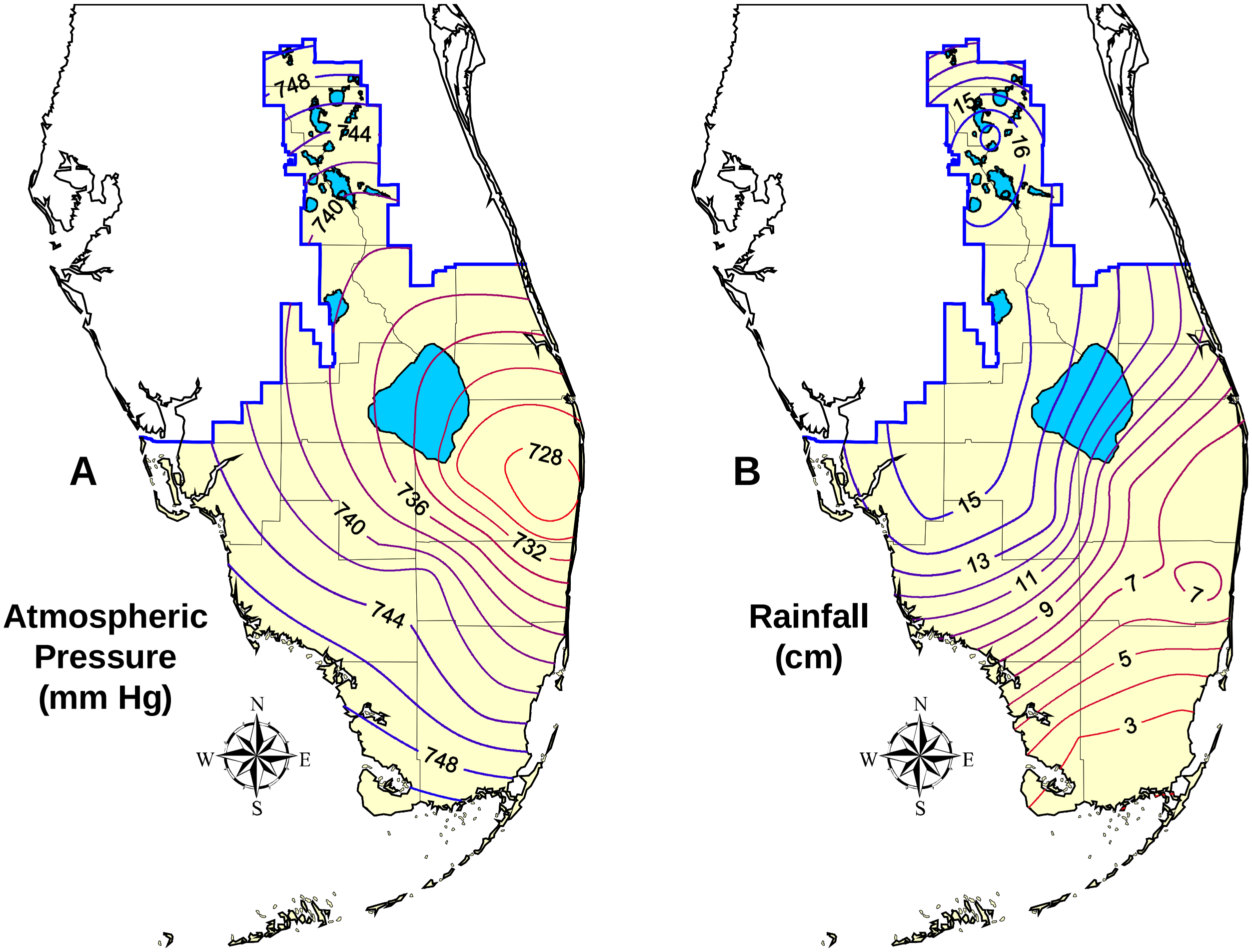


Figure 9. (A) Atmospheric pressure (mm mercury) at peak wind speed over Lake Okeechobee (10:30 am on October 24, 2005) and (B) rainfall (cm) from Hurricane Wilma (October 22-25, 2005).

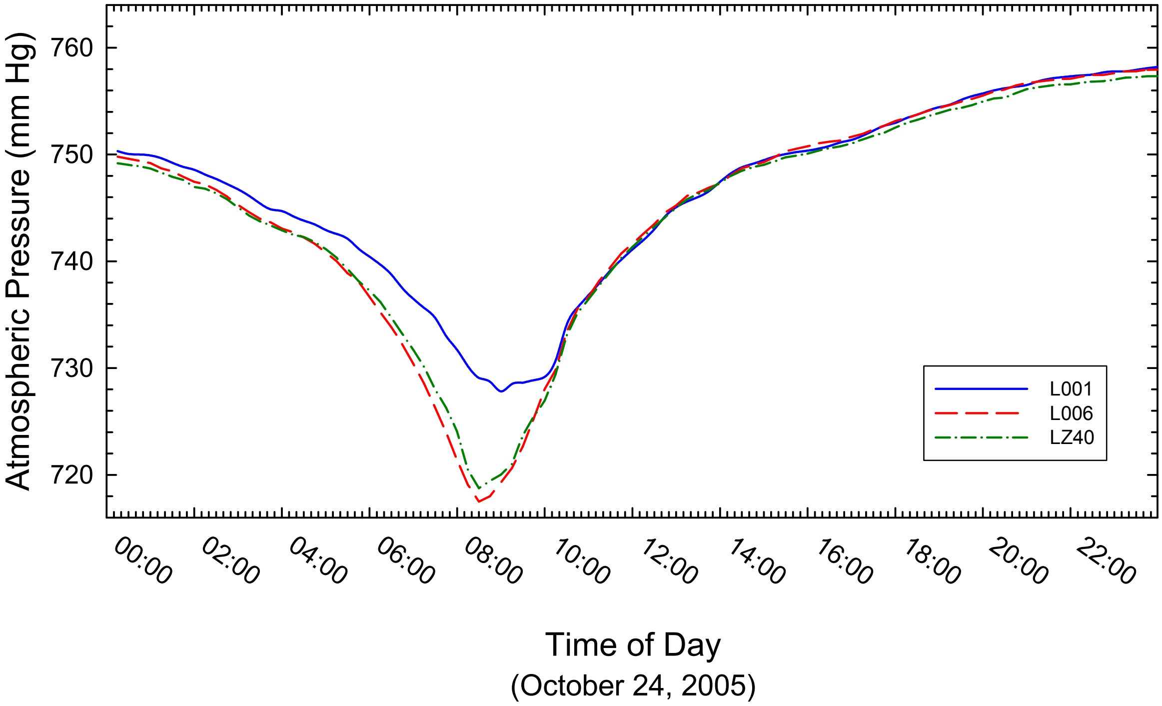


Figure 10. Atmospheric pressure changes (in mm of Hg) over Lake Okeechobee during the passage of Hurricane Wilma over South Florida; L001 (north), L006 (south central) and LZ40 (south).

Rainfall Accumulation and Spatial Distribution

Rainfall from Hurricane Wilma ranged from a spatial average of 17 cm over the Upper Kissimmee rain area to the north to 3 cm over the Everglades National Park to the south (Figure 9B). The rainfall was higher in the left quadrant of the hurricane and lower on the right quadrant (Figure 4, 9B). The characteristics of rainfall from a tropical system are that the spatial coverage is large with regional effect. This type of coverage results in generation of a very large volume of water over the region in a short time. The isohyetal map (Figure 9B) shows the spatial rainfall from Hurricane Wilma accumulated from October 22 through October 25, 2005, during the influence of the hurricane. Runoff associated with the hurricane rainfall had a lingering effect on the lake. Rise in lake stage results in a high rate of discharge to manage the lake water level. Such discharges include releases to environmentally sensitive estuaries to the east and to the west. Fortunately, Hurricane Wilma moved quickly through the area. Slower movement of the hurricane might have had extensive hydrologic and structural impact that would have included large-scale flooding as wave erosion increases with duration of impact.

WATER QUALITY EFFECTS

Water quality is routinely sampled in Lake Okeechobee at 30 monitoring stations. The number of stations sampled each month is dependent on the water level and surface area of the lake. Of the 30 monitoring stations, 8 sampling stations are located in the limnetic zone (open surface waters farther from shore in a lake), 14 nearshore sampling stations, and 8 stations in the lake's littoral zone. A graphical summary of spatial monthly mean TP and total suspended solid (TSS) concentrations from May 1994 through March 2007 in Lake Okeechobee is provided in Figure 11. The period from May 1994 through October 15, 1999, was used to establish background or "pre-hurricane" conditions for the lake. This five-year period was selected because no hurricane directly impacted Lake Okeechobee. The plots in this figure also provide dates when tropical systems directly affected the lake as well as lines showing the calculated 12-month moving average for both parameters. A 12-month moving average smoothes out the data by removing seasonal and incidental effects, and therefore, providing a better representation of the underlying trend.

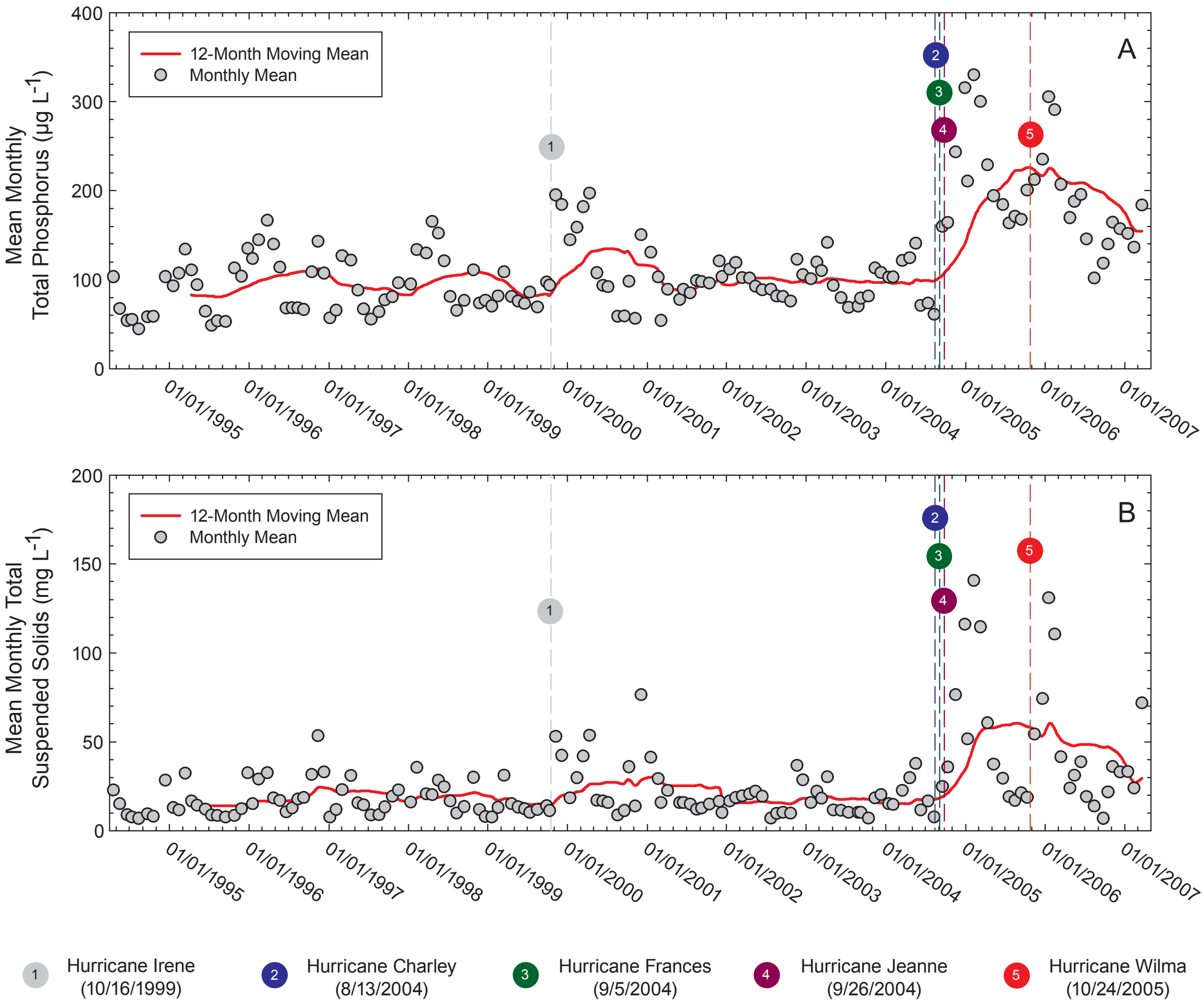


Figure 11. Spatial monthly mean total phosphorus concentrations (top) and total suspended solids (bottom) in Lake Okeechobee from May 1994 through March 2007. Vertical lines show dates when hurricanes directly impacted the lake. Data following March 2007 were not included in plot due to severe drought conditions

During the pre-hurricane period, spatial monthly mean TP and TSS ranged from 45 to 167 µg L^{-1} and 7 to 53 mg L^{-1}, respectively (Figure 11). Temporal mean concentrations for this period were 90 µg L^{-1} for TP and 18 mg L^{-1} for TSS. The 12-month moving average line for the pre-hurricane period shows no major trend in the data.

A category 1 storm, Hurricane Irene, passed to the east of Lake Okeechobee on October 16, 1999, with wind speeds reaching 90 km h^{-1} over the lake. The path of the storm, the changing wind directions, and the moderate strength of the hurricane were sufficient to cause lake churning with a series of circulation gyres. As a result, Lake Okeechobee experienced increases in TSS and TP concentrations from October 1999 through April 2000 (Figure 11). During this seven month period, temporal mean TP and TSS concentrations in the lake were 165 µg L^{-1} and 36 mg L^{-1}, respectively. These parameters exhibited spatial monthly mean concentrations ranging from 94 to 197 µg L^{-1} for TP and 11 to 54 mg L^{-1} for TSS. As a result of Hurricane Irene, temporal mean concentrations increase by 83 percent for TP and 100 percent for TSS. These increases were a result of re-suspension of P-rich, fine-grained sediments and, to a lesser degree, inflows to the lake. In their assessment of impacts from Hurricane Irene on Lake Okeechobee, Havens et al. (2001) reported that the pre-hurricane spatial TP mean concentration of 90 µg L^{-1} (measured two weeks prior to the hurricane) increased to a mean of 220 µg L^{-1} two weeks following the hurricane. The net mass load through inflows during this period can not increase concentrations by more than two-fold as net inflow was a fraction of the lake volume.

By May 2000, spatial mean TP and TSS concentrations in the lake decreased (Figure 11). Although Lake Okeechobee did not experience any direct impact from hurricanes from May 2000 through the first half of August 2004, lake management and a severe drought affected the lake and may have contributed to reducing the impact from Hurricane Irene. From April 25 through June 30, 2000, the lake was under a "managed recession" and water levels were brought down to improve the lake's littoral region. By the start of 2001, Lake Okeechobee was experiencing a severe drought which lasted well through September 2001. As a result of these conditions, TP and TSS concentrations during the period from May 2000 through August 12, 2004, were comparable to pre-hurricane levels (Figure 11). The 12-month moving average line is relatively flat suggesting no trend for the period.

Following this relatively quiescent period, the lake was affected by three hurricanes within two months (Figure 11). Concentrations of TP and TSS in Lake Okeechobee increased from August through December 2004 with temporal means of 189 µg L^{-1} and 52 mg L^{-1}, respectively, with maximum monthly concentrations reaching 316 µg L^{-1} and 116 mg L^{-1}. Over the next 10 months, TP and TSS concentrations remained high (Figure 11).

On October 24, 2005, Hurricane Wilma passed directly over Lake Okeechobee. As a result of the hurricane, spatial monthly mean TP and TSS concentrations increased through January 2006 reaching 305 µg L^{-1} and 131 mg L^{-1}, respectively (Figure 11). By April 2006, spatial monthly mean TP and TSS concentrations decreased to 170 µg L^{-1} and 24 mg L^{-1}. More than one year after Hurricane Wilma impacted Lake Okeechobee, TP and TSS concentrations continue to decrease (Figure 11) but remain higher than during the pre-hurricane period with spatial monthly means for March 2007 at 184 µg L^{-1} and 71 mg L^{-1}, respectively. After March 2007, another severe drought has significantly reduced the stage of the lake and surface area. Therefore, water quality data after March 2007 was not used in this analysis because the number of sampling stations was severely reduced compared to the 2001 drought.

Spatial monthly mean TP and TSS concentrations in Lake Okeechobee did not reach their peak levels until several months following the passage of hurricanes. This observation was also reported by Havens et al. (2001) in their discussions regarding the impact of Hurricane Irene on water quality of the lake.

When net phosphorus loads to Lake Okeechobee are evaluated for the period impacted by Hurricane Wilma, it is evident that increased TP and TSS levels observed in the lake resulted from internal re-suspension rather than net inputs from outside sources. In addition, phosphorus in the water column is strongly correlated with suspended solids. Using spatial monthly means from May 1994 through March 2007, a strong positive linear relationship (r=0.88) was found between TSS and TP (Figure 12). Suspended solids limit growth of submerged vegetation by reducing the depth of light penetration. The hurricanes uprooted and dislocated vegetation from wetlands and littoral zones around the lake resulting in increased suspended detritus.

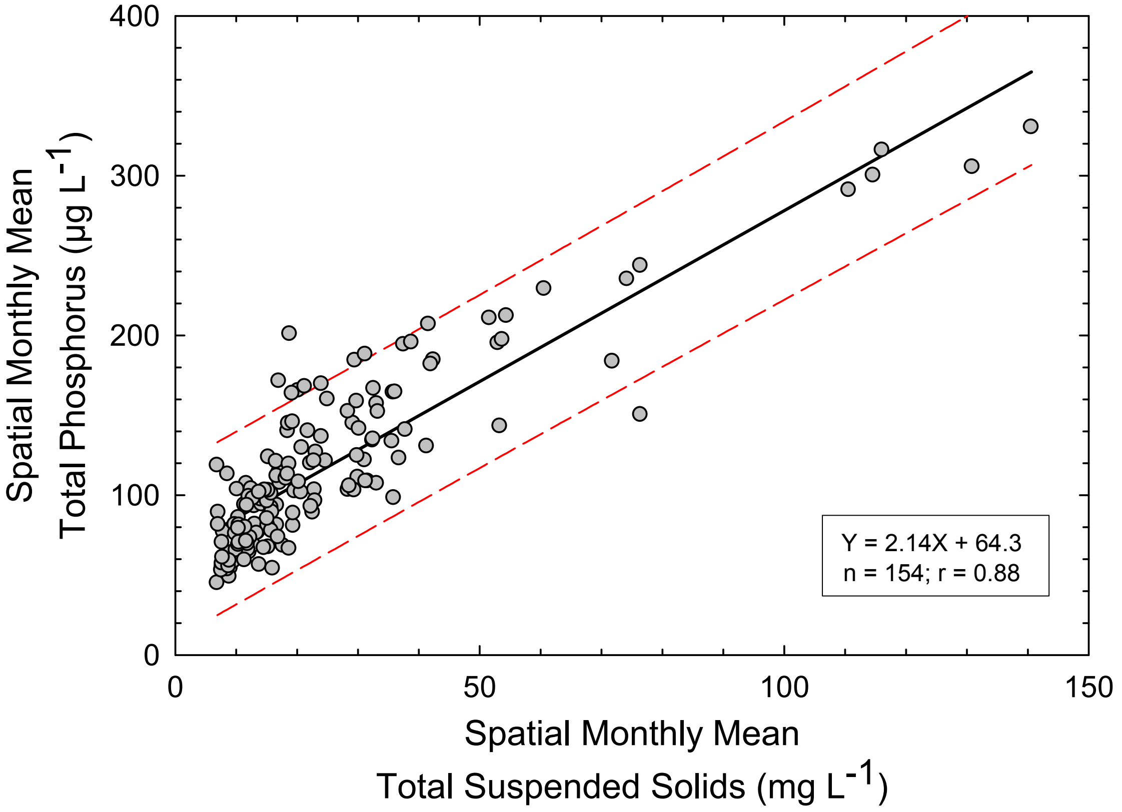
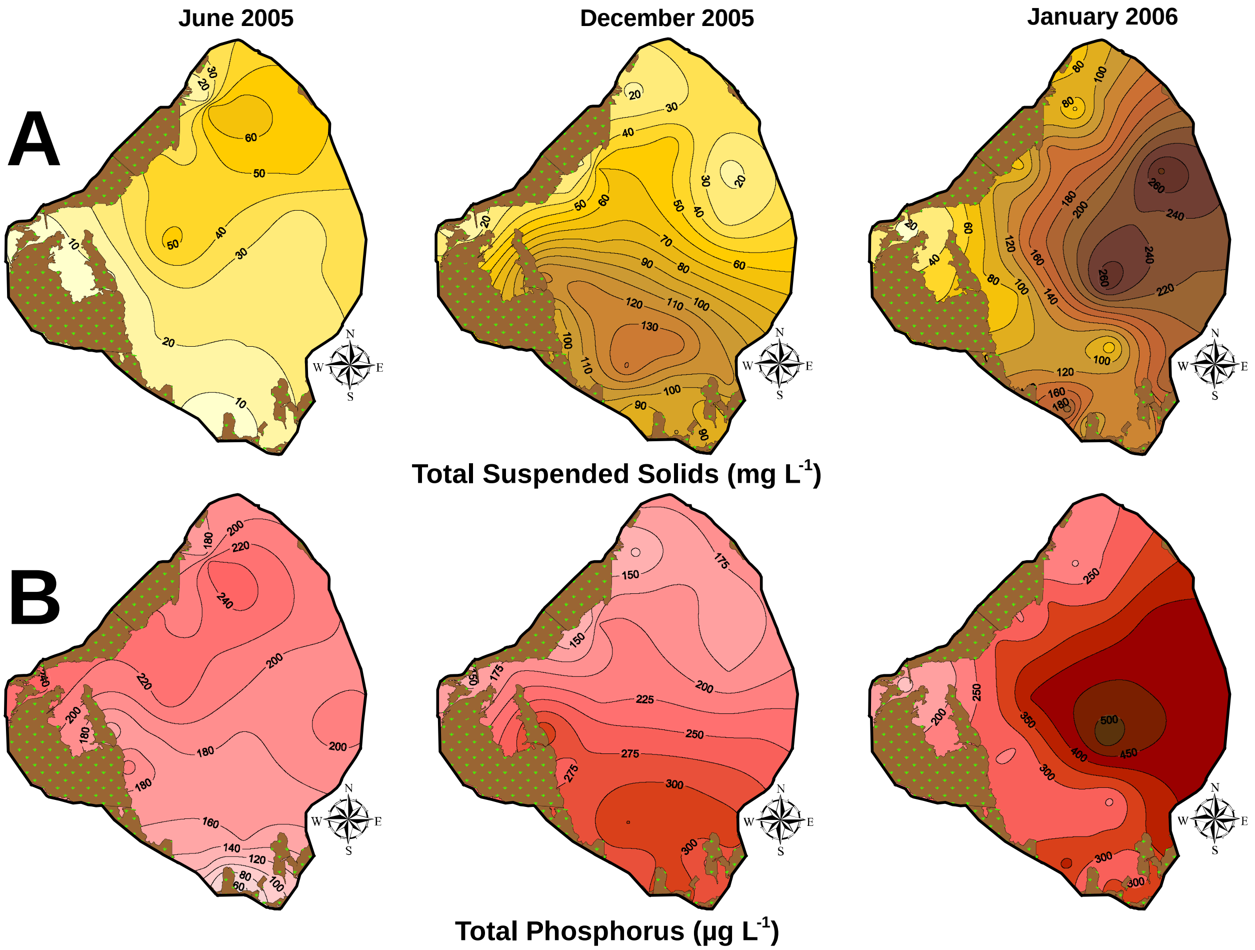


Figure 12. Correlation plot of spatial monthly mean total suspended solids with mean monthly total phosphorus concentrations in Lake Okeechobee from May 1994 through March 2007. Dashed lines show the 95th prediction intervals for the regression.

Spatial and Temporal Changes in Water Quality as a Result of Hurricane Wilma

Havens et al. (2001) used isoline maps to show effects of Hurricane Irene on the spatial distribution of TP and TSS in Lake Okeechobee. Isoline maps for TP and TSS were also generated for this study using the monthly monitoring data from individual monitoring stations to illustrate the spatial and temporal effects of Hurricane Wilma on the lake's water quality. These maps represent the spatial distribution of TP and TSS over the lake in a single month. Three months were selected to demonstrate these changes: June 2005 (start of hurricane season); December 2005 (one month after hurricane season); and January 2006 (two months following hurricane season).

At the start of the 2005 hurricane season (June 2005), TP and TSS levels across the lake did not exceed 250 µg L^{-1} and 100 mg L^{-1}, respectively. In addition, more than 50 percent of the lake (based on the isoline maps) had TP concentrations less than 200 µg L^{-1} (Figure 13). Immediately following the hurricane season (December 2005), 72 percent of the lake exhibited TP concentrations more than 200 µg L^{-1} while 23 percent of the lake had TSS levels greater than 100 mg L^{-1}. By January 2006, more than 90 percent of the lake exhibited TP concentrations in excess of 200 µg L^{-1} (Figure 13). Additionally, approximately 69 percent of the lake had TSS levels greater than 100 mg L^{-1} for this month. Both parameters generally exhibited higher concentrations in the limnetic zone than nearshore or littoral regions following the hurricane (Figure 13).


June 2005

December 2005

January 2006

A

Total Suspended Solids (mg L^{-1})

B

Total Phosphorus (µg L^{-1})

Figure 13. Isoline maps showing lake-wide concentrations of (A) total suspended solids and (B) total phosphorus in Lake Okeechobee starting from the beginning of the 2005 hurricane season (June 2005), December 2005, and January 2006.

Statistical Analysis and Results for Water Quality during the 2005 Hurricane Season

Temporal distributions of monthly in-lake TP and TSS concentrations measured at monitoring stations in Lake Okeechobee, from June 2005 through January 2006, are shown as notched box and whisker plots in Figure 14. Figures 14A and 14B show TP and TSS concentrations for all monitoring stations. Nearshore and limnetic TP and TSS concentrations were also plotted for the same period to show spatial distribution for these two parameters (Figures 14C and 14D). In all cases, TP and TSS concentrations were lower prior to Hurricane Wilma. Following the hurricane, median concentrations for all monitoring stations increased significantly from 163 µg L^{-1} to 240 µg L^{-1} for TP and from 16 mg L^{-1} to 74 mg L^{-1} for TSS.

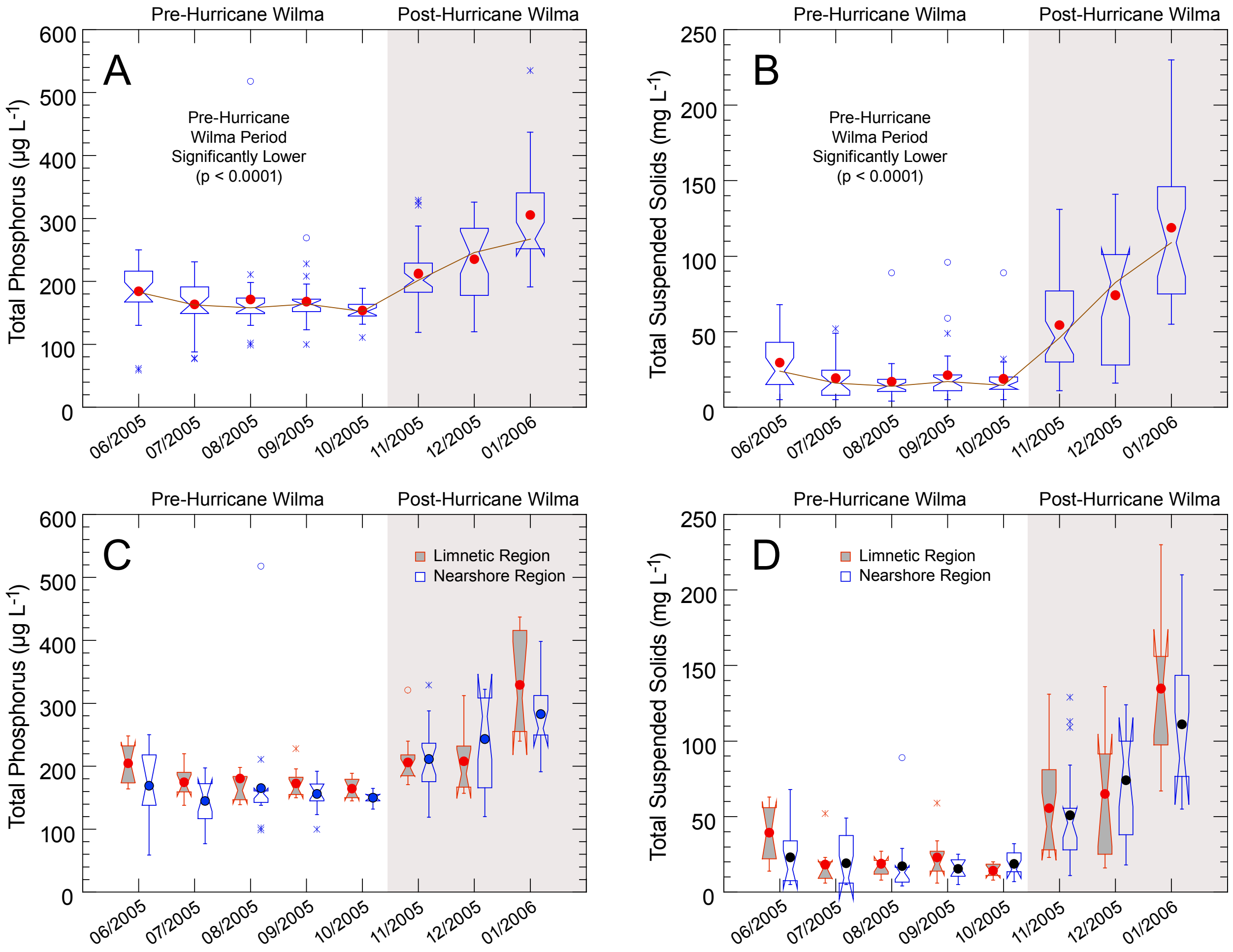


Figure 14. Monthly box-and-whisker plots of total phosphorus concentrations (A and C) and total suspended solids (B and D) in Lake Okeechobee from the start of the 2005 hurricane season (June 2005) through January 2006. Plots A and B contain data for all in-lake monitoring stations while plots C and D contain only stations located in the limnetic and nearshore regions. The solid circles represent the mean and the notch represents the median concentration. Upper and lower boundaries of boxes are 25th and 75th percentiles. Upper and lower whiskers represent the lowest and highest values not outside 2 standard deviations from the median. Shaded region in each plot denotes the post –Hurricane Wilma data.

A statistical comparison of TP and TSS data for the pre- (June 2005 through October 2005) and post-hurricane (November 2005 through January 2006) periods was performed using a non-parametric test (Mann-Whitney) because the data were not normally distributed. A significance level (α) of 0.05 was used to indicate statistical significance. The analysis showed TP and TSS concentrations for these two periods were statistically different (p-value <0.0001) with the post-hurricane period having significantly higher concentrations. In addition, a Kruskal-Wallis test was used to determine whether the months of the pre-hurricane period had statistically different concentrations. The results indicate that TP and TSS concentrations during the pre-hurricane period were statistically different between months (p-values at 0.007 and 0.049, respectively). A post-hoc analysis, using the Mann-Whitney test, revealed that June 2005 TP and TSS concentrations were significantly higher (p-value <0.04) than the other four months of the pre-hurricane period. It has to be noted that water quality for October 2005 was sampled two weeks prior to Hurricane Wilma and was included in the pre-hurricane data. This decreasing trend in TP and TSS concentrations for the pre-hurricane period is shown in Figure 14.

Similar analyses were performed for the post-hurricane period revealing that the three months following Hurricane Wilma had significantly different TP and TSS concentrations (p-value <0.0001) with January 2006 exhibiting significantly higher concentrations. These increases during the post-hurricane period are also shown in Figure 14. In addition, a comparison was made between the nearshore and limnetic regions during the 8-month period to determine if TP and TSS concentrations differed by region. Neither region exhibited statistically different concentrations (p-value <0.05).

SUMMARY AND CONCLUSIONS

Tropical systems are part of the hydrometeorology of South Florida. The potential effect of hurricanes on water management structures is an important area that demands analysis of historical data and anticipation of similar results. Determining a critical wind speed, direction and duration that could affect the current levee around Lake Okeechobee can assist in evaluating effects of hurricanes. Hurricane Wilma's wind speed and direction were capable of severely damaging segments of the Lake Okeechobee levee. This was demonstrated by the observed wave setup and damage to the levee. The short duration of the hurricane over the area minimized the impact on the levee as wave erosion increases with duration of impact. The hurricane uprooted and dislocated vegetation from wetlands and littoral zones around the lake. Flood conveyance through canals and water control structures was severely limited due to accumulated uprooted vegetation and other debris.

Water quality is an important factor in evaluating the effect of hurricanes on lakes. During the period from May 1994 through March 2007, Lake Okeechobee was impacted by five hurricanes. After the 1999 hurricane, water quality returned to pre-hurricane conditions over a six month period. As a result of the 2004 and 2005 hurricanes, water quality in the lake has remained above pre-hurricane conditions even after 17 months from the last hurricane.

Hurricane Wilma-induced winds generated high TP and TSS concentrations throughout Lake Okeechobee as observed from previous events. The increase in TP and TSS was mainly due to re-suspension of P-rich, fine-grained lake sediment rather than net inflow loads. A positive correlation was observed between TP and TSS concentrations. The impact of the hurricane affected water quality in both the limnetic and nearshore regions. Increased concentrations resulting from hurricane activity persist for more than 12 months. Hurricane winds damaged submerged vegetation and reduced light penetration as a result of increased suspended solids. These suspended materials can further limit growth of submerged vegetation and, over the long-term, result in higher amounts of suspended detritus. Treatment capacity of stormwater treatment wetlands is affected by hurricane winds as settled nutrient laden sediments are re-suspended into the water column and submerged aquatic vegetation are uprooted. Rehabilitating the treatment wetlands was needed to improve treatment performance.

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APPENDIX: Conversions for atmospheric pressure units

1 bar = 1013 mb
29.9 in mercury = 1 bar
760 mm mercury = 1 bar
1 mb = 0.02953 in mercury