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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. Mean total suspended solids concentration increased from 28 mg L^{-1} to 124 mg L^{-1} (343 percent), while mean total phosphorus concentration increased from 188 µg L^{-1} to 296 µg L^{-1} (57 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). Between 1871 and 1996, 1,000 tropical storms have occurred in the North Atlantic, Caribbean Sea, and Gulf of Mexico (Williams and Duedall, 1997).

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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. There were 114 hurricanes and tropical storms that affected the Florida peninsula between 1871 and 1996, with hurricanes comprising about half of these (Attaway, 1999). A storm is classified as tropical storm at 56 km h^{-1} wind speed and as hurricane at 120 km h^{-1}.

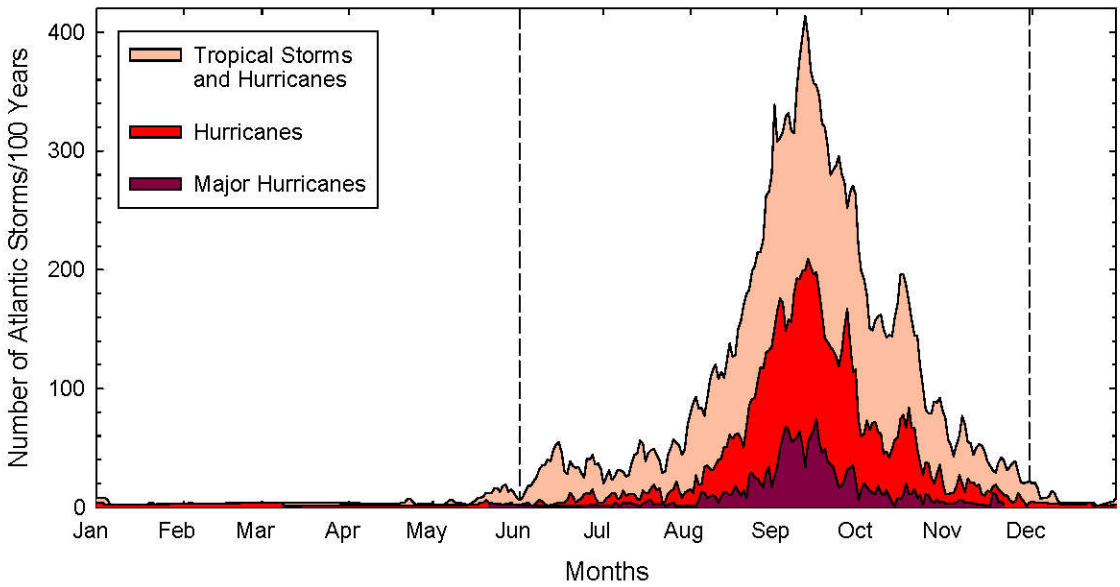

Figure 1. Distribution of North Atlantic tropical storms from 1906 through 2006. Data source (http://weather.unisys.com/hurricane/atlantic/index.html accessed on November 15, 2007).

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.

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.

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

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 levee 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 affected by Hurricanes 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 information posted on the U.S. Army Corps of Engineers web site (http://www.saj.usace.-army.mil/h2o/reports/r-sitrep.txt), Normal Lake Okeechobee operation water level is 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. Currently, regulation of lake water level is influenced by the potential risk of levee failure from seepage and hurricane winds.

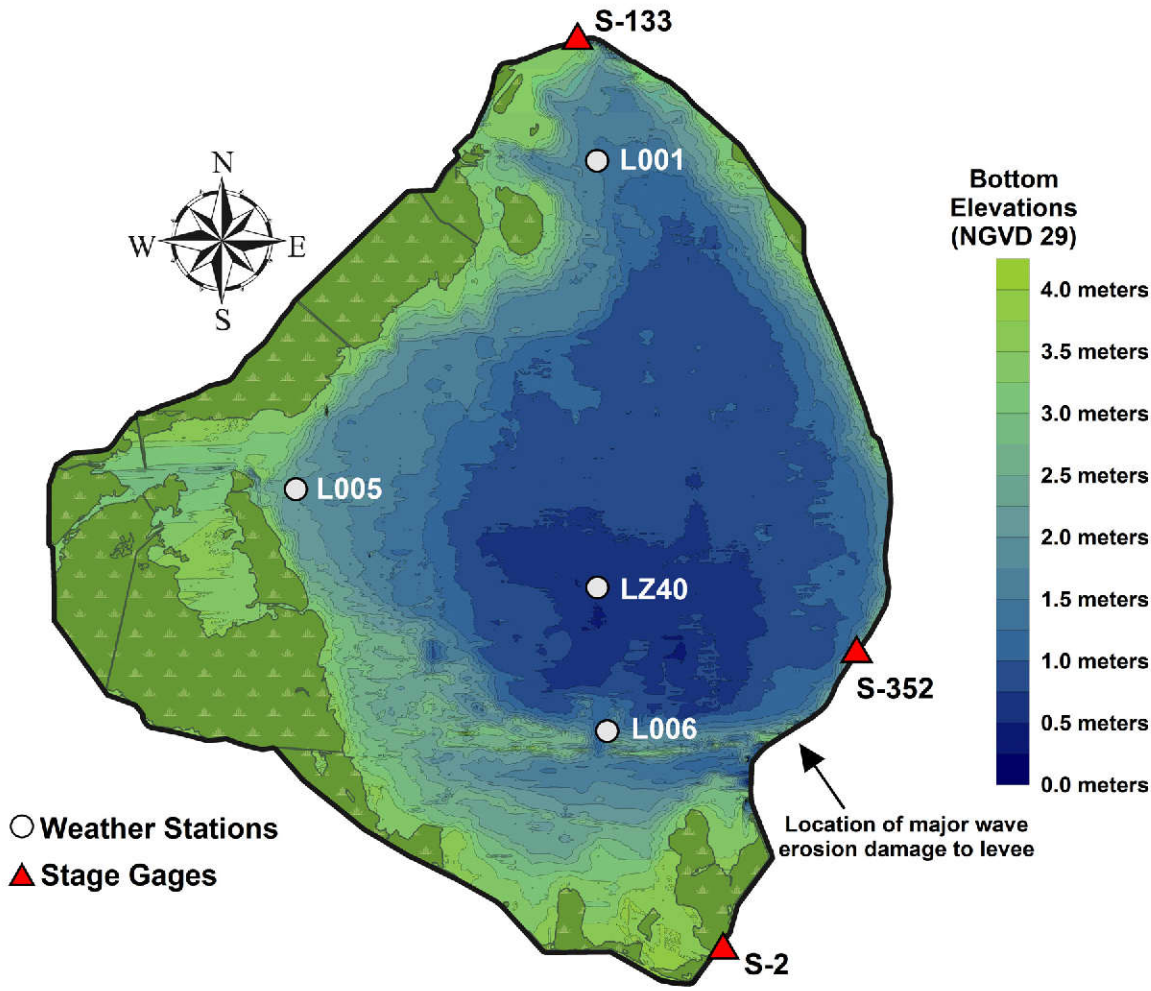

Figure 3. Map of Lake Okeechobee bottom elevations with locations for weather stations (circles), water level measurement sites (triangles), and location of levee erosion.

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 (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.

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 and, after prolonged battering of the northeastern section, it 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.

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 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.

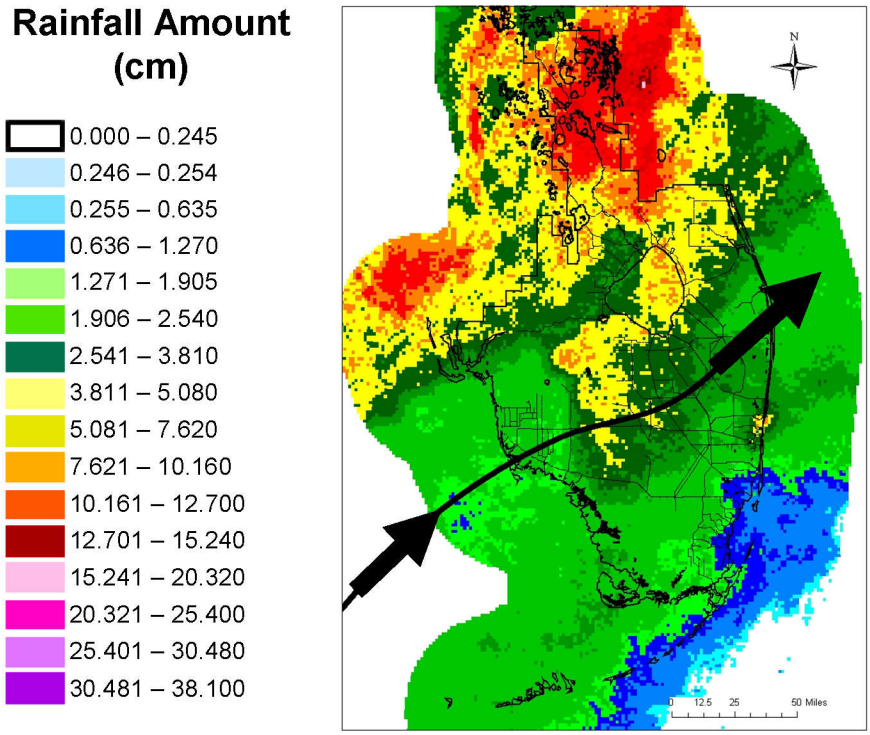

Figure 4. Path of Hurricane Wilma across South Florida on October 24, 2005 and cumulative rainfall amounts generated by the hurricane (October 22-25, 2005).

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.

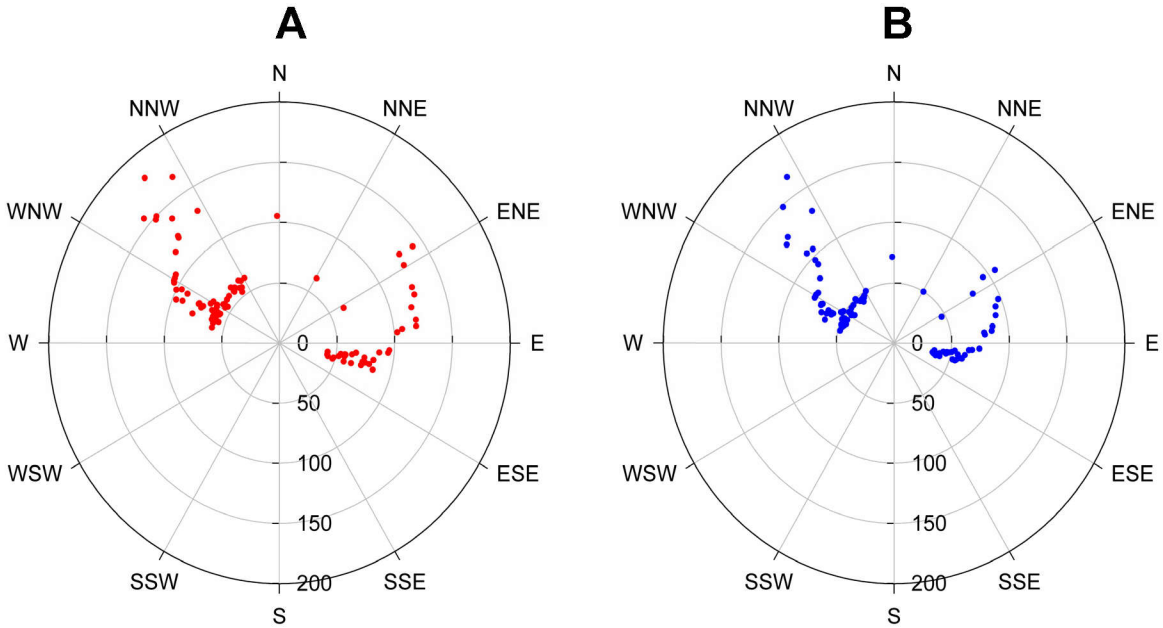

Figure 5. (A) Maximum gust wind speed (km h^{-1}), (B) Average wind speed (km h^{-1}) and wind direction at L006 weather station in Lake Okeechobee during Hurricane Wilma at 15-minute intervals (October 24th, 2005).

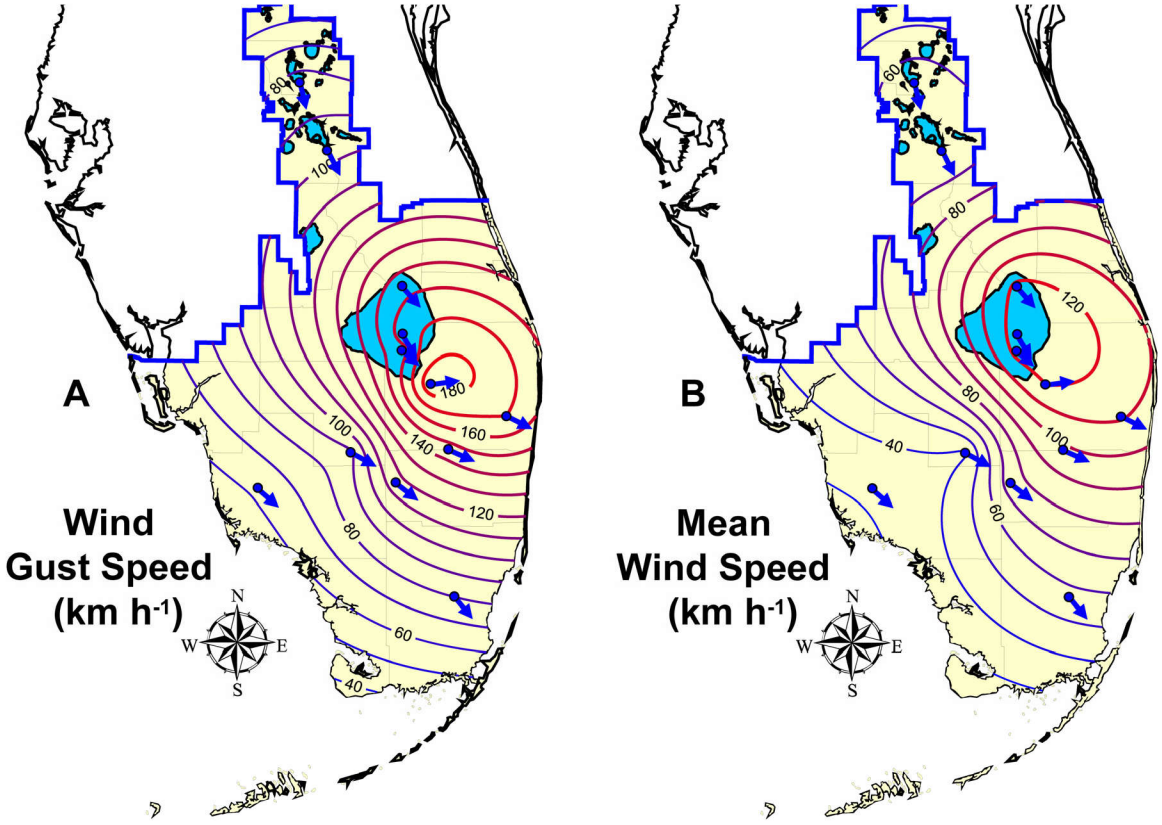

Figure 6. (A) Maximum gust wind speed (km h^{-1}) and (B) 15-minute average wind speed and directions from Hurricane Wilma over South Florida at 10:30 am on October 24th, 2005.

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):

$$Z_w = 0.005V^{1.06}F^{0.47} \quad (1)$$

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 the 15-minute highest average wind speed over the lake of 120 km h^{-1}, 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).

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. Canals were filled with debris limiting capacity to move flood waters. There was significant cost of rehabilitation of the treatment wetlands to restore the treatment performance. Canals and water control structures were clogged with hurricane dislocated vegetation and other debris resulting in reduction of conveyance capacity.

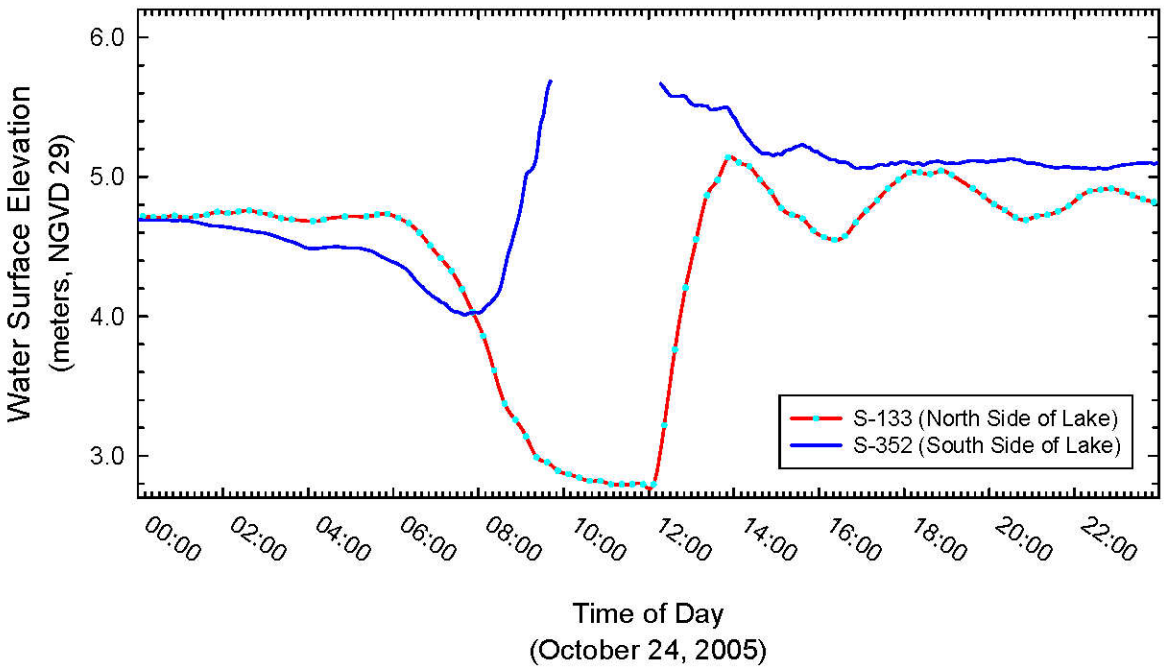

Figure 8. Water surface elevation changes in Lake Okeechobee during the passage of Hurricane Wilma over South Florida at gauge S-133 (upwind) and S-352 (downwind). The break in elevation for the S-352 gauge resulted in wave height exceeding water level sensor maximum reading.

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 (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).

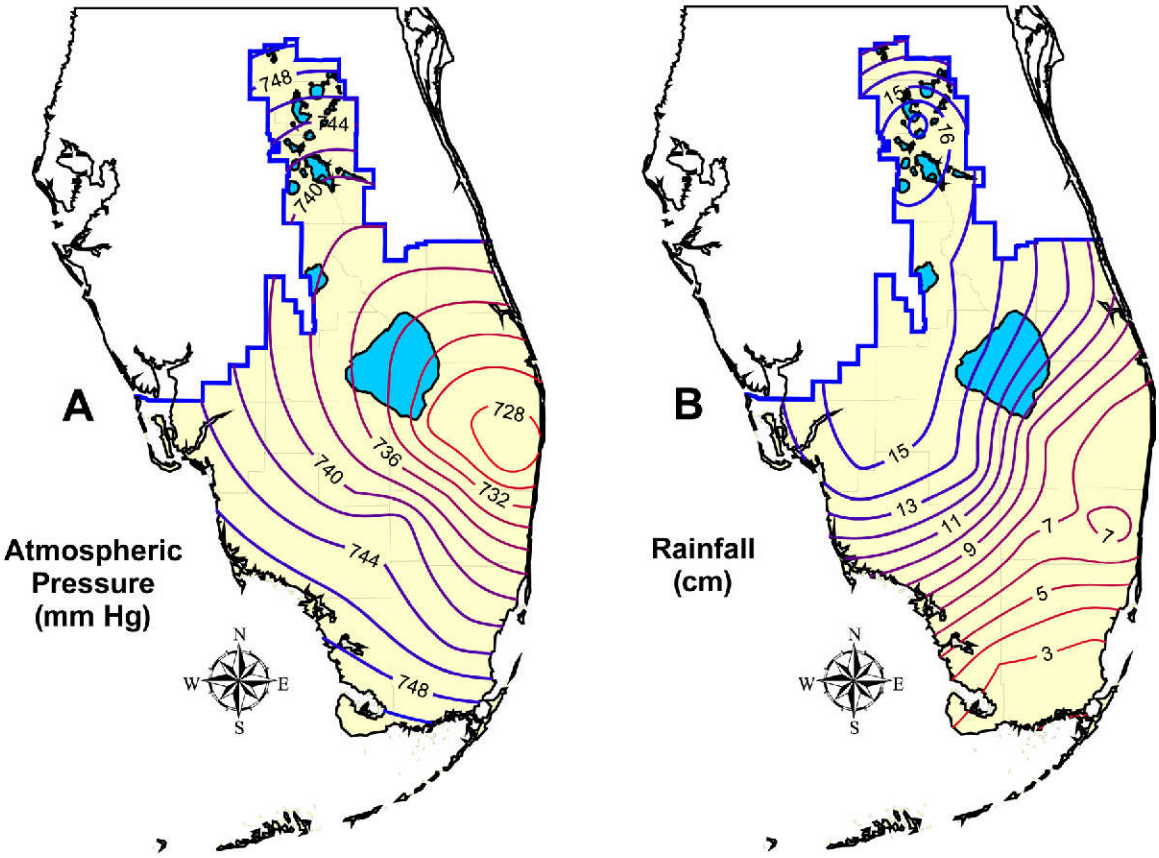

Figure 9. (A) Atmospheric pressure (mm mercury) at peak wind speed over Lake Okeechobee (10:30 am on October 24, 2005) and (B) rainfall (cm) from Hurricane Wilma (October 22-25, 2005).

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 average 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.

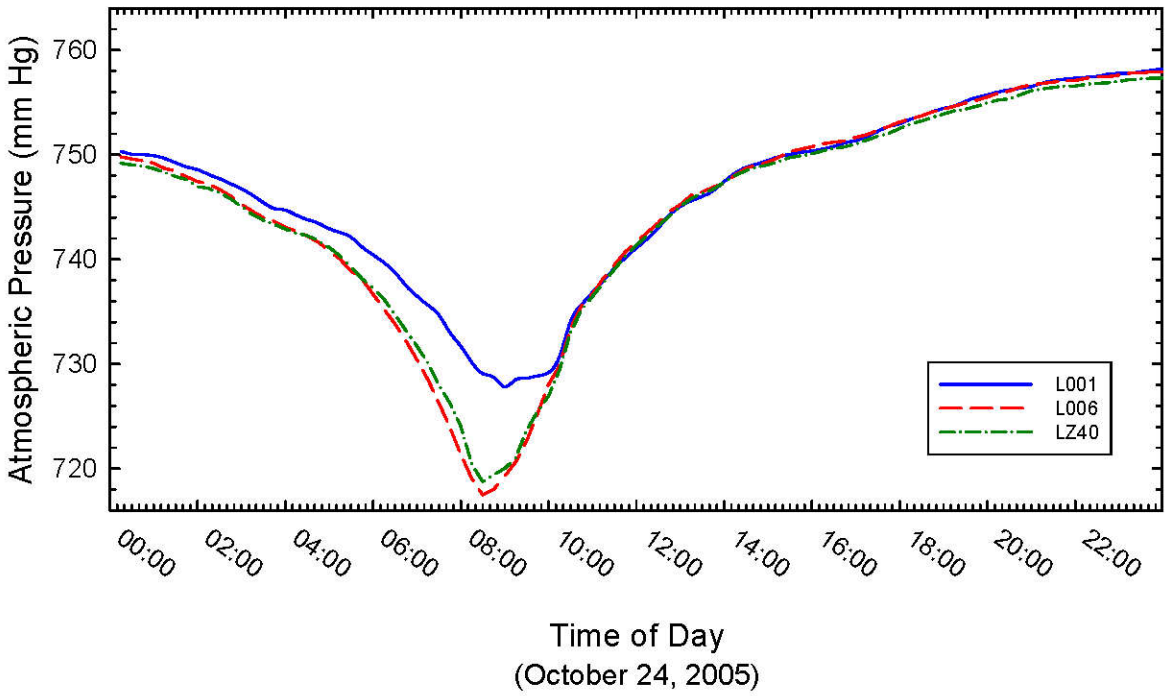

Figure 10. Atmospheric pressure changes (in mm of Hg) over Lake Okeechobee during the passage of Hurricane Wilma over South Florida; L001 (north), L006 (south central) and LZ40 (south).

WATER QUALITY EFFECTS

Monthly mean total phosphorus (TP) concentrations in Lake Okeechobee ranged from 45 to 167 $\mu g\ L^{-1}$ for the period from May 1994 through September 1999. Means are based on total phosphorus measurements from approximately 30 stations in the lake. An increase in monthly TP concentrations was observed from October 1999 through July 2004 with concentrations ranging from 54 to 198 $\mu g\ L^{-1}$. A Category 1 hurricane, Irene of October 1999, passed to the east of Lake Okeechobee with a peak wind speed of 90 km h^{-1} over the lake. The path of the hurricane, the changing wind directions, and the moderate strength of the lake resulted in lake churning with a series of circulation gyres. As a result, high amounts of sediment re-suspension and increased phosphorus concentration in the water column occurred. The pre-hurricane TP lake-wide mean concentration of 90 $\mu g\ L^{-1}$ increased to a mean of 220 $\mu g\ L^{-1}$ two weeks after the hurricane (Havens et al., 2001).

Three hurricanes affected the lake between August 2004 and September 2004, with one hurricane affecting the lake in October 2005 (Hurricane Wilma). As a result, TP concentrations in Lake Okeechobee exhibited monthly averages ranging from 61 to 330 μg L^{-1} for the period from August 2004 to April 2006 (Figure 11). It is evident from Figure 11 that mean TP concentrations in the lake did not decrease below 160 μg L^{-1} following August 2004. It is important to note that peaks in monthly mean TP concentrations were not observed until several months after a hurricane had affected the lake. Havens et al. (2001) also reported a similar time lag of increased concentrations following the passage of the 1999 hurricane by the lake.

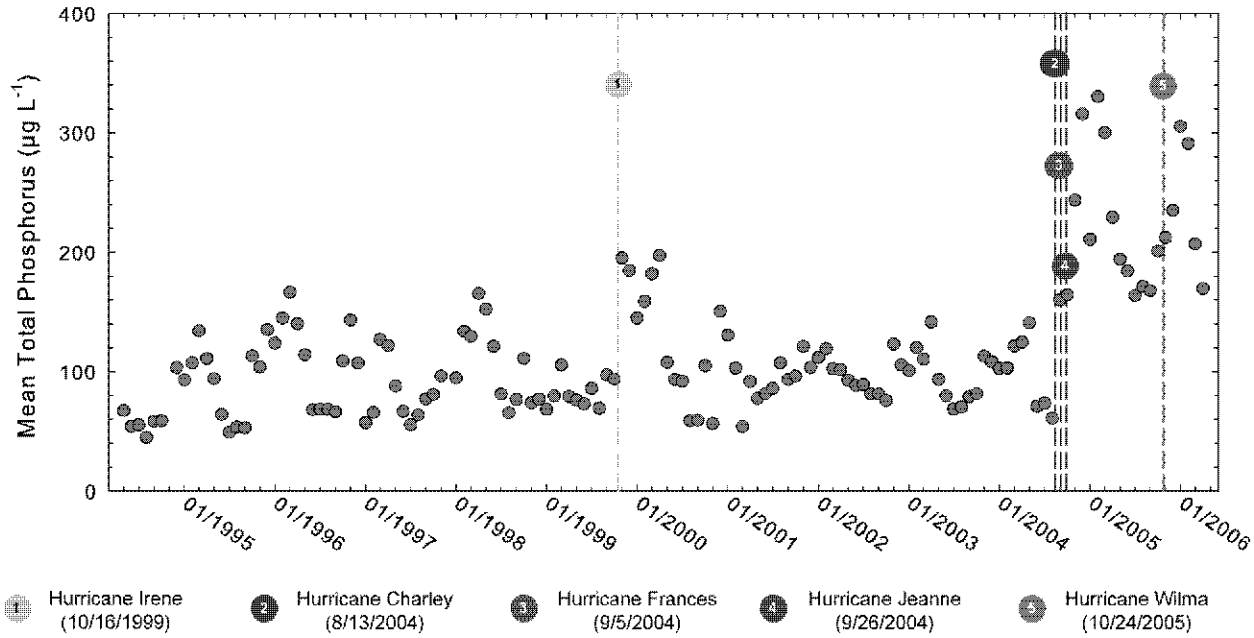

Figure 11. Monthly mean total phosphorus concentrations in Lake Okeechobee from May 1994 through April 2006. Vertical lines show dates when hurricanes have impacted the lake.

Spatial and Temporal Changes in Water Quality

Isoline maps were generated from the monthly monitoring data to show the effect of Hurricane Wilma on Lake Okeechobee water quality. Three months were selected to demonstrate these changes in water quality: June 2005 (start of hurricane season); December 2005 (end of hurricane season); and January 2006 (approximately one month following the end of hurricane season). Since previous studies have illustrated the effects of wind on TP and total suspended solids (TSS) in Lake Okeechobee (Havens et al., 2001), monthly isoline maps were generated for these two parameters (Figure 12).

At the start of the 2005 hurricane season (June 2005), TP and TSS levels did not exceed 250 μg L^{-1} and 70 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 12). By the end of the hurricane season (December 2005), 38 percent of the lake exhibited TP concentrations less than 200 μg L^{-1} while 77 percent of the lake had TSS levels less than 100 mg L^{-1}. Nutrient and suspended solid levels

continued to increase with more than 90 percent of the lake exhibiting TP concentrations in excess of 200 µg L^{-1} for January 2006. Additionally, approximately 69 percent of the lake (January 2006) had TSS levels greater than 100 mg L^{-1}. These suspended materials limit growth of submerged vegetation by reducing light penetration depth. The hurricane uprooted and dislocated vegetation from wetlands and littoral zones around the lake resulting in increased suspended detritus.

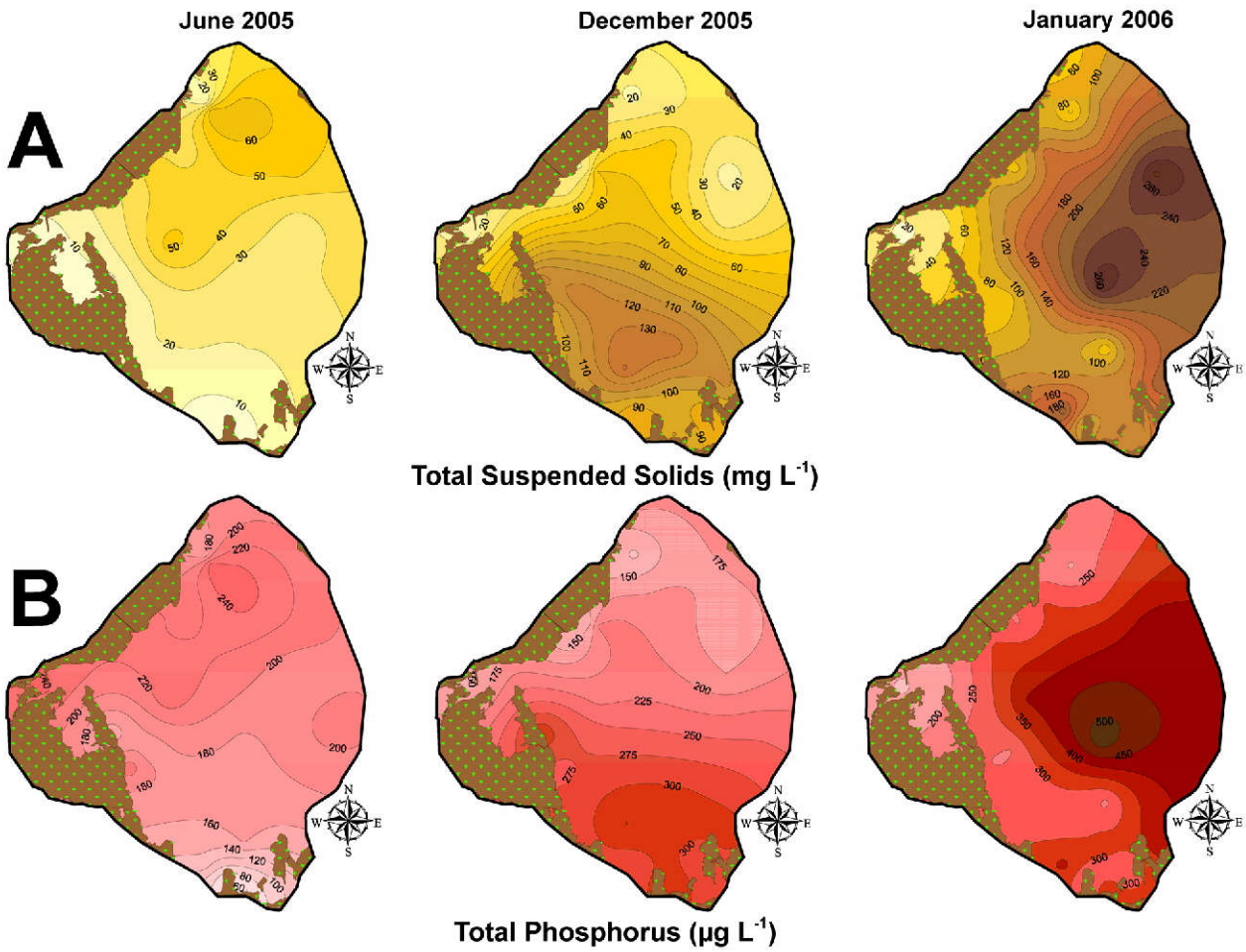

Figure 12. Isoline maps showing lake-wide concentrations of (A) total suspended solids and (B) total phosphorus in Lake Okeechobee starting from the beginning of the 2005 hurricane season (June 2005) to end of the 2005 hurricane season (December 2005) and the following month (January 2006).

Statistical Analysis and Results

Summary statistics of monthly TP and TSS data for Lake Okeechobee measured during these three months are depicted in Table 1. Maximum concentrations of TP more than doubled from June 2005 to January 2006, while TSS levels increased more than four-fold. Distributions of monthly in-lake concentrations measured at 30 monitoring stations for these two parameters also show the increase over these three months (Figure 13).

A statistical comparison of TP and TSS data for these three months was performed using a non-parametric test (Kruskal-Wallis), 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 had statistically different concentrations for these three months with a probability value (p) less than 0.0001. A post-hoc analysis was performed using the Mann-Whitney test to determine which month was significantly different from the others. The resulting p-values for these analyses are provided in Table 2. Statistical significance was found for each comparison indicating that TP and TSS concentrations increased significantly from June 2005 (start of the hurricane season) to January 2006 (Tables 1 and 2).

Table 1. Summary statistics for total phosphorus and total suspended solids concentrations measured at monitoring stations located in Lake Okeechobee at the start of the 2005 hurricane season (June 2005), end of the 2005 hurricane season (December 2005) and the following month (January 2006).

Statistic	Total Phosphorus (µg l^{-1})				Total Suspended Solids (mg l^{-1})			
	June 2005	December 2005	January 2006	Three Month Summary	June 2005	December 2005	January 2006	Three Month Summary
No. of Samples	27	27	29	83	27	28	29	84
Mean	187.9	231	295.6	239.5	28.1	70.8	123.5	75.3
Standard Deviation	49.1	66.1	88.7	82.8	18.8	40	69.3	61.6
Minimum	59	120	143	59	5	10	14	5
Median	197	240	264	233	21	80.5	109	62.5
Maximum	250	326	535	535	68	141	284	284

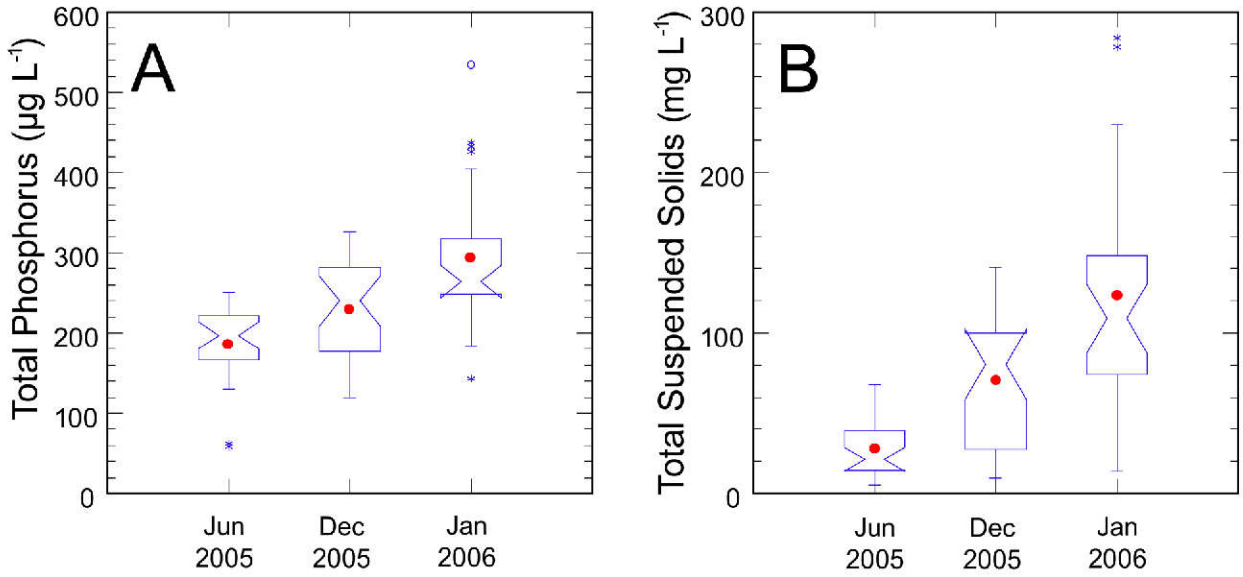

Figure 13. Box-and-whisker plots of (A) total phosphorus and (B) total suspended solids concentrations in Lake Okeechobee at the start of the 2005 hurricane season (June 2005), end of the 2005 hurricane season (December 2005) and the following month (January 2006). The solid circles represent the mean and the notch represents the median concentration. Upper and lower boundaries of boxes are 75th and 25th percentiles. Upper and lower whiskers represent the highest and lowest values not outside 2 standard deviations from the median.

Table 2. Probability values (p-values with α of 0.05) from Mann-Whitney comparison of total phosphorus and total suspended solids concentrations in Lake Okeechobee for the start of the 2005 hurricane season (June 2005), end of the 2005 hurricane season (December 2005) and the following month (January 2006).

Probability Values for Mann-Whitney Comparison					
Total Phosphorus			Total Suspended Solids		
Months	June 2005	December 2005	Months	June 2005	December 2005
December 2005	0.03		December 2005	<0.0001	
January 2006	<0.0001	0.02	January 2006	<0.0001	0.003

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. Water quality is an important factor in evaluating the effect of hurricanes on lakes. Hurricane Wilma-induced winds generated high TSS and TP concentrations throughout Lake Okeechobee. The water quality affect resulting from hurricane activity persist for a long period. 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. 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. 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 to improve performance incurs significant costs.

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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