Impacts of Hurricanes on Surface Water Flow within a Wetland

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Abstract: Between 2001 and 2005, seven category 3 or higher major hurricanes made landfall within the U.S. The hydrologic impacts of these distinct climatic phenomena frequently occurring in wetland watersheds, however, are not well understood. The focus of this study was to evaluate the impacts of hurricane wind and rainfall conditions on water velocity and water elevations within the study wetland, the Florida Everglades. Specifically water velocity data was measured near two tree islands (Gumbo Limbo (GL) and Satin Leaf (SL)) and wind speed, water elevation, and rainfall were obtained from nearby wind observation stations. During the direct impacts of the hurricanes (Hurricanes Katrina and Wilma), water speed, flow direction, and hydraulic gradients were altered, and the extent of variation was positively related to wind characteristics, with significant alterations in flow direction at depth during Hurricane Wilma due to higher wind speeds. After the direct impacts, the longer lasting effect of hurricanes (time scale of a few days) resulted in altered flow speeds that changed by 50% or less. These longer lasting changes in flow speeds may be due to the redistribution of emergent vegetation.

Keywords: hurricane; wetland; water velocity; wind velocity

1. Introduction

Water flow is a major determinant in all wetlands significantly impacting ecosystem quality and function (Reimold, 1994). Anectodal evidence indicates that hurricanes are able to cause major changes in wetland hydrology thereby affecting processes that influence wetland sustainability (Twilley, 2007). However, due to the recent advancements and proliferation of monitoring systems quantitative studies evaluating the impacts of hurricanes on wetlands are generally very recent and have been limited to evaluation of phosphorous releases from wetlands (Novak et al. 2007), changes in wetland microbial communities (Williams et al., 2008), impacts on salinity (Batllori and Febles 2007), changes in plant communities (Goode et al. 2008; Hoeppner et al. 2008; Ugarte et al. 2006; Kovacs et al. 2001), changes in sedimentation rates (Turner et al. 2007; Turner et al. 2006; Parsons 1998; Kang and Trefrey 2003) and overall changes in wetland size (Costanza et al. 2008; Ramsey et al. 1998). But limited information is available on wetland water flows under hurricane conditions. The only publication available on this topic is from Harvey et al. (2009) who found that during Hurricane Wilma in 2005 water speed and water levels increased above pre-hurricane levels. Considering the key role of surface water flow patterns in shaping substrates, biogeochemical cycling, restoration, and ecosystem characteristics in wetlands, the impacts of extremely strong winds, such as hurricanes, on wetland water flow are of great interest. For example, surface water speed is recognized as a critical factor in particulate settling and re-suspension in wetlands, two processes in maintaining the ridge and slough ecosystems (Bazante et al. 2006; Larsen et al. 2007). In the Everglades, a subtropical wetland in Florida, USA, the estimated critical surface water velocity to re-suspend particles in water ranges within 2.5 - 7.0 cm/s (Bazante et al. 2006; Larsen et al. 2007). However, water speed measured in the wetland rarely exceeds the rate, suggesting that re-suspension of particulars is almost non-existent (He et al., 2010). Nevertheless, the amount of suspended solids likely increases dramatically during storm conditions, as a result of increases in water speed. Hurricanes are ranked based on their maximum sustained wind speeds using the Saffir-Simpson Hurricane Scale. A category 1 hurricane has the lowest maximum wind speed of 33-42.5 m/s (119-153 km/h), whereas the maximum wind speed of a category 5 hurricane is greater than 69 m/s (249 km/h). In a typical 3-year span, the U. S. coastline is struck on average five times by hurricanes, two of which are designated as major hurricanes (⩾ category 3). Between 2001 and 2005, seven major hurricanes made landfall in the United States, making it difficult to design monitoring systems specifically tailored to assess the impacts of hurricanes.

To our knowledge, this study is one of two (Harvey et al. 2009) which provide quantitative measures of water speed and direction within a wetland under hurricane conditions. These data (as were those collected by Harvey et al. 2009) were collected as part of a long-term monitoring network used to evaluate water velocity within the Everglades. By chance two hurricanes, Hurricanes Katrina and Wilma, traveled through the Everglades either directly over or very near our monitoring sites during the monitoring period, which thus provided a unique opportunity to document and assess water velocity impacts during hurricane wind conditions for two events during the same hurricane season. Harvey et al. (2009), because of the location of their monitoring stations located 20 km to the north of our sites, monitored the effects of one of the two hurricanes and the wind speeds for that hurricane (Hurricane Wilma) were about ½ of those observed at the sites described as part of the current manuscript.

The objectives of this paper are to: 1) document the characteristics of water flow (speed and direction) within the wetland during hurricanes; 2) to compare variations of water flow before and after these hurricanes; and 3) to evaluate effects of local rainfall, hydraulic gradient, water elevation, upstream gate operation, and wind speed on water speed during hurricanes. Given that data were collected during two different hurricanes, the results were compared to establish whether the flow responses were different during each hurricane event.

2. Site Description

The Everglades is a large (10,000 km^2) sub-tropical wetland located in the southern portion of the U.S. within the State of Florida and is characterized by densely vegetated ridges, relatively open sloughs, and tear-shaped tree islands. Shallow, slow-moving surface water in the Everglades flows southwardly or southwestwardly from Lake Okeechobee to Florida Bay and to the Gulf Coast of Florida. Everglades National Park (ENP), which includes the southern portion of the Everglades, is located in southeastern part of the State of Florida (Figure 1). Shark River Slough is the major water flow pathway through the central Everglades, with an approximately 32 km wide northern border, and a 10 km wide discharge at the mangrove ecotone. The hydraulic gradient along its longitudinal northeast–southwest axis is generally 3 to 4.7 cm/km (Olmsted and Armentano, 1997). The climatic characteristics in this area are: an average annual air temperature of about 24^{o}C; an average annual precipitation of 1320 mm; and periods of intense evapotranspiration (ET) resulting in estimated ET of 70–90% of the total amount of rainfall (Mcpherson and Halley, 1997). The region is characterized by two seasons, a wet season (typically from June to November), and a dry season (typically from December to May) (Noe et al., 2001). A series of water control structures (S-12A, S-12B, S-12C, S-12D, and S 333) located on Tamiami Trail Road, which are operated by South Florida Water Management District (SFWMD), defines the northern boundary of ENP (Figure 1). Water control structures impacting flow to our sites are S-12C, S-12D, and S 333, as a roadway exists immediately to the west of the study site thereby minimizing impacts from gates S-12A and S-12B (Figure 1).

Water flow data in the Shark River Slough have been investigated temporally and spatially. Bazante et al. (2006) showed that mean velocities observed near three tree islands varied from 0.9 to 1.4 cm/s, with slightly higher mean velocities of 1.2–1.6 cm/s during the wet season versus 0.8–1.3 cm/s during the dry season. He et al. (2010) found consistent results with low flow speeds at five sites (< 3 cm/s) and showed that 70% of the variance of the measured speed could be explained by the local hydraulic gradient, water depth, and vegetative resistance. Riscassi and Schaffranek (2002, 2004) reported that horizontal velocities in several locations with different hydrological conditions varied between 0.0 and 4.5 cm/s, and horizontal flow direction generally ranged from 180 to 275 degrees, clockwise with respect to magnetic north (MN), during the wet seasons of 1999-2001 and 2002-2003.

Water velocity measurements for this study were collected at sites in the vicinity of two tree islands within the Shark River Slough of ENP, known as Gumbo Limbo Hammock (GL) (25.6305°N, 80.7430°W), and Satin Leaf Hammock (SL) (25.6591°N, 80.7571°W) (Figure 1). The latter island has also been referred to as Indian Camp Hammock and Tiger Hammock in other documents. The measurements recorded during the hurricanes were collected as part of a continuous monitoring program focusing on the hydrology of these islands. These data collection stations were installed in *Cladium jamaicense* (sawgrass) marsh on the west side of each tree island just south of the hardwood hammocks in areas not covered by the tree canopies (Bazante et al.2006; Leonard et al. 2006). Soils in the vicinity of GL and SL are peats with a high organic matter content of >80%, except for small areas at the elevated heads of the tree islands where outcropping limestone and carbonate rich mineral soils are found (Ross et al., 2004).

3. Hurricanes Katrina and Wilma through South Florida

At approximately 17:30 (Eastern Standard Time, EST) on 25 August, 2005, Hurricane Katrina made its first landfall in the United States to the east of the Everglades (Figure 1) as a category 1 hurricane with maximum sustained winds of 36 m/s (130 km/hr). A well-defined eye was evident and remained intact as it crossed South Florida with the strongest winds and heaviest rains occurring to the southeast of the hurricane track. The center of Katrina emerged into the southeastern Gulf of Mexico 6 hours later on 26 August, weakened to a tropical storm with maximum sustained winds of 31 m/s (111 km/hr). Rain totals were greater than 25 cm to the south of the hurricane track and 5 to 10 cm to the north (Knabb et al., 2005).

In contrast to Hurrican Katrina, Hurricane Wilma approached southwestern Florida from the Gulf of Mexico and made land fall at 5:30 (EST) on 24 October, 2005, with maximum sustained winds of 54 m/s (195 km/h) (category 3). Four and a half hours later, the eye reached the Atlantic coast and moved out over open water. By this time, maximum wind speeds had decreased to 49 m/s (176 km/h) (category 2). Rain totals in Florida ranged from 7 to 17 cm (Pasch et al., 2006).

4. Methods

Hourly rainfall and water elevation data were obtained from three monitoring stations NP 201 (25.718^o N, 80.726^{o}W), NP 202 (25.661^o N, 80.712^{o}W) and NP 203 (25.624^o N, 80.739^{o}W) operated by Everglades National Park. As shown in Figure 1, NP 201, 202, and 203 are approximately aligned in the direction of flow within 3 km of GL and SL. The distances between NP 201 and 202 and between NP 202 and 203 are 6.52 and 5.15 km, respectively. The hydraulic gradients of NP 201-202, NP 202-203, and NP 201-203 were calculated according to their water elevation differences and distances, respectively.

Water velocities at the two monitoring stations (GL and SL) were measured in three dimensions (x, y, and z directions) in 15 min intervals using fixed Acoustical Doppler Velocity meters (ADV) (SonTek Argonaut-ADV, San Diego, CA, firmware version 11.6). These units were designed with a ‘‘sidelooking’’ orientation where the acoustical signal was transmitted to the side of the instrument rather than below, thereby allowing for measurements of water velocity in x, y, and z directions in water as shallow as 15 cm. Horizontal velocities were computed through the vector sum of the x and y coordinates. The fixed ADVs were programmed to store averages of 3000 measurements over a period of 5 minutes for each 15-min interval. An approximately 6/10 depth of measurement was maintained through vertical adjustment of the probes.

Surface mean wind velocity data were available from several weather observation stations, the two closest of which were within Everglades National Park at a height of 2 m from ground surface, at stations known as Tenraw (TE), and Chekika (CH) (MesoWest Data website, http://www.met.utah.edu/jhorel/html/mesonet/ of the Department of Meteorology at the University of Utah). TE (25.6097 ^{o}N 80.8503 ^{o}W) and CH (25.6250 ^{o}N 80.5797 ^{o}W) were located 11.9 km west and 18.2 km east from GL, respectively. Wind data were collected at TE and CH at 1 hour time intervals. Wind data at TE and CH were first interpolated in terms of time to estimate values during time periods consistent with the sampling periods for the velocity measurements. These interpolated wind data for TE and CH were then interpolated in terms of longitude to estimate the wind characteristics at GL and SL during the hurricanes. To readily compare the directions of water flow and wind, the wind in this study is described as where it blows to, clockwise with respect to magnetic north (MN). All times mentioned are U.S. eastern standard times (EST). Water flow data before and after the hurricanes were compared using the Students' t-tests (95% confidence limits). The period of hurricane influence was arbitrarily defined as the time period characterized by sustained wind speeds of at least 10 m/s, which was rarely found during non-hurricane conditions.

5. Results

5.1 Hurricane Katrina

During Hurricane Katrina, the estimated wind speeds at GL and SL first increased over 10 m/s at 19:45 25 August, 2005, and were oriented toward the southeast. The wind direction started to deflect clockwise at 22:30, and moved toward the northwest (277^{o}) at 22:45 with a speed of 7 m/s. The wind speed in the northwest direction reached a maximum of 17.3 m/s at 3:15 on 26 August, 2005, and then decreased to less than 10 m/s after 7:45 on 26 August, 2005. The wind speeds as measured at TE and CH did not reach hurricane strength (33 m/s) as these stations were located just north of the hurricane track on the weaker side of the hurricane.

During the peak storm conditions, the magnitude of water flow in the horizontal plane decreased at both GL and SL, but continued to flow primarily southward (Figure 2). After the wind shifted from a southeastward to northwestward direction, the water flow direction at GL also was deflected toward the west. During peak wind conditions, both the wind and water flow direction exhibit a strong westerly component. Interestingly, water flow was still essentially southward even though the strongest winds were blowing toward the north.

The mean values of variables measured by the fixed ADVs before and after Katrina are shown in Table 1. The time periods before and after the hurricane correspond to 4 days before the winds reached 10 m/s and 4 days after the winds receded from 10 m/s. This time frame was chosen since it also corresponds to a period when gate discharges, ambient temperature, and water depths were comparable before and after hurricane passage, thereby providing a baseline upon which hurricane impacts could be compared. Mean horizontal water speed significantly increased at both GL ($p < 0.01$) and SL ($p < 0.01$) during the four day period immediately following Hurricane Katrina. The mean horizontal water speed increased by 30% above pre-storm values at GL (1.30 to 1.69 cm/s) and by 10% at SL (1.89 to 2.07 cm/s). In spite of these apparent increases, these values are comparable to mean water speeds measured at GL and SL during the previous wet season (Bazante et al., 2006). The results also showed a sinusoidal flow pattern at GL after the storm showing higher flows during the late night and early morning hours and lower flows during the middle of the day. This pattern may have been related to changes in evapo-transpiration rates throughout the day. The same was not readily observed for SL. Gate flow through upstream stations remained relatively constant before, during, and after Hurricane Katrina. The precipitation was recorded at NP 201, 202, and 203 during the hurricane (Figure 3). The highest hourly rainfall occurred at NP

202 and was as much as 51.5 cm/hr, much greater than 7.9 and 13.7 cm/hr recorded at NP 201 and NP 203, respectively. In response to rainfall, water elevations at NP 201, 202 and 203 increased by 6, 10, and 20 cm, respectively. Over the five following days, these elevated water levels did not return to the levels observed before the hurricane.

The hourly hydraulic gradients between these sites were characterized by short-term fluctuations associated with storm passage (Figure 3). The gradient was steeper between NP 202 and NP 203 in comparison to the gradients between NP 201 and NP 202 and between NP 201 and 203 during the 8-day period. During Hurricane Katrina, the largest change in hydraulic gradient occurred between NP 202 and NP 203; increasing from 5.5 to 6.0 cm/km and then decreasing to 5.0 cm/km. Change in hydraulic gradient was less pronounced between NP 201 to 203, decreasing from 4.6 to 4.0 cm/km and then returning to 4.4 cm/km The smallest change in hydraulic gradient was observed between 202 and 203, decreasing from 3.5 to 3.0 cm/km and then returning to 3.5 cm/km. These changes in hydraulic gradient are coincident with the larger peak rainfall measured at NP 202 which resulted in larger fluctuations in hydraulic gradient.

The horizontal water speeds at GL and SL apparently responded to the changes in these gradients during the hurricane (Figure 3). At SL, the water speed was roughly synchronized with the hydraulic gradient between NP201 and NP202, since the site was the geographically closest to NP 202. Similarly at GL, water speed followed a very similar pattern as the gradient curve between NP202 and NP203 since GL is closer to NP 203. The minimum water speeds were also coincident with the peak wind speed, because the wind direction was roughly in a direction opposite to flow.

5.2 Hurricane Wilma

During Hurricane Wilma, estimated wind speeds at GL and SL increased to over 10 m/s at 0:30 on 24 October 2005 (Figure 4). The wind direction was initially to the northwest, and gradually rotated towards the northeast after 7:15 when wind speeds peaked at 31 m/s. The wind speed gradually declined to less than 10 m/s by 17:15. Although Hurricane Wilma made landfall in South Florida as a category 3 hurricane, the wind speeds measured in the study area were below the minimum value of a category 3 storm (54 m/s) because the study area was 75 km south of the hurricane center. Compared to Hurricane Katrina, however, Wilma generated wind speeds that were 2-fold higher at GL and SL.

The directions of water flow at GL and SL were deflected clockwise following the clockwise rotation of the wind during the passage of peak storm conditions (Figure 4). As the storm crossed to the north, the direction of water flow at SL was first deflected to the north (308^o). This deflection in flow direction from almost west to the NNW began when the wind speed exceeded 24 m/s (6:30 on Oct. 24). Flow direction remained toward the north, and in opposition to the ambient flow direction, over the next three hours until wind speed returned to less than 24 m/s (6:30 on 10/24/05, Figure 4). After this time, flow returned to a southerly direction. The maximum water speed recorded at SL (5.3 cm/s) occurred during the peak of the hurricane when both flow direction and wind direction were oriented to the north. The flow direction at GL also was deflected clockwise following the clockwise rotation of the wind, however, not to the extent as observed at SL. Northerly flow occurred only briefly at approximately 7:15 on Oct. 24 when peak wind (31 m/s) conditions existed. As observed for SL, the water flow direction observed at GL during this time represents almost a complete reversal of the natural flow direction.

The mean values of variables measured by the fixed ADVs before and after Hurricane Wilma are shown in Table 1. Significant differences in mean horizontal water speeds and water flow direction were observed at both stations ($p < 0.01$). Following Hurricane Wilma, the mean horizontal water speed decreased to 50% (1.80 to 0.90 cm/s) of the pre-storm mean at GL. In contrast at SL, mean horizontal water speed increased above the pre-storm mean by more than 2 times (0.59 to 1.32 cm/s). Of note, the flow pattern after Hurricane Wilma for both stations showed a daily sinusoidal pattern again with higher velocities during late night and early morning and lower velocities during mid-day. After the storm, wind speeds were very low and could not explain this pattern. The reason for this pattern is not known, but, as mentioned earlier, may be related to daily evapotranspiration cycles. Further, the flow direction was changed from 214^o to 211^o at GL and from 154^o to 215^o at SL. Of note, the water flow direction at SL was variable before Hurricane Wilma, but was relatively constant after the hurricane.

The sum of discharges (S-12C, S-12D and S-333) was not appreciably altered by the hurricane although gate discharge was slightly higher following the storm and gradually increased (Figure 5). Water elevations at NP 201, 202 and 203, however, displayed abrupt increases in response to high precipitation during the hurricane. This was particularly the case at NP 201 where the water elevation increased from 273.1 cm to 284.7 cm when Hurricane Wilma crossed the station. After storm passage, the water elevation at NP 202 and 203 quickly decreased to levels comparable to those observed before the hurricane, but at NP 201 water elevation did not return to its initial level until approximately three days after the hurricane. The dissimilarity in the water elevation variations at the three sites may be ascribed to the localized variations in amounts and rates of the local rainfall.

During Hurricane Wilma, the hydraulic gradient from NP 201 to 202 increased from a pre-storm gradient of 3.60 cm/km to a maximum of 4.9 cm/km. After storm passage, it gradually decreased to the pre-storm level (3.6 cm/km). Finally, the hydraulic gradient stabilized at 2.90 cm/km by 8:00 on Oct. 27 which was lower than prior to the hurricane. The hydraulic gradient between NP 201 and NP 203 had a similar trend, increasing from 4.5 cm/km to 5.2 cm/km during the hurricane and decreasing back to the pre-storm level within 2 days. Interestingly, the hydraulic gradient between NP 202 and NP 203 decreased from 5.8 cm/km before Hurricane Wilma to 4.8 cm/km during storm passage. It then quickly returned to the pre-storm level of 5.8 cm/km at 10:00 on Oct. 28. This response contrasts with the NP201 to 202 gradient and also with the hydraulic gradients observed during Hurricane Katrina.

As for Hurricane Katrina, water speed at SL during Hurricane Wilma showed an increase in speed when the gradient increased between NP201 and NP202. At GL the speed increased, but not as much. The diminished response at GL is likely associated with the reversal of hydraulic gradient between NP202 and NP203, and the smaller increase in water levels at NP203 as GL is closer to this station.

6.0 Discussion and Conclusion

Comparisons Between Hurricanes: The maximum mean wind speeds at GL and SL during Hurricane Wilma (31 m/s) were almost twice that during Katrina (ca. 17 m/s), and, accordingly, the water flow was much more strongly affected in magnitude and direction by Hurricane Wilma than by Hurricane Katrina. Thus, critical wind strengths appeared to exist, above which the water flow was altered, with stronger winds causing greater impacts on water flow. Moreover, the characteristics of water flow after the two hurricanes were significantly different. Hurricane Katrina with relatively low strength did not cause a large sustained alternation of the mean speed (10 to 50%) and mean direction (up to 2^o) at GL and SL (Table 1). However, after Hurricane Wilma, a stronger hurricane, the mean magnitude of water flow sustained after the event at GL was decreased by a half, but the magnitude at SL doubled. Overall the impacts of the hurricanes on flow speed were larger at SL as compared to GL. The differences observed between the two stations is likely due to depth effects, as SL is located at the edge of Shark River Slough in shallower water (about 30 cm), whereas GL is located in deeper water (between 84 and 87 cm) within the center of the slough.

Short Term Alterations in Flow: The hurricanes, in particular the larger one, Wilma, caused both short term (during hurricane conditions) and longer term (days after the storm) alterations in flow characteristics. The short term alterations coincided with high wind speeds, localized variations in rainfall, changes in water depth, and changes in hydraulic gradients (as observed from figures 3 and 5). He et al. (2010) found that hydraulic gradient, water depth, and vegetative resistance could explain about 70% of the variation in water flow within these same sites during non-hurricane conditions. The short term variations observed during hurricane conditions were consistent with the significance of hydraulic gradients and water depths, as identified by He et al. (2010).

The observations from the current study are consistent with those from Harvey et al. (2009) as observed during Hurricane Wilma at a surface water monitoring site located about 20 km to the north of our sites. Maximum wind speeds observed by Harvey et al. (2009) were at about ½ (14 m/s) those observed in the current study. Flow responded in our study in a similar fashion as documented by Harvey et al. (2009) with maximum velocities of 5 cm/s, as compared to a maximum at SL of 5 cm/s and at GL of 3 cm/s, during this same storm. In the wet season of 2005, the mean water velocities at SL and GL were 1.90 cm/s and 1.29 cm/s, respectively (He et al., 2010). Obviously, the maximum velocities at the two sites during Hurricane Wilma were greater than mean levels. Bazante et al. (2006) proposed 7 cm/s to be a critical water speed for re-suspension of the particles (3.3 μm) in the Shark River Slough. Larsen et al. (2009) measured a critical bed shear stress of 0.01 Pa to re-suspend the flocculated particles (100 μm) collected from the Everglades, corresponding to a critical water speed of 2.5 cm/s. In the current study, the maximum measured water speeds during Hurricane Wilma were over or close to the estimated critical rates, suggesting that at least a part of the particles in the slough were re-suspended. Of note, such re-suspension rarely occurs in the slough during non-hurricane conditions. Thus hurricanes have the potential to resuspend particulates within this wetland, a process required for the formation of a ridge and slough topography, an important component of Everglades restoration.

Harvey et al. (2009) reported a large spike in water level during the hurricane (up to 22 cm above the pre-hurricane level), and attributed the changes in water speed and direction to an inverse barometric effect. Our interpretation of the cause of the shift in flow speed and direction is somewhat different, as we attribute the changes to the combined effects of wind shear, differential rainfall, shift in hydraulic gradients, and changes in the structure of submerged vegetation. We recognize that barometric effects can also serve as a factor and we cannot disregard this effect as contributing to the changes in flow that were observed.

Another factor that played an important role during hurricane conditions was wind speed. Wind did not notably affect the water flow in the study wetland at depth for wind speeds less than 10 m/s, as shown in Figures 2 and 4. During hurricane conditions wind impacts were observed with an obvious alteration of water flow direction which followed the direction of the wind (as observed in figure 4). During Hurricane Wilma, the clockwise rotation of water flow direction followed the clockwise rotation of wind direction. The wind can cause a deviation from the preferential flow path through forces applied at the surface of the water plus forces placed on vegetation that is emerging above the surface of the water. The emergent vegetation would likely bend in the direction of the wind perhaps facilitating the shift in water flow direction.

Moreover local vegetation likely played another role, by minimizing the extreme changes in velocity during peak wind conditions. For open water, the impacts of hurricanes are greater. During Hurricane Frances and Jeanne in 2004, greater current velocities and large surface seiches occurred in Lake Okeechobee (a shallow lake, with the mean depth of 3 m, located in Florida, USA) (James et al., 2008). Even, the slope of the water surface reversed itself as wind direction changed during the both hurricanes (Chimney, 2005). In 1999, when the Hurricane Irene passed over the Lake Okeechobee, the local wind speed was increased to 25 m/s, causing a great increase in the surface water speed from 5 cm/s to 100 cm/s (Haven et al., 2001). In contrast, our maximum water speed at SL was 5 cm/s during Hurricane Wilma and the maximum wind speeds observed in our study was 31 m/s, greater than the speeds observed over Lake Okeechobee during Hurricane Irene. The dissimilarity in the water velocity increase caused by the hurricanes over open water such as Lake Okeechobee versus highly vegetated wetlands is likely due to the emergent vegetation shielding the wetland surface from strong wind conditions.

Long Term Alterations in Flow: One would expect that once the water levels receded and hydraulic gradients returned back to their normal state, flow would resume as before; however, our observations suggest a longer time-scale for changes in flow (on the order of days). For example a shift in water flow direction at SL was observed after Hurricane Wilma. Before Hurricane Wilma the flow direction at SL considerably varied from northwards to southwards (standard deviation of direction = 94^o); after the hurricane the flow (mean flow direction $215\,^o$) was characterized by a more constant average flow direction (standard deviation of direction = 11^o). We hypothesize that these longer time-scale changes are likely due to the effects of the hurricanes on vegetation structure.

Vegetative structure is considered to be a significant factor controlling water velocity (Harvey et al., 2009). Typically, the flow velocity increases with the fourth power of stem diameter, and decreases in direct proportion with the increasing frontal area of vegetation. Under a strong storm, destruction in vegetative structure is typically significant. Doyle et al. (2009) correlated observed plantfall and destruction patterns with wind speed and direction in the Everglades using a hurricane simulation model. They found mangrove forests within the storm's eyepath and in the right-side (forewind) quadrants suffered whole or partial blowdowns. Smith et al. (2009) also studied cumulative impacts of hurricanes on Florida wetland mangrove ecosystem, and reported immediate effects of the hurricanes including changes to stem size-frequency distributions and to species relative abundance and density. Immediately after Hurricane Wilma, our reconnaissance of the area showed *Cladium jamaicense* (sawgrass) stands blown down along with underwater vegetation pushed up against these stands, suggesting that the vegetation was blown into water under the strong winds. These changes in vegetative structure might explain some of the changes in velocity that were observed after hurricane conditions.

Summary and Recommendations: In summary, results from the current study suggest that baseline wind conditions (< 10 m/s) were not a major factor influencing water flow at depth. Extreme wind events, such as those during hurricanes, can influence water flow with larger hurricane events causing larger impacts. During the brief hurricane period (on the order of an hour) flow speed and direction can be radically altered due to the combined alterations in wind speed, water depth, rainfall variations, hydraulic gradients, and possibly barometric effects; emergent vegetation also likely plays a role during hurricane conditions by shielding the water surface from wind shear but also influencing underwater vegetation structure through the wind's influence on the movement of emergent vegetation. The longer lasting effects of hurricanes (time scale of a few days) resulted in altered flow speeds that changed by 50% or less with flow directions very close to those observed during non-hurricane conditions. These longer lasting changes in flow characteristics, although not extreme for the study watershed, may be due to the redistribution of emergent vegetation causing an alteration in flow resistance and preferential flow paths.

Our observations in this study were relatively qualitative in nature as quantitative relationships between the various factors could not be established. Future work is highly recommended to disaggregate the different factors that influence water flow during hurricane conditions through improvements in wind measurements (including the installation of wind meters immediately above the point of water flow measurements). Wind measurements and water velocity measurements should also be taken at various points in the vertical to evaluate the distribution of wind as the emergent vegetation is approached and also to evaluate the impact of this wind with water depth.

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Table 1 Mean values of variables measured by the fixed ADVs before and after Hurricanes Katrina and Wilma. The time periods corresponded to 4 days before the winds reached 10 m/s and 4 days after the winds receded from 10 m/s. For Hurricane Katrina the "before" data corresponded to 0:00 on 21 Aug. to 23:45 on 24 Aug. 2005; the "after" data corresponded to 0:00 on 27 Aug. to 23:45 on 30 Aug. 2005. For Hurricane Wilma the "before" data corresponded to 0:00 on 19 Oct. to 23:45 on 22 Oct. 2005; the "after" data corresponded to 0:00 on 25 Oct. 25 to 23:45 on 28 Oct. 2005.

Parameters	GL		SL	
	Before	After	Before	After
Hurricane Katrina				
Mean horizontal water speed (cm/s)	1.30	1.69	1.89	2.07
Standard deviation	0.29	0.26	0.21	0.17
Direction of horizontal flow, degrees from magnetic north	209	209	188	186
Standard deviation	16	8	9	3
Hurricane Wilma				
Mean horizontal water speed (cm/s)	1.80	0.90	0.59	1.32
Standard deviation	0.32	0.22	0.54	0.63
Direction of horizontal flow, degrees from magnetic north	214	211	154	215
Standard deviation	6	6	94	11

Figure 1 Hurricane tracks and locations of fixed Acoustical Doppler Velocity meters (ADV) and wind measurement stations. These locations include the fixed ADVs (GL and SL) and two closest wind measurement stations (TE and CH). Inset figure shows locations of gates and water level stations maintained by Everglades National Park.

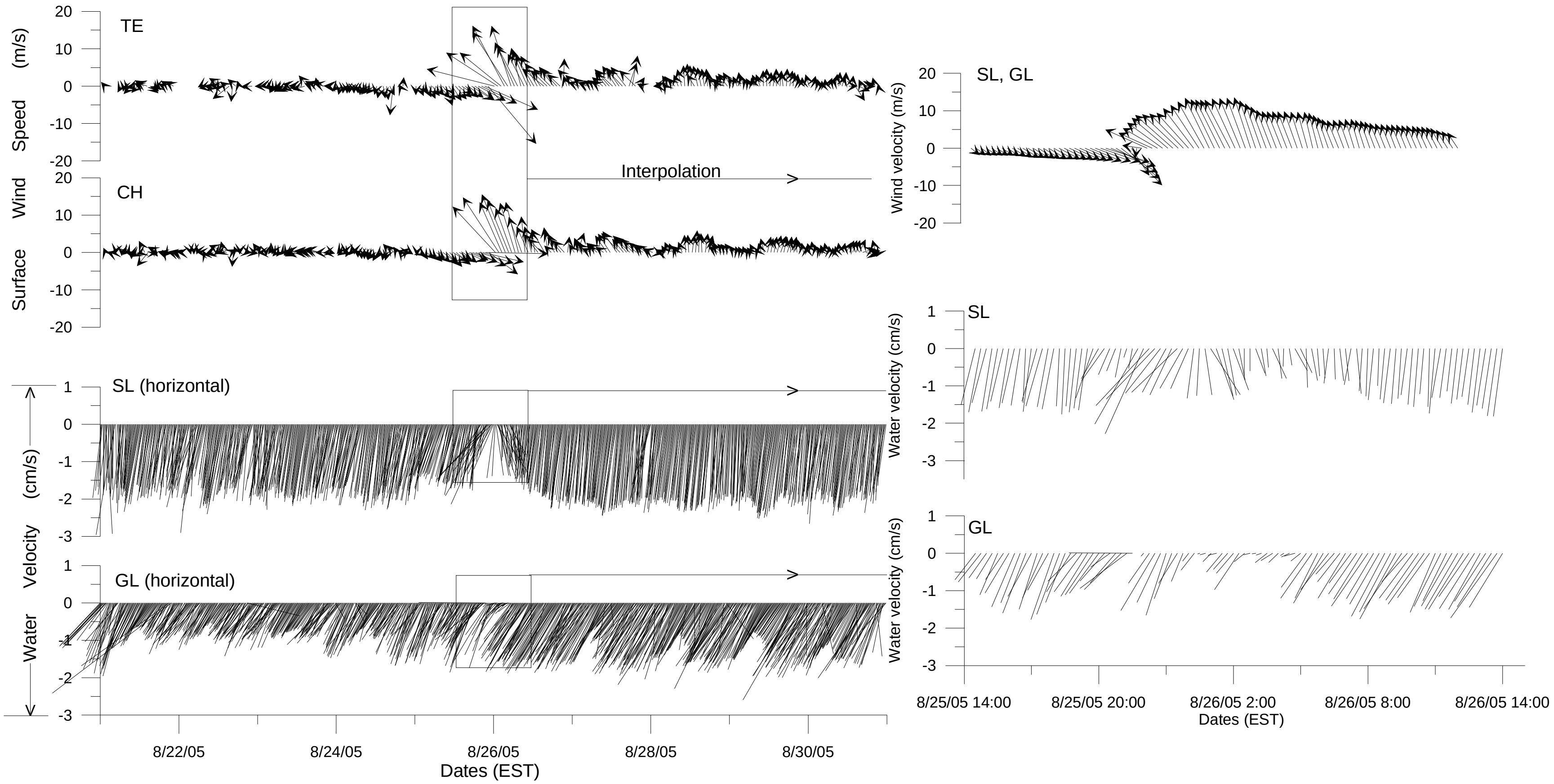

Figure 2 Water flow vs. wind speed during Hurricane Katrina. Top two plots correspond to wind speed and direction at the TE and CH stations. Inset plot to the right corresponds to interpolated wind speed and direction at SL and GL. Bottom two plots indicate horizontal water speed and direction at SL and GL, and inset two plots to the right correspond to horizontal water flow during the Hurricane Katrina period, respectively. Vertical scale on vector plots provides wind or water speed magnitude corresponding to the full length of the vector. Up direction indicates magnetic north.

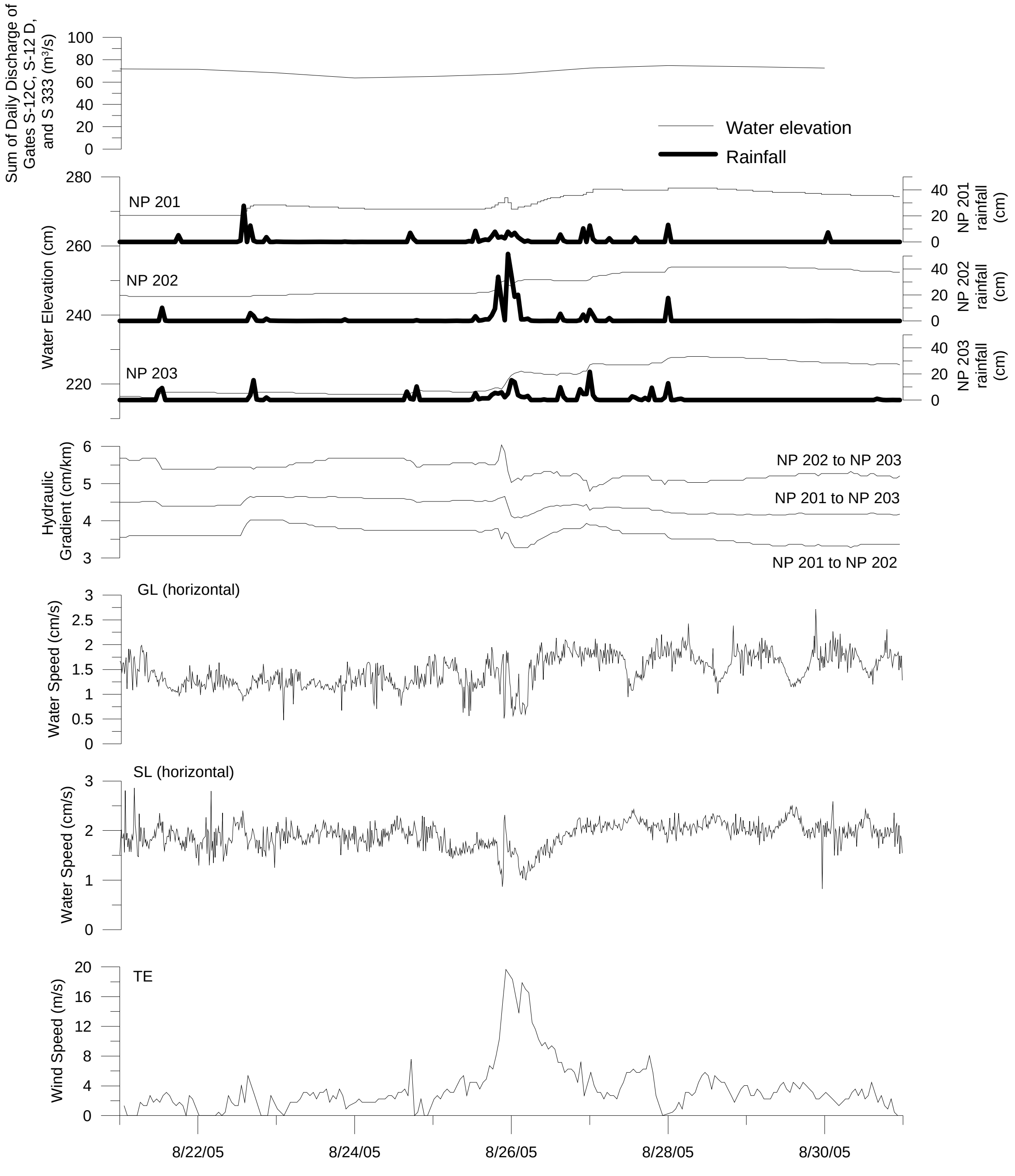

Figure 3 Upstream gate discharge, water elevations (NP 201, NP 202, and NP 203), hydraulic gradients, versus horizontal flow (GL and SL) and wind speed during Hurricane Katrina

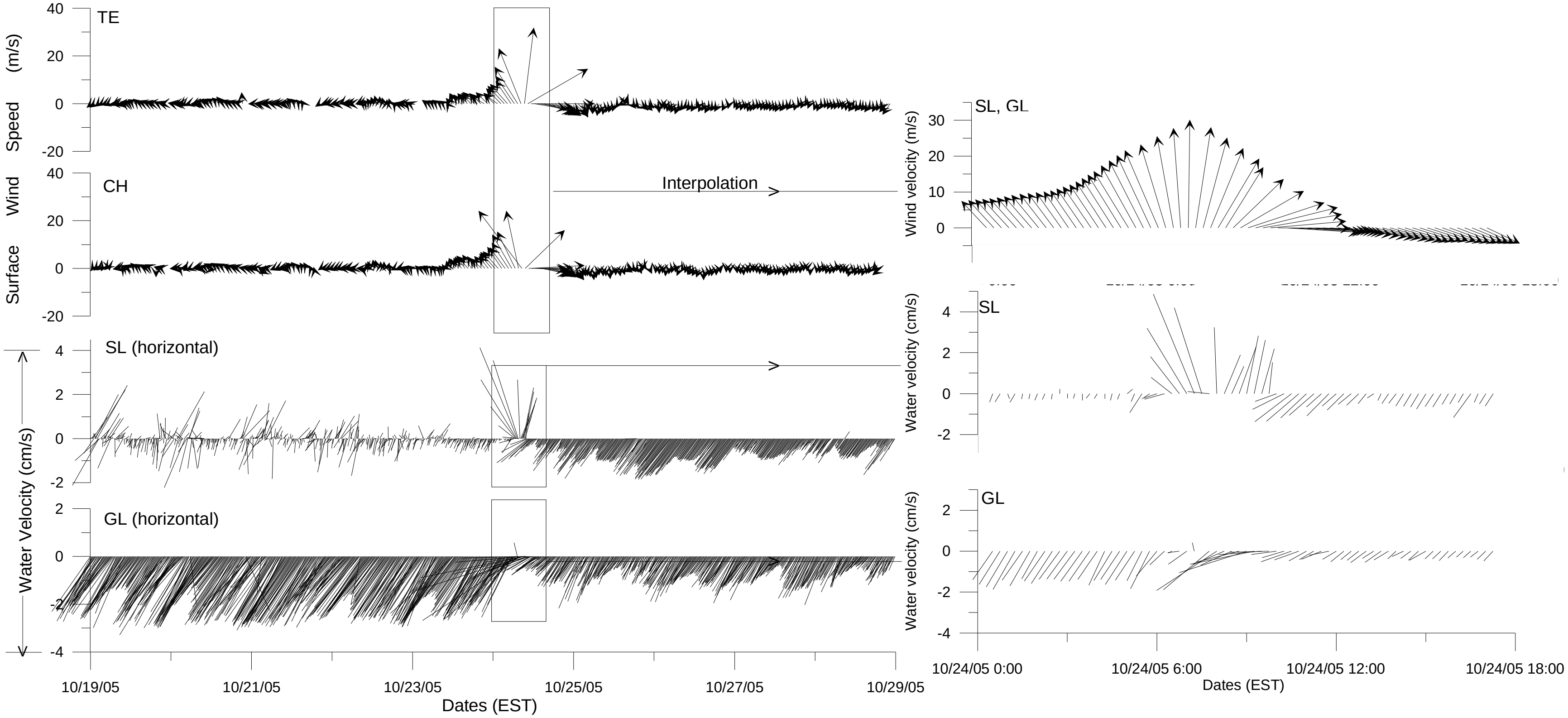

Figure 4 Water flow vs. wind speed during Hurricane Wilma. Top two plots correspond to wind speed and direction at the TE and CH stations. Inset plot to the right corresponds to interpolated wind speed and direction at SL and GL. Bottom two plots indicate horizontal water speed and direction at SL and GL, and inset two plots to the right correspond to horizontal water flow during the Hurricane Wilma period, respectively. Vertical scale on vector plots provides wind or water speed magnitude corresponding to the full length of the vector. Up direction indicates magnetic north.

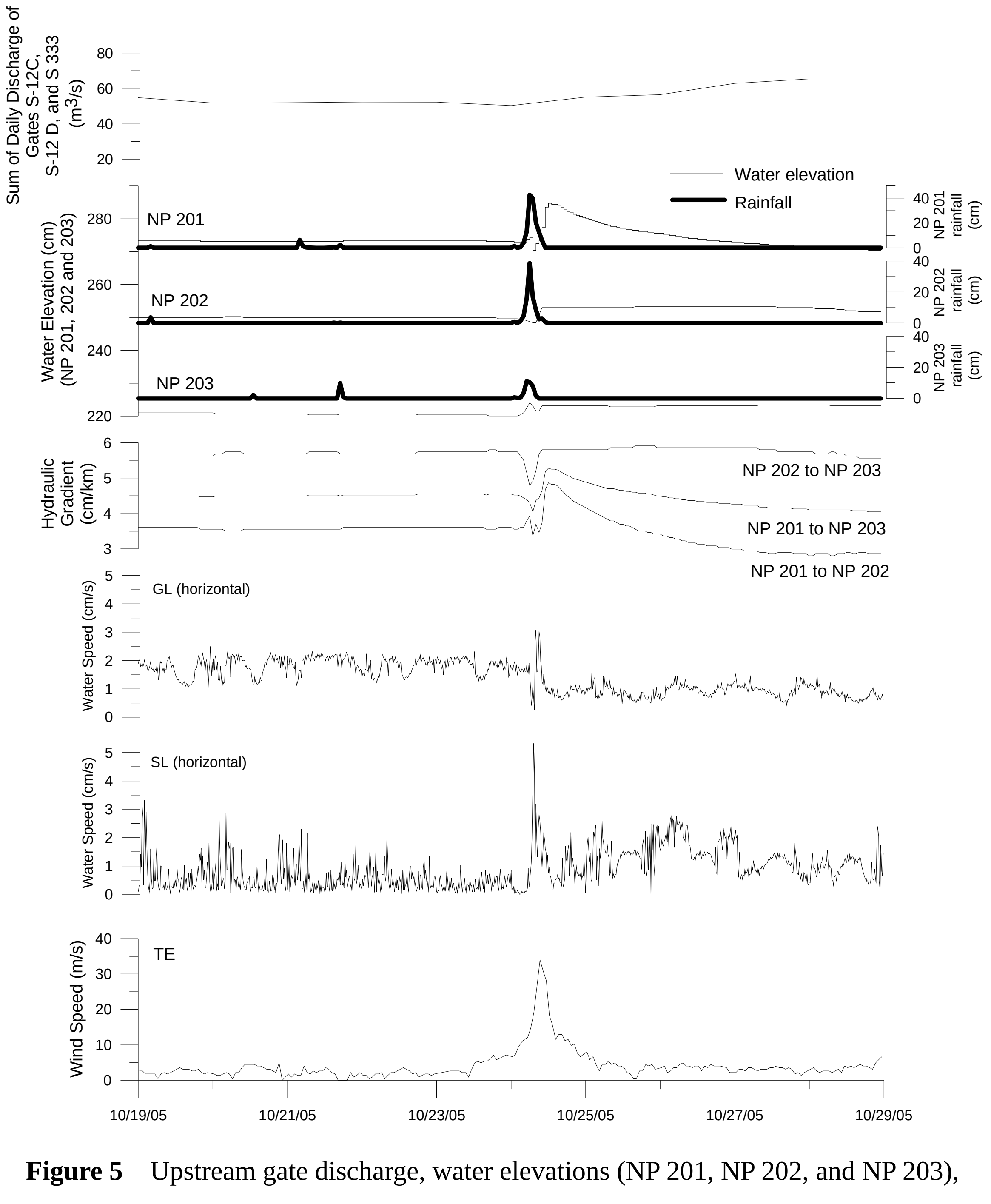

Figure 5 Upstream gate discharge, water elevations (NP 201, NP 202, and NP 203), hydraulic gradients, versus horizontal flow (GL and SL) and wind speed during Hurricane Wilma.