Appendix 2-2: Water Year 2013 Hurricane Season

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HYDROLOGIC IMPACT OF TROPICAL STORMS DEBBY AND ISAAC AND HURRICANE SANDY ON SOUTH FLORIDA

INTRODUCTION

Documenting hydrologic events such as hurricanes, storms, and droughts provides supporting information for water management decision making. According to Chaston (1996), hurricanes transport 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' voyage to the New World in the 1490s. There were 114 hurricanes and tropical storms affecting peninsular Florida between 1871 and 1996, with about half as hurricanes (Attaway, 1999). The frequency of occurrence is about one named storm every year and a hurricane every two to three years. As the area of interest decreases, the frequency of being affected by a hurricane decreases.

The general area of the South Florida Water Management District (District or SFWMD) has been affected by about 56 hurricanes, 42 tropical storms, and 9 tropical cyclones (hurricanes or tropical storms) from 1871–2012 (Abtew and Huebner, 2000; Abtew et al., 2005). Between 1900 and 1996, Southeast Florida had 26 hurricanes directly hit (Herbert et al., 1997) and 16 additional hurricanes since 1997. Southeast Florida had impacts from Hurricane George and Tropical Storm Mitch in 1998; Hurricane Irene in1999; Hurricane Gabrielle in 2001; Hurricanes Charley, Frances, Jeanne, and Ivan (as extra-tropical storm) in 2004; Hurricanes Dennis, Katrina, Rita, and Wilma in 2005; Tropical Storm Ernesto in 2006; Tropical Storm Barry in 2007; Tropical Storm Fay in 2008; Tropical Storm Bonnie in 2010; and Tropical Storms Debby and Isaac and Hurricane Sandy in 2012. Several storms passed close to South Florida and contributed some rainfall to the region. Tropical systems are a critical part of South Florida hydro-ecology, contributing a substantial amount of rainfall at certain locations (Walther and Abtew, 2006). Considering the District area, about 7 percent of regional rainfall is from hurricanes and tropical storms (Brandes, 1981; Geoff Shaughessy, personal communication, 2013).

Characteristic of rainfall from tropical storms, the spatial coverage is large and intensity is high, usually creating flooding as the drainage system capacity is overcome by the high volume of runoff. In recent years, Hurricane Irene in 1999 and Tropical Storm Isaac in 2012 contributed relatively high rainfall and created wide-scale flooding. The temporal distribution of tropical storms is shown in **Figure 1**. The highest frequency of occurrence is between the last weeks of August and September. The Water Year (WY) 2013 hurricane season (June–November 2012) had 19 named storms. This was the third consecutive year that produced 19 storms. 2011 had eighteen named and one unnamed storm. In 2012, two storms, Tropical Storms Alberto (May 19–22) and Beryl (May 26–30), occurred in May, before the official season started. During the season, two storms that contributed a significant rainfall amount to the District area were Tropical Storm Debby (June 22–27) and Tropical Storm Isaac (August 24–28). Hurricane Sandy (October 24–27) contributed some rainfall, 0.83 inches over the District, with Broward and Miami-Dade rainfall areas receiving close to two inches.

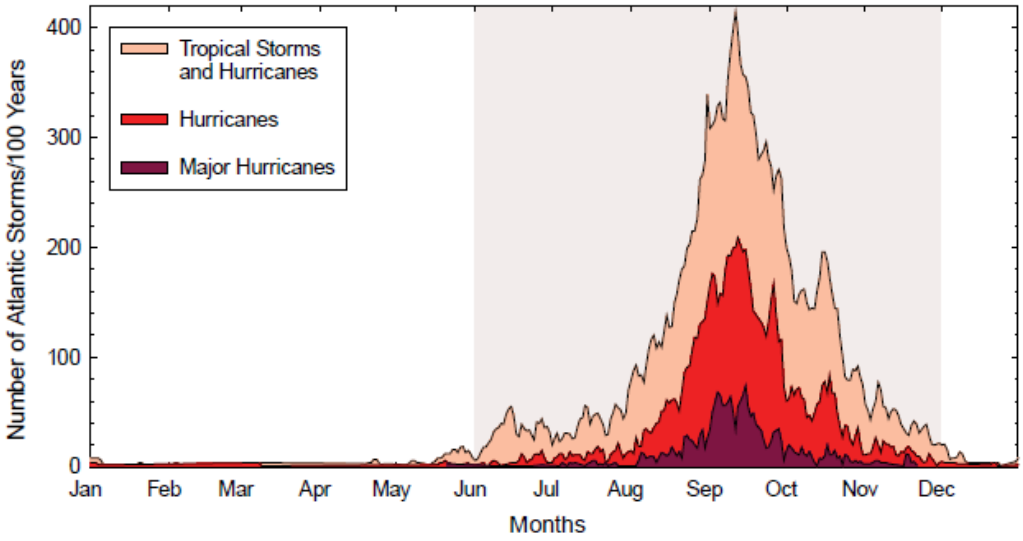

Figure 1. Distribution of North Atlantic tropical storms from 1906–2006. (Data source: http://weather.unisys.com/hurricane/atlantic/index.html, accessed on November 15, 2007).

TROPICAL STORM DEBBY

The first tropical system that contributed significant rainfall to the District area in WY2013 was Tropical Storm Debby (June 22–27, 2012). Tropical Storm Debby formed in the eastern Gulf of Mexico and crossed to the Atlantic (**Figure 2**) after drenching North Florida with as much as 24 inches of rainfall and causing flooding. It contributed a significant amount of rainfall to the District area to the south. The District received an average of 3 inches of rainfall associated with Tropical Storm Debby. The Upper Kissimmee rainfall area received 5.23 inches (**Table 1a**) contributing to a wet June (12.18 inches). The runoff generated was limited, as June followed a preceding dry season drought. Sites in Palm Beach and Upper Kissimmee received over 5 inches of rainfall in a 24-hour period (**Table 1b**). **Figure 3** depicts rainfall received by each rainfall area from Tropical Storm Debby.

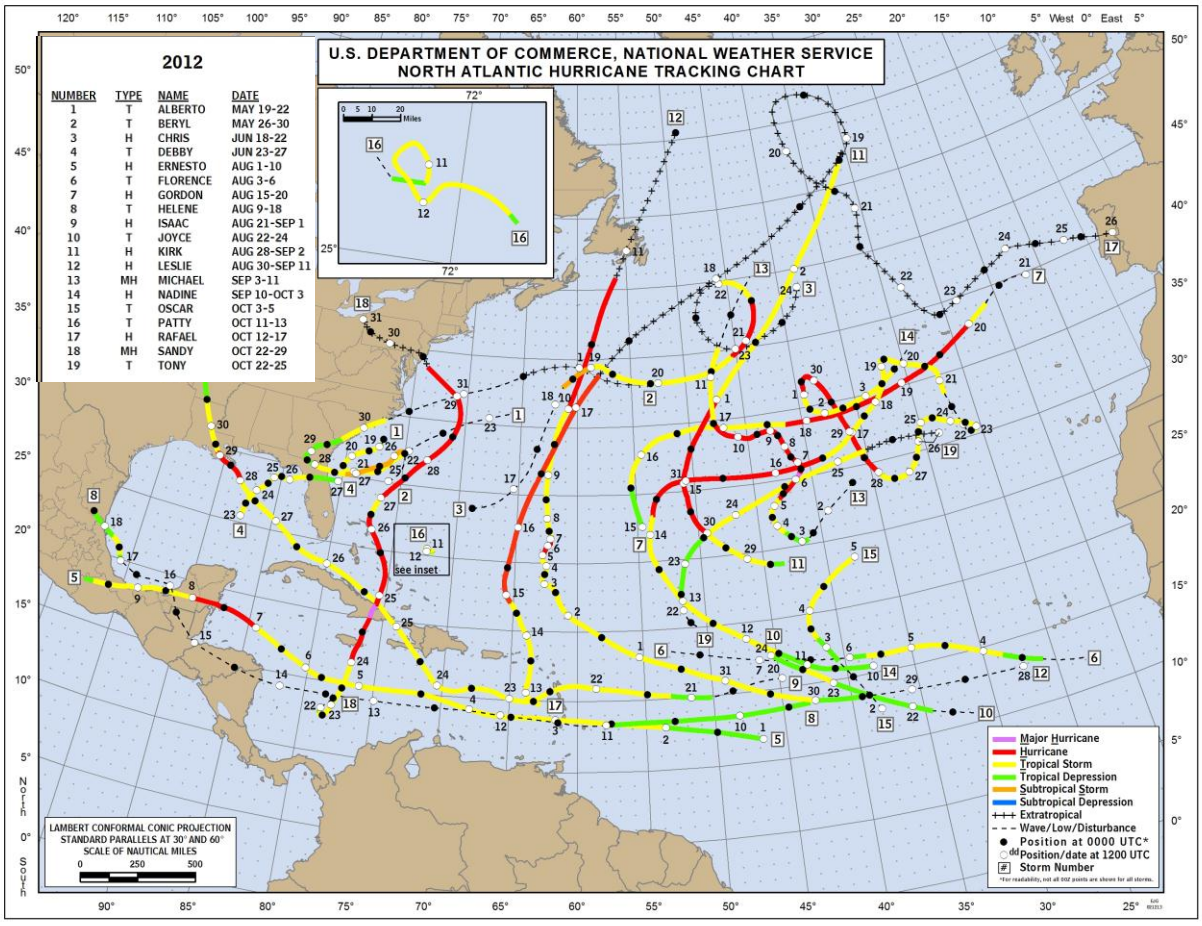

Figure 2. Water Year (WY) 2013 tropical storms track (http://www.nhc.noaa.gov/2012atlan.shtml, accessed on December 3, 2012).

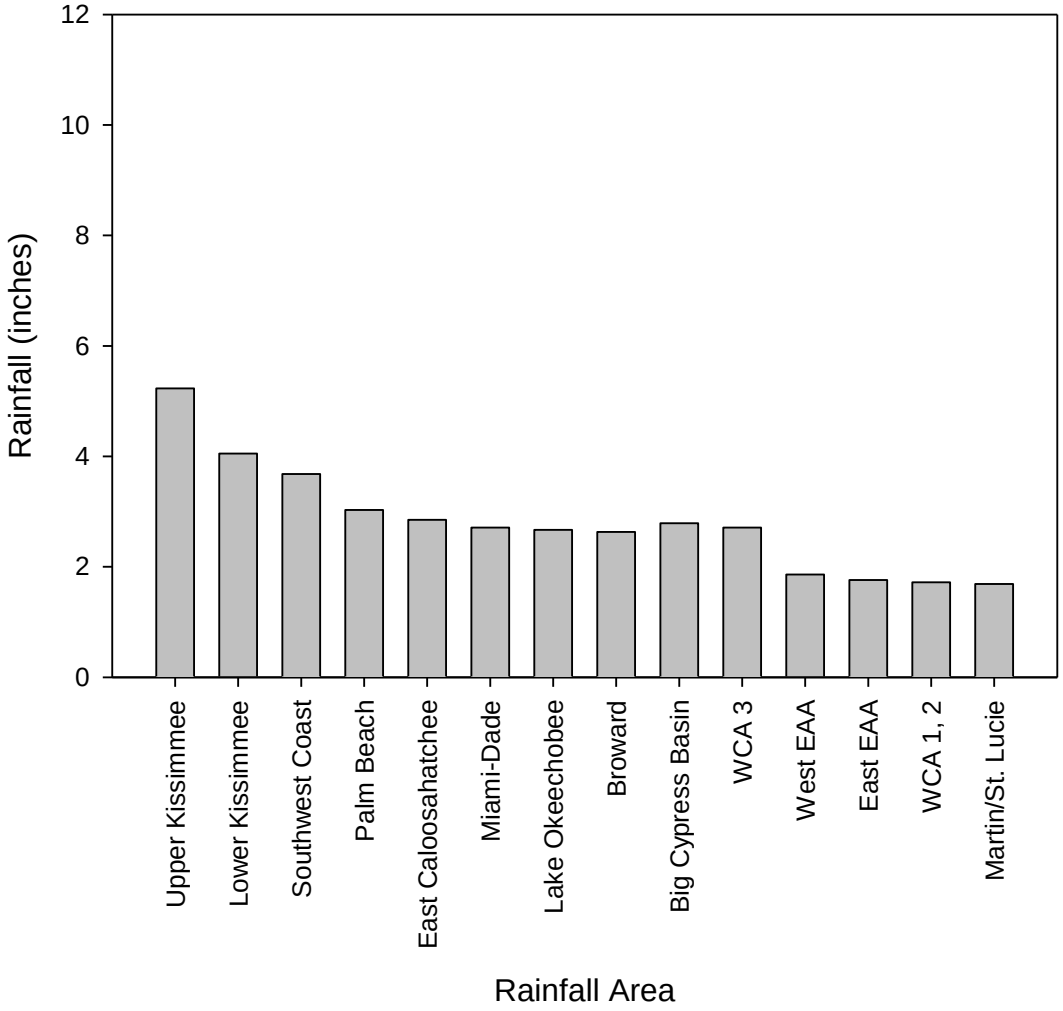

Figure 3. Rainfall from Tropical Storm Debby over each rainfall area (June 22-27, 2012).

Table 1a. Rainfall (inches) from Tropical Storm Debby over each rainfall area and District average.

Date		Upper Kissimmee	Lower Kissimmee	Lake Okeechobee	East Everglades Agricultural Area	West Everglades Agricultural Area	Water Conserv-ation Areas 1,2	Water Conserva-tion Area 3	Martin/St Lucie	Palm Beach	Broward	Miami-Dade	East Caloosah-atchee	Big Cypress Preserve	Southwest Coast	District
2012	22-Jun	0.21	0.49	0.26	0.19	0.25	0.04	0.25	0.04	0.05	0.11	0.14	0.36	0.51	0.26	0.25
2012	23-Jun	0.44	0.57	0.38	0.84	0.65	0.6	1.66	0.6	1.09	0.79	1.6	0.25	1.33	0.9	0.82
2012	24-Jun	0.12	0.12	0.11	0.35	0.32	0.63	0.65	0.43	0.7	1.11	0.66	0.19	0.58	0.75	0.43
2012	25-Jun	2.74	1.73	1.2	0.35	0.22	0.42	0.1	0.38	1.15	0.43	0.06	1.11	0.18	1.07	0.93
2012	26-Jun	1.09	0.45	0.39	0.02	0.34	0	0	0.15	0	0	0	0.39	0.09	0.34	0.29
2012	27-Jun	0.63	0.69	0.33	0.01	0.08	0.03	0.05	0.09	0.04	0.19	0.25	0.55	0.1	0.36	0.28
Total rainfall (in)		**5.23**	**4.05**	**2.67**	**1.76**	**1.86**	**1.72**	**2.71**	**1.69**	**3.03**	**2.63**	**2.71**	**2.85**	**2.79**	**3.68**	**3**

Table 1b. One-day maximum rainfall from Tropical Storm Debby at a site in each rainfall area.

Year 2012	Upper Kissimmee	Lower Kissimmee	Lake Okeechobee	East Everglades Agricultural Area	West Everglades Agricultural Area	Water Conservation Areas 1,2	Water Conservation Area 3	Martin/St Lucie	Palm Beach	Broward	Miami-Dade	East Caloosah-atchee	Big Cypress Preserve	Southwest Coast
Date of Max	**25-Jun**	**25-Jun**	**25-Jun**	**23-Jun**	**23-Jun**	**23-Jun**	**23-Jun**	**23-Jun**	**25-Jun**	**25-Jun**	**23-Jun**	**25-Jun**	**23-Jun**	**25-Jun**
Gage Name	AVALON	ARCHBOLD	ARCHBOLD	DUP3	G3ANW	S-34	G3AS33	DUP3	PBIA	G-57	NWSFIU	LEHIGH	G3AS33	FTMYERS_PL
Max Rainfall (in)	**5.33**	**4.51**	**4.51**	**3.56**	**2.66**	**1.76**	**4.24**	**3.56**	**5.27**	**2.35**	**3.28**	**2.29**	**4.24**	**2.53**

TROPICAL STORM ISAAC

Following Tropical Storm Debby, Tropical Storm Isaac largely impacted South Florida from August 24–28, 2012. Although the storm passed far to the west of South Florida (**Figure 2**), outer band chains of rainfall concentrated on the eastern coast resulting in record rainfall amounts especially in the C-51 and L-8 basins (**Figure 4**). Normally, as a storm moves away from a region, the impact decreases, but not in this case. The hydrologic impact of Tropical Storm Isaac on the District area was severe. The extreme rainfall from the storm resulted in wide-scale flooding and erosion of water-ways. In this brief report, the spatial distribution and the magnitude of rainfall from the tropical storm are included along with an estimated frequency of occurrence. Water level rise at key water management system locations and surface water flows through major structures are also presented. Also, rainfall from Tropical Storm Isaac is compared to previous storms to show the extremity of that event.

In Palm Beach County, flooding occurred in many areas including Indian Trails Improvement District, City of Green Acres, the Village of Wellington, Royal Palm Beach, Boynton Beach, and Jupiter farms. Areas such as Deer Run, the Acreage, and Loxahatchee were heavily flooded for several days. Many other neighboring streets in Palm Beach County were flooded, limiting travel for local residents. In St. Lucie County, flooding in West St. Lucie and erosion of infrastructure were reported (TCPalm, August 28, 2012). In Broward County, there was concern from high rainfall events in the areas of Lauderhill, Margate, Sunrise, and Tamarac, with heavy flooding reported in Pembroke Pines and Lauderhill (The Miami Herald, August 28, 2012). In Okeechobee County, the City of Okeechobee had also reports of flooding. In Miami-Dade County, high water conditions were reported in Homestead. In general, areas of primary concern for flooding were the C-51 basin, C-17, C-18, L-8 basin, areas north of Lake Okeechobee, C-13 and C-14.

Tropical Storm Isaac brought lots of rainfall at several locations in South Florida. The storm contributed an areal average rainfall of 5.74 inches over the District area. Rainfall areas with the most rainfall were Palm Beach (9.98 inches), Water Conservation Areas 1 and 2 (9.41 inches), Martin/St. Lucie (8.42 inches), Broward (7.82 inches), East Everglades Agricultural Area (7.11 inches), Lake Okeechobee (6.58 inches), Lower Kissimmee (6.35 inches), and Miami-Dade (5.84 inches), as shown in **Table 2a** and **Figure 5**. **Table 2b** shows sites with 5-day and 24-hour maximum rainfall in each rainfall area from the District operations rainfall gauges monitoring network. **Figure 6** depicts the spatial variation of rainfall from the storm, showing the highest intensity of rainfall in flooded areas such as the C-51 basin. From this monitoring network, the highest rainfall was at site C-18 (12.99 inches). However, sites from other monitoring network and radar rainfall observations recorded higher amount of rainfall at various locations. **Table 3** depicts extreme rainfall observations and return periods. Rainfall observations with 100-year return periods have been recorded at sites in the C-51 basin for 3-day and 5-day periods and the entire month of August, which resulted in substantial flooding. **Figures 7a** and **b** show typical flooding in neighborhoods where detention pond and local canals overflowed into roads and yards, leaving mostly the elevated houses dry. **Figure 7c** depicts flooding in less developed areas of western Palm Beach County along the L-8 Canal, with the L-8 Reservoir in the background. There were some cases where houses were flooded, although this was not widespread.

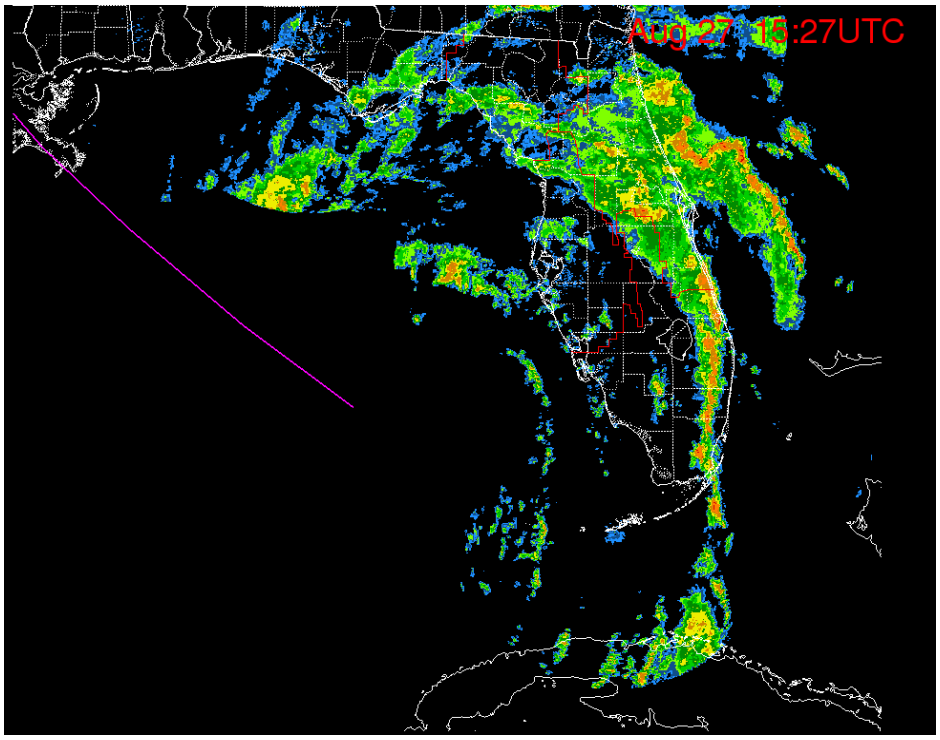

Figure 4. Band of rainfall over eastern South Florida, farther out from the path of Tropical Storm Isaac.

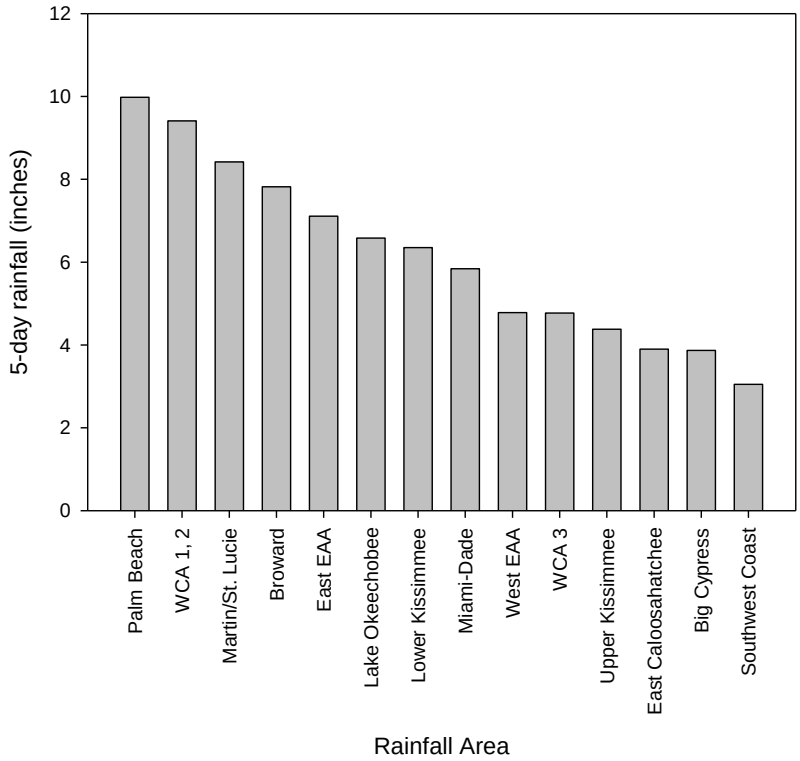

Figure 5. Rainfall from Tropical Storm Isaac over each rainfall area (August 24-28, 2012).

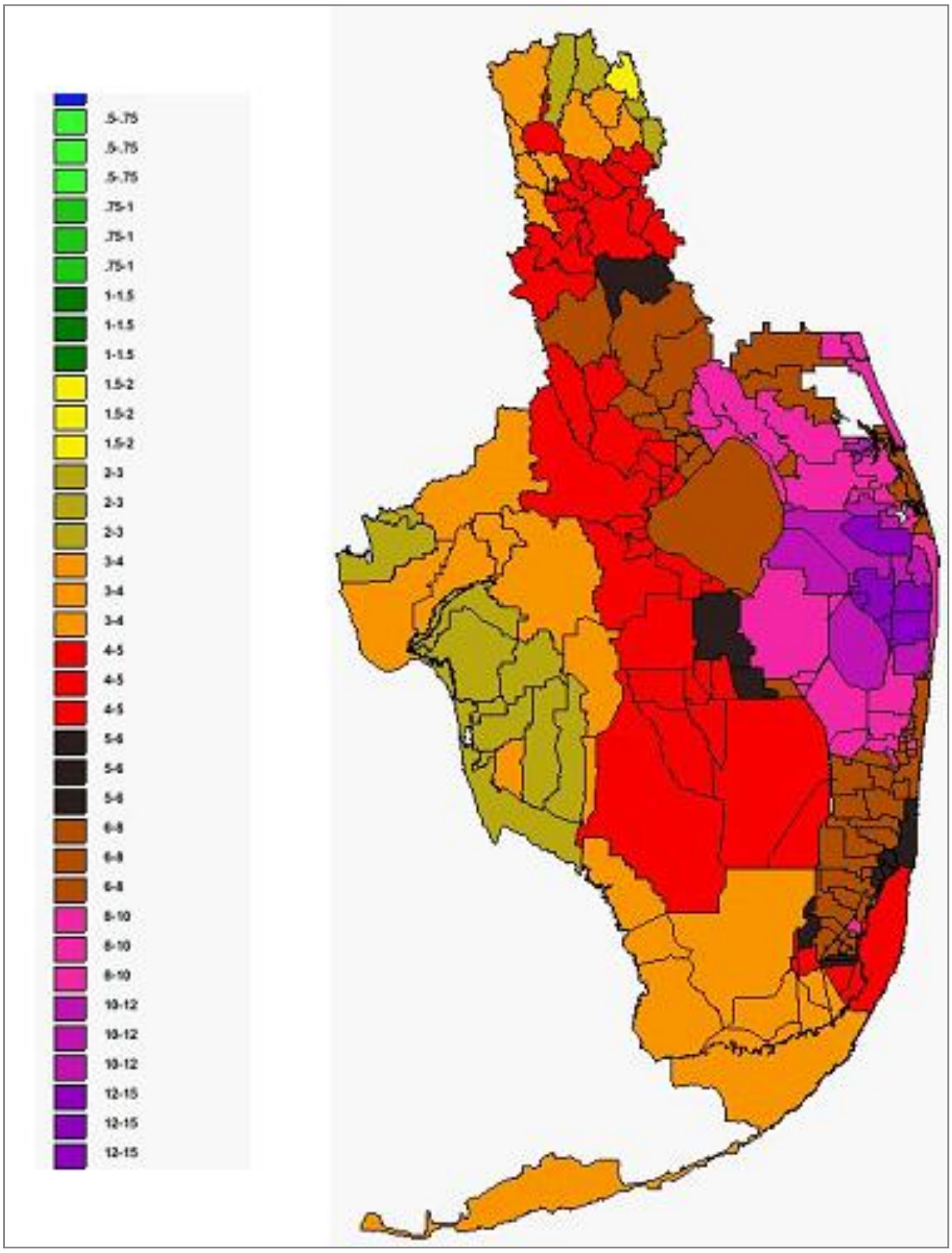

Figure 6. Spatial distribution of rainfall (inches) from Tropical Storm Isaac (August 24–28, 2012).

Table 2a. Rainfall (inches) from Tropical Storm Isaac over each rainfall area and District averages (operation rain gauges are rainfall records from 7:00 am of previous day to 7:00 am of following day).

Date		Upper Kissimmee	Lower Kissimmee	Lake Okeechobee	East Everglades Agricultural Area	West Everglades Agricultural Area	Water Conservation Areas 1,2	Water Conservation Area 3	Martin/St Lucie	Palm Beach	Broward	Miami-Dade	East Caloosaha-tchee	Big Cypress Preserve	Southwest Coast	District
2012	25-Aug	0.1	0.12	0.12	0.16	0.18	0.42	0.22	0.79	1.14	0.49	0.76	0.01	0.13	0.12	0.29
2012	26-Aug	0.01	0	0.06	0.12	0.18	0.35	0.85	0.31	0.39	0.6	1.32	0	0.46	0.04	0.28
2012	27-Aug	2.41	4.78	5.24	5.78	4.03	5.86	2.93	4.31	5.59	4.59	2.66	3.6	3.08	2.36	3.89
2012	28-Aug	1.39	0.39	0.55	0.51	0.11	2.33	0.46	2.53	2.15	2.02	1.08	0.2	0.1	0.4	0.88
2012	29-Aug	0.47	1.06	0.61	0.54	0.28	0.45	0.31	0.48	0.71	0.12	0.02	0.09	0.1	0.13	0.4
Total rainfall (in)		**4.38**	**6.35**	**6.58**	**7.11**	**4.78**	**9.41**	**4.77**	**8.42**	**9.98**	**7.82**	**5.84**	**3.9**	**3.87**	**3.05**	**5.74**

Table 2b. 24-hour and 5-day maximum rainfall from Tropical Storm Isaac at a site in each rainfall area.

Rainfall Area	Station name	5-day maximum at a site (inches)	Station name	24-Hour maximum at a site (inches)
Upper Kissimmee	EXOT	7.87	LOTELA	5.54
Lower Kissimmee	S-127	9.88	PC61	8.37
Lake Okeechobee	S-352	11.67	S-352	8.35
East Everglades Agricultural Area	S-352	11.67	Belleglade,S-352	8.35
West Everglades Agricultural Area	ALICO	5.72	ALICO	4.54
Water Conservation Areas 1,2	LXWS	12.04	G331D	6.85
Water Conservation Area 3	S-7	7.07	S-7	4.75
Martin/St Lucie	C18W	12.99	S-308	6.77
Palm Beach	C18W	12.99	S-308	6.77
Broward	S-38	10.36	S-38	6.45
Miami-Dade	HOMESTEADA	10.59	HOMESTEADARB	5.54
East Caloosahatchee	S-47B	4.99	S47B	4.7
Big Cypress Preserve	OASF1	5.55	SIXL3	4.44
Southwest Coast	BCA14	4.49	BCA14	4.06

Table 3. Extreme rainfall observations from Tropical Storm Isaac and return periods.

Site or Location	Three-day Rainfall (inches) and return period	Five-day Rainfall (inches) and return period	August 2012 Rainfall (inches) and return period
Pump Station 4 (Wellington)	14.70 (100-yr)	15.52 (100-yr)	20.27 (>>100-yr)
Structure 40 (Wellington)	14.04 (100-yr)	14.32 (100-yr)	19.54 (>>100-yr)
C-51 Basin (raindar* rainfall)	14.7 (100-yr)	N/A	N/A
S-352	11.43 (> 50-yr)	11.67 (50-yr)	14.77 (50-yr)
Structure 42 (Wellington)	10.89 (25-yr)	13.42 (100-yr)	20.37 (100-yr)
C-18W	11.16 (>10-yr)	12.99 (<25-yr)	21.92 (100-yr)
PBIA	9.7 (10-yr)	10.76 (<25-yr)	21.43 (>>100-yr)
WCA1ME	11.21 (25-yr)	11.90 (25-yr)	21.22 (100-yr)
* rain gauge adjusted radar rainfall			

Figure 7a. Flooded urban areas in the C-51 basin with detention ponds full and flooded streets during Tropical Storm Isaac (photo by the SFWMD).

Figure 7b. Typical neighborhood flooding with streets and swales flooded during Tropical Storm Isaac (photo by the SFWMD).

Figure 7c. Flooded areas in western Palm Beach County along the L-8 Canal, with the L-8 Reservoir in background, during Tropical Storm Isaac (photo by the SFWMD).

Comparison with Recent Storms

Comparing rainfall from Tropical Storm Isaac with recent storms that impacted the region provides perspective for the regional impact of the storm. Since 1998, 13 storms (tropical storms and hurricanes) have affected the District area. The comparable storm to Tropical Storm Isaac is Hurricane Irene in 1999. Hurricane Irene (October 15–16, 1999) moved through Cuba and the Florida Straits, with landfall at Flamingo in the southwest. It moved across South Florida exiting to the east near Jupiter, creating wide-scale flooding in Broward, Miami-Dade, and Palm Beach counties. **Figure 8** depicts average rainfall over Palm Beach, Broward, and Miami-Dade rainfall areas from tropical systems that impacted the region since 1998. Averaging rain over a rainfall area dampens extreme intensities at localities and sub-basins, which are key factors for flooding.

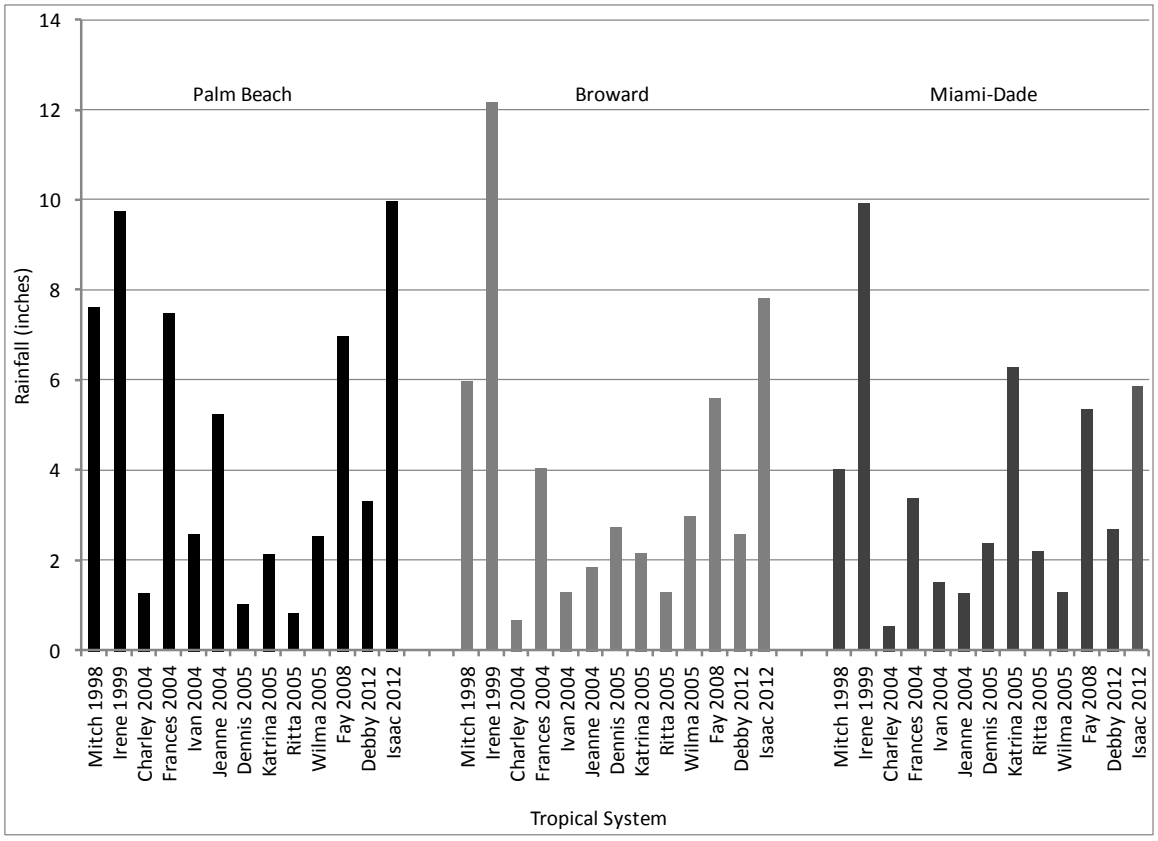

Figure 8. Average rainfall over Palm Beach, Broward, and Miami-Dade rainfall areas from tropical systems since 1998.

Water Levels and Flows

High intensity rainfall from Tropical Storm Isaac resulted in a quick rise of water levels in canals, lakes and impoundments, and surface water flow rates increased. **Figure 9a** depicts daily average water levels in the L-8 Canal at the S-5A Complex (S-5AE_H) and at Lake Okeechobee, CULV10A_H (canal side). **Figure 9b** shows daily average water levels in the West Palm Beach Canal at S-5A pump station (S-5AW_H); West Palm Beach Canal at Big Mound, between Lake Okeechobee and S-5A pump station (WPBC); and West Palm Beach Canal at Lake Okeechobee (S-352_T). Water level rose fast except in the West Palm Beach Canal at S-5A pump station (S-5AW_H) due to pumping (**Figure 10**). **Figure 9c** presents water level changes in the C-51 Canal at the west end of the canal (S-5AE_T); at SR7 west side of divide structure S-155A (S-155A_H); at east side of S-155A (S155A_T), and at canal side of S-155 outflows (S-155_H).

Due to two consecutive years of below average rainfall, Lake Okeechobee water level was relatively low at 11.68 feet National Geodetic Vertical Datum (ft NGVD) on May 1, 2012. Net inflow into the lake from May 1–August 24, 2012, was low resulting in a water level rise of only 0.71 ft in close to three months of the wet part of the year. Saturation of the watershed, filling of surface and sub-surface storage, precedes substantial runoff generation that resulted in increased inflow into the lake. However, as a result of high rainfall from Tropical Storm Isaac and other rainfall, the lake water level rose by 3 ft in one month. **Figure 11** depicts Lake Okeechobee water levels and main inflows through the S-65E structure before, during, and after Tropical Storm Isaac.

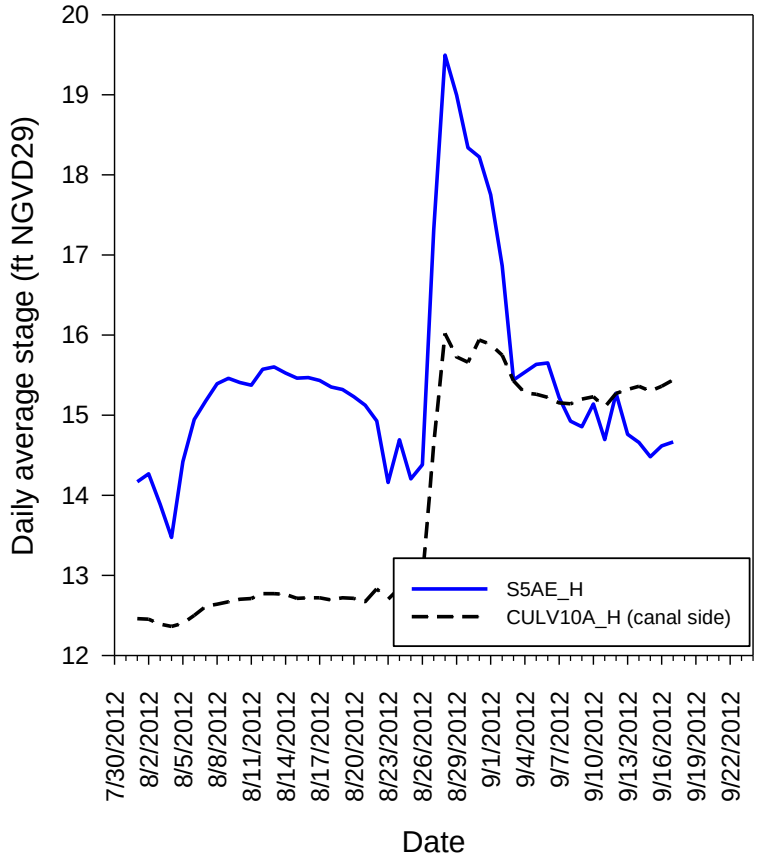

Figure 9a. Daily average water levels in L-8 Canal.

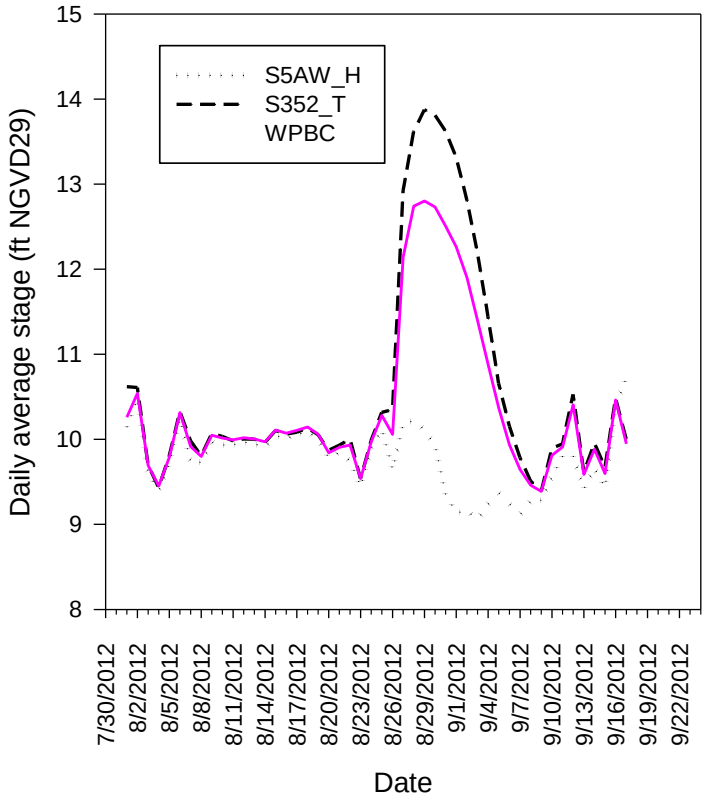

Figure 9b. Daily average water levels in the West Palm Beach Canal.

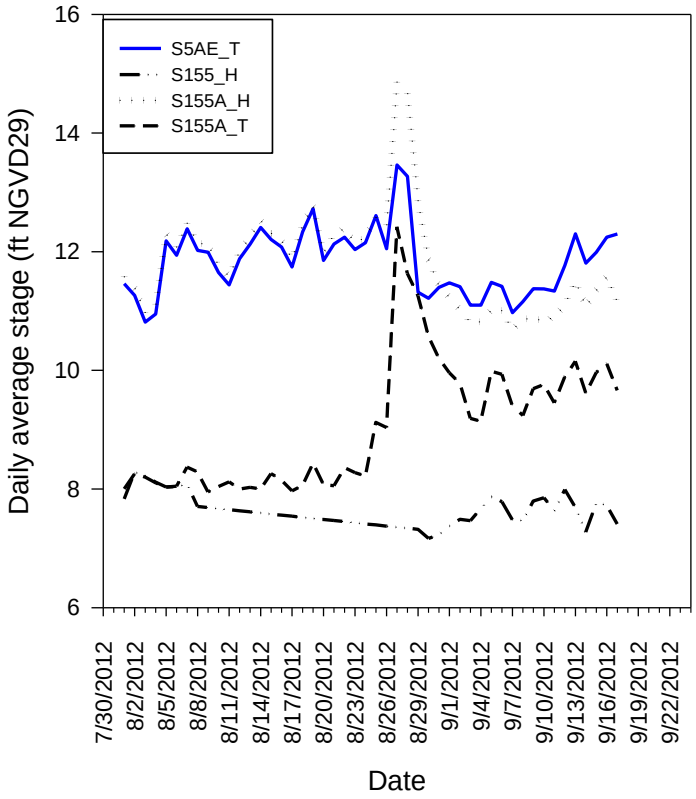

Figure 9c. Daily average water levels in C-51 Canal.

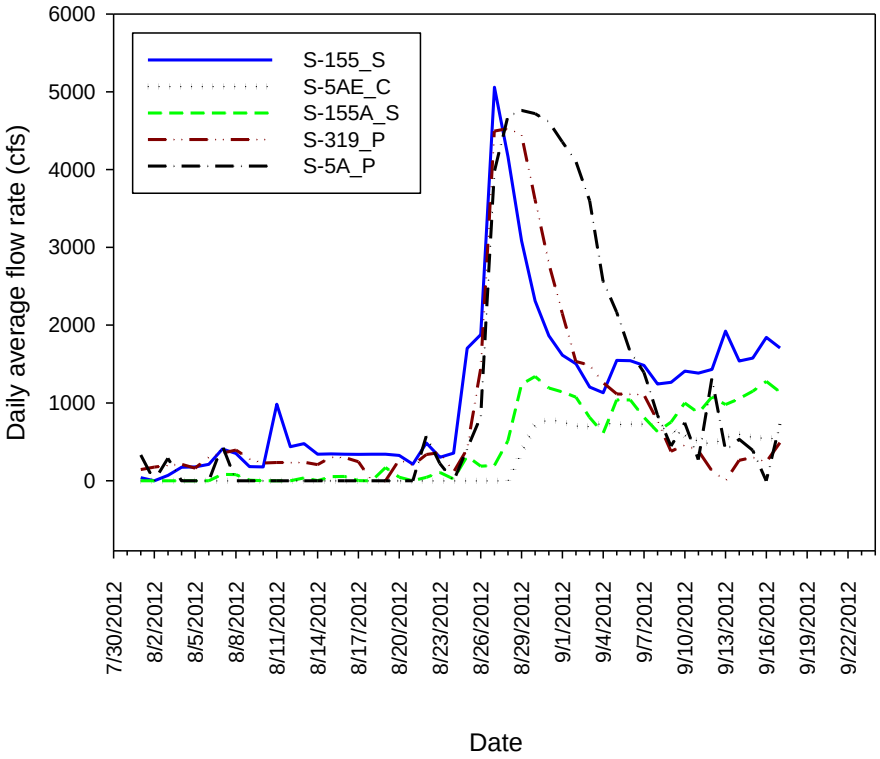

Figure 10. Flows in the C-51 and S-5A basins.

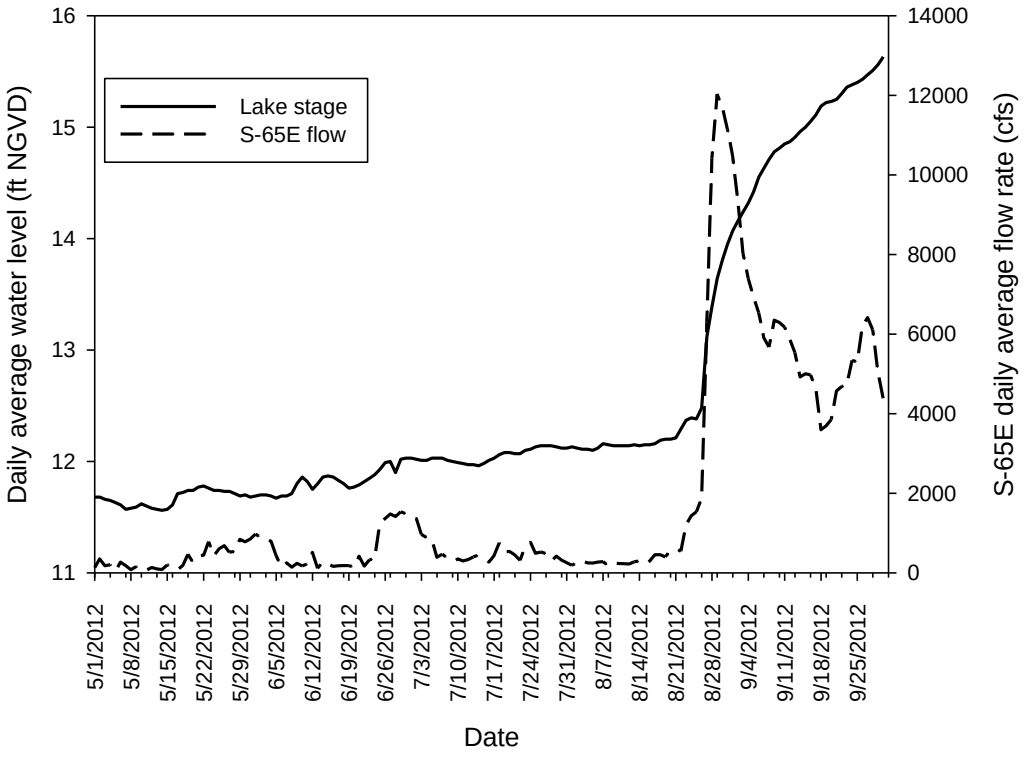

Figure 11. Lake Okeechobee major inflows and water levels preceding, during, and following Tropical Storm Isaac.

Water Conditions during Tropical Storm Isaac

Water management during tropical storm events is very challenging for the several reasons. The South Florida water management system has limited storage for excessive rainfall events. It is a constant challenge to hold enough water for water supply or draw down canals and water storage units to accommodate future runoff events. If an anticipated runoff event does not materialize, then the potential for water shortage increases due to discharging from storage and lowering canal levels. Water shortage results in water use restrictions, saltwater intrusion into utility wells, and shortage of water for environmental purposes. Operations during emergency events such as tropical systems face uncertainties of the path of the storm, amount of rainfall over the District area, intensity and spatial distribution of rainfall, and water control infrastructure damages. Water control infrastructure damages include water control facilities damage, levee erosion, and canal blockage. The highest rainfall from Tropical Storm Isaac was concentrated on Palm Beach County, specifically the C-51 basin. The storm created excessive runoff that resulted in flooding and challenged the tertiary, secondary, and primary water management systems. A water conditions summary for Tropical Storm Isaac, with briefs of readiness, response and recovery, news releases, and after-action assessment are shown in www.sfwmd.gov/portal/page/portal/levelthree/drought%20and%20flood/tropical%20storm%20isaac.

HURRICANE SANDY

Hurricane Sandy started in the Caribbean and moved north, passing east of the District from October 24–27, 2012. The impact to the District was limited to 0.83 inches average rainfall over the four-day period. Some localities received a significant amount of rainfall (**Table 4**). The hurricane made landfall in New Jersey and New York on October 29 as an extra-tropical storm, as a result of fusing with an arctic front that moved into the area in front of Hurricane Sandy. The storm caused loss of lives and severe property, infrastructure, beach, and environmental damages. Other states in the area were also notably affected by the storm.

Table 4. Rainfall observations from Hurricane Sandy (October 24-27, 2012).

Rainfall Area	Site	1-day Max Rainfall (in.)	Oct 24-27 Total Rainfall (in.)
Upper Kissimmee	EXOT	1.79	0.84
Lower Kissimmee	S-65C	1.42	0.8
Lake Okeechobee	S-135	0.81	0.58
East Everglades Agricultural Area	ROTNWX	0.84	0.67
West Everglades Agricultural Area	S-140	1.05	0.62
Water Conservation Areas 1,2	LXWS	0.96	1.29
Water Conservation Area 3	S-30	1.86	1.16
Martin/St Lucie	NEWS JUICE	0.84	1.34
Palm Beach	PBIA	1.23	1.4
Broward	S-30	1.86	1.36
Miami-Dade	S-30	1.86	1.84
East Caloosahatchee	BRYGR	0.43	0.2
Big Cypress Preserve	RACCOONPOINT	1.15	0.72
Southwest Coast	OCHOPEE	0.48	0.14
District (average)	**--**	--	**0.83**

SUMMARY

Tropical systems are an important part of the hydrometeorology of South Florida. Although tropical systems can break long-term drought and replenish surface and sub-surface storage, there is always the risk of flooding due to the high intensity, long duration, and large areal coverage of rainfall. The impact of rainfall from tropical systems on South Florida is higher when the event occurs with soils saturated and available surface water storage is limited. During the WY2013 hurricane season, Tropical Storm Isaac in August contributed to raising surface and subsurface storage bringing to an end the WY2011 drought year and WY2012 drier-than-average-year deficits. Significant rise in lake water levels and surface water discharge had hydraulic, ecological, and water quality impacts and caused significant localized flooding. Sites in the C-51 basin received the 100-year return period of rainfall for 3-day and 5-day periods as well as the entire month of August. The resulting surface water flows raised the water level in Lake Okeechobee by 3 ft in one month, resulting in a storage increase of 1,277,000 ac-ft. Often, storm-related impacts on surface water management in South Florida can continue for months after the tropical event, securing water supply in storage or increasing flooding risks, particularly if followed by another storm. However, in 2012, Tropical Storm Isaac was not followed by any storms of significant rainfall contribution to the District region.

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