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Hydrologic Impact of Hurricane Irene on South Florida (October 13 through 17, 1999)

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by

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EXECUTIVE SUMMARY

Documenting hydrologic events such as hurricanes, storms and droughts contributes to the knowledge base for water management decision making. This report summarizes the hydrologic impact of Hurricane Irene on South Florida. Information pertaining to the operation of the water management system and flooding effects of the hurricane are covered in the South Florida Water Management District report, "Hurricane Irene After-Action Assessment" (Schweigart, 1999).

According to previous studies, hurricanes and tropical storms in the North Atlantic Ocean average 9.4 per year with 4.9 reaching hurricane strength. Peninsular Florida is affected on the average by one named storm a year and by a hurricane every two to three years. Most of the storms (79 percent) occur in August, September and October. Hurricane Irene passed over the Keys on October 15, 1999 and landfall on mainland Florida at Flamingo later that day. It moved across Southeast Florida parallel to the coast dropping torrential rains with tropical storm and category one hurricane force winds. The center of Irene moved offshore near Jupiter later on the morning of October 16. Between October 13 and 17, a lot of sites in Broward, Miami-Dade, Martin and Palm Beach counties received more than 10 inches of rainfall. The most affected were Broward, Miami-Dade and Palm Beach counties. The maximum rainfall at a site was 17.46 inches at S-41 near the coast in Boynton Beach in Palm Beach County. The maximum rainfall at a site in Broward County was 14.15 inches at station FTL in Fort Lauderdale. Sites in Broward, Miami-Dade and Palm Beach counties received the 24-hour, 48-hour and 72-hour maximum rainfall that would occur once in 100 years.

Flows through water control structures and water levels in Lake Okeechobee, water conservation areas and canals showed significant increase due to the hurricane. The District pumped 646,654 acre feet (ac-ft) of water in October with 466,388 ac-ft being pumped from October 13 to 31. Few pump stations and several structures achieved record high daily average discharge rates. The total inflow and outflow for Lake Okeechobee for October was 565,136 ac-ft and 179,346 ac-ft, respectively. From October 13 to 31, the inflow to the Lake was 381,065 ac-ft and the outflow was 173,175 ac-ft. Outflow through coastal structures was 1,108,107 ac-ft for October with 976,757 ac-ft discharged from October 13 to 31. Discharge into the Everglades National Park was 365,785 ac-ft with 276,672 ac-ft occurring between October 13 and 31. Inflow and outflow to Stormwater Treatment Areas generally increased.

Water level in lakes, water conservation areas and canals rose sharply due to Hurricane Irene. There were many instances where historical high water levels were attained. In this report, the effect of the hurricane on the water level of major water bodies and primary canals is presented. Groundwater table fluctuation due to the hurricane is also presented. The information in this study will contribute input to the operational decision making of the regional water management system for such events.

Casualty and damage statistics for Hurricane Irene are presented by L. A. Aliva (1999) of the National Hurricane Center in a preliminary report. It is stated that there were eight casualties in Broward, Miami-Dade and Palm Beach counties that were associated with Hurricane Irene. Additionally, Irene caused considerable damage due to flooding in South Florida, and in some residential areas, it lasted for a week. Agricultural and property losses were estimated near $600 million mostly in Broward, Miami-Dade and Palm Beach counties with additional $200 million losses in the rest of the state. An estimated 700,000 customers lost power.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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INTRODUCTION

Documenting hydrologic events such as hurricanes, storms and droughts contributes to the knowledge base for water management decision making. This report covers antecedent hydrologic conditions of South Florida and the hydrologic impact of Hurricane Irene during October 1999. Based on available data, the spatial distribution and the magnitude of the rainfall from the hurricane are presented along with an estimate for frequency of occurrence. Water level changes at critical locations of the water management system, as well as flow from the various structures and groundwater fluctuation are also presented. Information pertaining to the operation of the water management system and flooding effects of the hurricane are covered in the South Florida Water Management District report, "Hurricane Irene After-Action Assessment" (Schweigart, 1999).

Background

According to Chaston (1996), the hurricane is nature's way of transporting heat energy, moisture and momentum from the tropics to the poles in order to decrease the temperature differential and preserve the current climate of the earth. Tales and records indicate that Atlantic hurricanes have been observed since Christopher Columbus's voyage to the New World in the 1490s. Based on published records, the average annual number of subtropical storms, tropical storms and hurricanes in the North Atlantic Ocean between 1886 and 1994 is 9.4; 4.9 of these were hurricanes (Tait, 1995). Between 1871 and 1996, 1,000 tropical storms have occurred in the North Atlantic, Caribbean Sea and Gulf of Mexico of which 184 have reached Florida with 74 of them being hurricanes (Williams and Duedall, 1997). Monthly frequency of tropical systems, excluding depressions, is shown in **Figure 1.** As shown in this figure, the probability of occurrence of a tropical storm or a hurricane during August, September and October is 79 percent (Neumann, et al., 1993).

The number of hurricanes and tropical storms affecting peninsular Florida between 1871 and 1996 were 114 with about half being hurricanes (Attaway, 1999). The 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 has been affected by 42 hurricanes, 32 tropical storms and 9 tropical cyclones (hurricanes or tropical storms) from 1871 to 1999 (**Table 1**). Since 1871, the Miami area was affected by hurricanes in 1888, 1891, 1904, 1906, 1909, 1926, 1935, 1941, 1945, 1948, 1950, 1964, 1965, 1966, 1972, 1992 and 1999 (Williams and Duedall, 1997). Between 1900 and 1996, Southeast Florida had 26 hurricane direct hits. **Table 2** shows the distribution of these 26 hurricanes with respect to hurricane category (Herbert, et al., 1997).

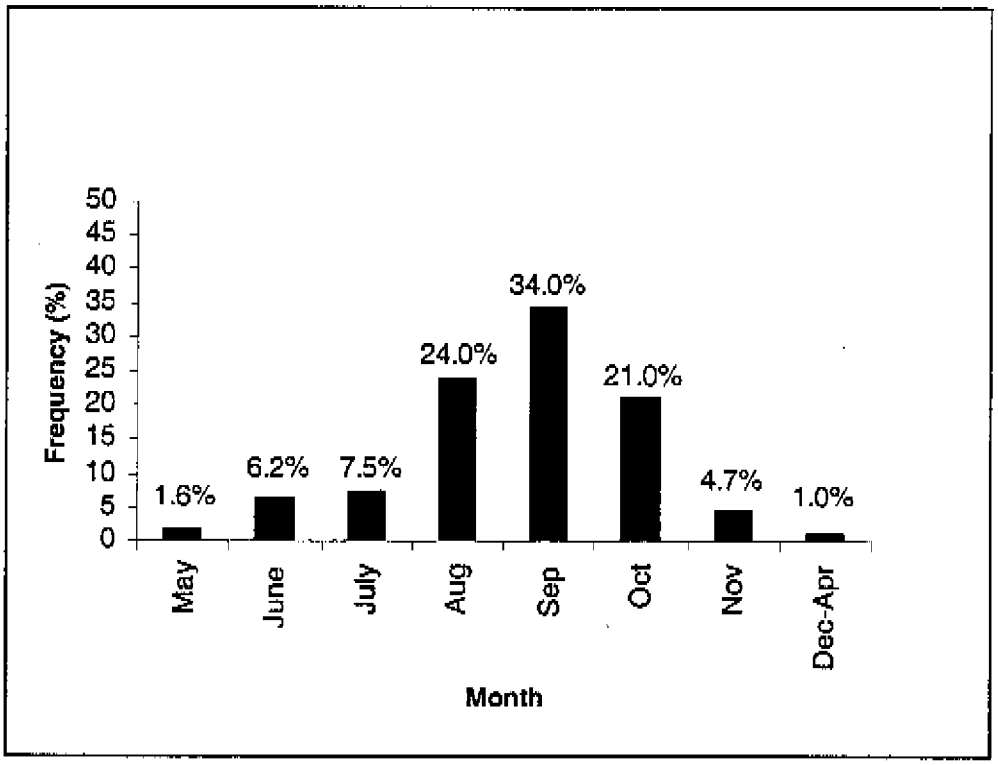


Figure 1. Frequency of North Atlantic Hurricanes and Tropical Storms.

Table 1. Historical Tropical Cyclones, Storms and Hurricanes Affecting Central and South Florida from 1871 to 1999 (Attaway, 1999, Neumann, et al., 1993)

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

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1893					
1894	September 25-26	Hurricane	Tampa to Titusville	16.2	rainfall was observed in Kissimmee
1895	October 16-17	Tropical Storm	Naples to West Palm Beach	24.39	Hypoluxo rainfall for the month
1896	October 8-9	Hurricane	Fort Myers to Melbourne		
1897	September 20-21	Tropical Storm	Fort Myers to Titusville		
	October 19-20	Tropical Storm	Tampa to St. Augustine		
1898	August 1-2	Hurricane	Fort Pierce to ClearWater		
	October 10-11	Tropical Storm	Naples to Melbourne		Rainfall from the storm was generally less than 1 inch.
1899					
1900					
1901	August 10-11	Tropical Storm	West Palm Beach to Sarasota		
1902					
1903	September 11-12	Hurricane	Broward to Tampa		Heavy rain resulted from the hurricane
1904	October 17-18	Hurricane	Miami loop through Everglades	6.03	Rainfall was observed in Miami
1905					
1906	June 10-11	Tropical Storm	east of Panama City		
	June 16-18	Hurricane	Naples to West Palm Beach		
1907					
1908					
1909	October 11-12	Hurricane	Southern Dade to Atlantic Ocean	10.17	24-hour rainfall observed in Miami
1910	October 17-19	Hurricane	Cape Romano to Jacksonville		
1911					
1912					
1913					
1914					
1915					
1916					
1917					
1918					
1919	September 10-11	Hurricane	Key West		hurricane went to Texas
1920					
1921	October 25-26	Hurricane	Tampa to north of Titusville		

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1922					
1923					
1924	October 20-21	Hurricane	Naple to Fort Lauderdale	16.74	rainfall observed in Fort Lauderdale
1925	November 30-December 1	Hurricane	Tampa to Titusville	15.1	rainfall observed south of Miami
1926	July 27-28	Hurricane	Fort Pierce to Southern Georgia		
	September 18-19	Hurricane	Miami to Bonita Springs	8.02	rainfall was observed in Fort Myers; high casualties in Moore Haven
1927					
1928	August 7-9	Hurricane	Vero Beach to N. W. Florida		
	September 16-17		Palm Beach to Jacksonville through Okeechobee		2000 died south of Lake Okeechobee
1929	September 28-29	Hurricane	Key West, southern tip of Florida	10.58	rainfall was observed in Miami
1930					
1931					
1932	August 29-30	Tropical Storm	Key Largo to Fort Myers	10.24	rainfall observed at Miami
1933	July 30-Aug. 1	Tropical Storm	Stuart to Punta Gorda		
	September 3-5	Hurricane	Jupiter to Brooksville to Lake City		
1934	May 27-28	Tropical Storm	Fort Myers to Daytona Beach		
1935	September 2-4	Hurricane	Key West to North Florida along west coast of Florida	13.25	narrow storm with high intensity, similar to Andrew of 1992 (rainfall observed at Punta Gorda)
	November 4-5	Hurricane	Miami to Cape Sable	11.8	rainfall observed at Long Key
1936	June 15	Tropical Storm	Fort Myers to Miami	12.47	rainfall observed at LaBelle
	July 28-29	Tropical Storm	Key Largo to Everglades City		
1937					
1938					
1939	August 11-12	Tropical Storm	Stuart to Tarpon Springs		
1940					
1941	October 6-7	Hurricane	Miami to Fort Myers		
1942					
1943					
1944	October 18-19	Hurricane	Sarasota to Jacksonville	7.49	rainfall observed in Orlando
1945	September 15-16	Hurricane	Key Largo to St. Augustine though central Florida		

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1946	October 7-8	Hurricane	Sarasota to Lake City		
	November 1-2	Tropical Storm	Palm Beach to Lakeland		
1947	September 17 -18	Hurricane	Fort Lauderdale to Fort Myers	8.72	rainfall observed in Fort Myers
	October 11-18	Hurricane	Cape Sable to Pompano		
1948	**September 21-22**	**Hurricane**	**Everglades City to Stuart**	**11**	**rainfall observed in Miami; path closely matched that of Hurricane Irene, October 1999**
	October 4-5	Hurricane	Miami to Fort Lauderdale	9.95	rainfall observed in Miami
1949	August 26-27	Hurricane	Palm Beach to Brooksville to Lake City	8.81	rainfall observed at Belle Glade Expt. Station
1950	October 17-19	Hurricane "King"	Miami to Georgia through Central Florida	14.19	rainfall observed in Orlando
1951	October 1-3	Tropical Storm	Fort Myers to Vero Beach	15.72	rainfall observed in Bonita Springs
1952	February 1-3	Tropical Storm	Cape Sable to Miami		
1953	October 8-9	Tropical Storm "Hazel"	Fort Myers to Vero Beach		
1954					
1955					
1956					
1957					
1958					
1959	October 18-19	Tropical Storm "Judith"	Fort Myers to Fort Pierce		
1960	September 9-11	Hurricane "Donna"	Naples to Flagler Beach	8.48	three days of rainfall in Miami
1961					
1962	August 26-27	Tropical Storm "Alma"	Miami to Titusville		
1963					
1964	August 27-28	Hurricane "Cleo"	Miami to Jacksonville along the coast	6.8	rainfall as observed in Miami
	October 14-15	Hurricane "Isbell"	Cape Sable to Palm Beach	5.09	rainfall observed at Everglades Expt. Station
1965	September 8	Hurricane "Betsy"	Florida Keys and tip of Florida	10.89	rainfall observed at Homestead AFB
1966	October 4-5	Tropical Storm "Inez"	Florida Keys and tip of Florida		
1967					
1968					
1969	September 6-7	Hurricane "Gerda"	Palm Beach to Vero Beach		tropical storm while on land
1970					
1971					
1972	September 5	Tropical Storm "Dawn"	Southeast Florida coast		

Year	Date	Type of Storm	Path	Rainfall (inches)	Remark
1973					
1974					
1975					
1976					
1977					
1978					
1979	September 3-4	Hurricane "David"	Palm Beach to Daytona Beach along the coast	8.92	rainfall observed in Vero Beach
1980					
1981	August 17-19	Tropical Storm "Dennis"	Cape Sable to Cape Canaveral	20.38	rainfall observed in Kendall
1982					
1983					
1984	September 26-28	Tropical Storm "Isidore"	Jupiter to Lakeland; turned north to Dade City	2.8	rainfall observed in West Palm Beach
1985	July 23	Tropical Storm "Bob"	Naples to Vero Beach		
1986					
1987	October 12	Hurricane "Floyd"	Keys and tip of Florida	5.2	rainfall observed in Naples
1988	November 23	Tropical Storm "Keith"	Sarasota to Melbourne	11	rainfall observed in Largo
1989					
1990	October 11-12	Tropical Storm "Marco"	Keys to Cedar Key along the west coast	4.78	rainfall observed at McDill AFB
1991					
1992	August 24	Hurricane "Andrew"	Homestead to Everglades City	6.9	estimated at Homestead
1993					
1994	November 16	Tropical Storm "Gordon"		16.0	rainfall observed in Andytown
1995	August 1-3	Hurricane "Erin"	Vero Beach to north of Tampa	8.81	rainfall observed in Melbourne
	August 23-26	Tropical Storm "Jerry"	Jupiter to Cedar Key	16.18	rainfall observed in Naples
1996					
1997					
1998	September 25	Hurricane "Georges"	Florida Keys to Biloxi, Mississippi		
1999	October 13-17	Hurricane "Irene"	Flamingo to Jupiter	17.46	rainfall observed in Boynton Beach

Table 2. Southeast Florida Hurricanes between 1900 and 1996.

Category	Wind Speed (mph)	Number of Hurricanes
1	74-95	5
2	96-110	10
3	111-130	7
4	131-155	4
5	≥155	0

Hurricane Irene

According to the National Weather Service in Miami, Hurricane Irene originated in the Southwest Caribbean from a broad area of low pressure. After a period of organization, a tropical depression was formed on October 13, 1999, which strengthened to a tropical storm later on the same day. Irene moved north, north-east and made landfall on the Isle of Youths, Cuba, on October 14. The center of Irene moved to the Florida Straits and attained Category I hurricane strength. The center passed over Key West on October 15 and made landfall on mainland Florida at Flamingo later that day. It moved across Southeast Florida parallel to the coast, dropping torrential rains with tropical storm and hurricane force winds. The center of Irene moved offshore near Jupiter later on the morning of October 16 (**Figure 2**). According to the National Hurricane Center, tropical-force winds were experienced on mainland Florida with Category I hurricane-force winds confined to squalls off the Florida east coast. The National Weather Service provided 24 forecast advisories between 11 a.m., October 13 and 11 p.m., October 18, 1999. Heavy rains of 10 to 15 inches with locally higher amounts were forecasted in the advisories.

Casualty and damage statistics for Hurricane Irene are presented by L. A. Aliva (1999) of the National Hurricane Center in a preliminary report. It is stated that there were eight casualties in Broward, Miami-Dade and Palm Beach counties that were associated with Hurricane Irene. Additionally, Irene caused considerable damage due to flooding in South Florida, and, in some residential areas, it lasted for a week. Agricultural and property losses were estimated near $600 million, mostly in Broward, Miami-Dade and Palm Beach counties, with additional $200 million losses in the rest of the state. An estimated 700,000 customers lost power.

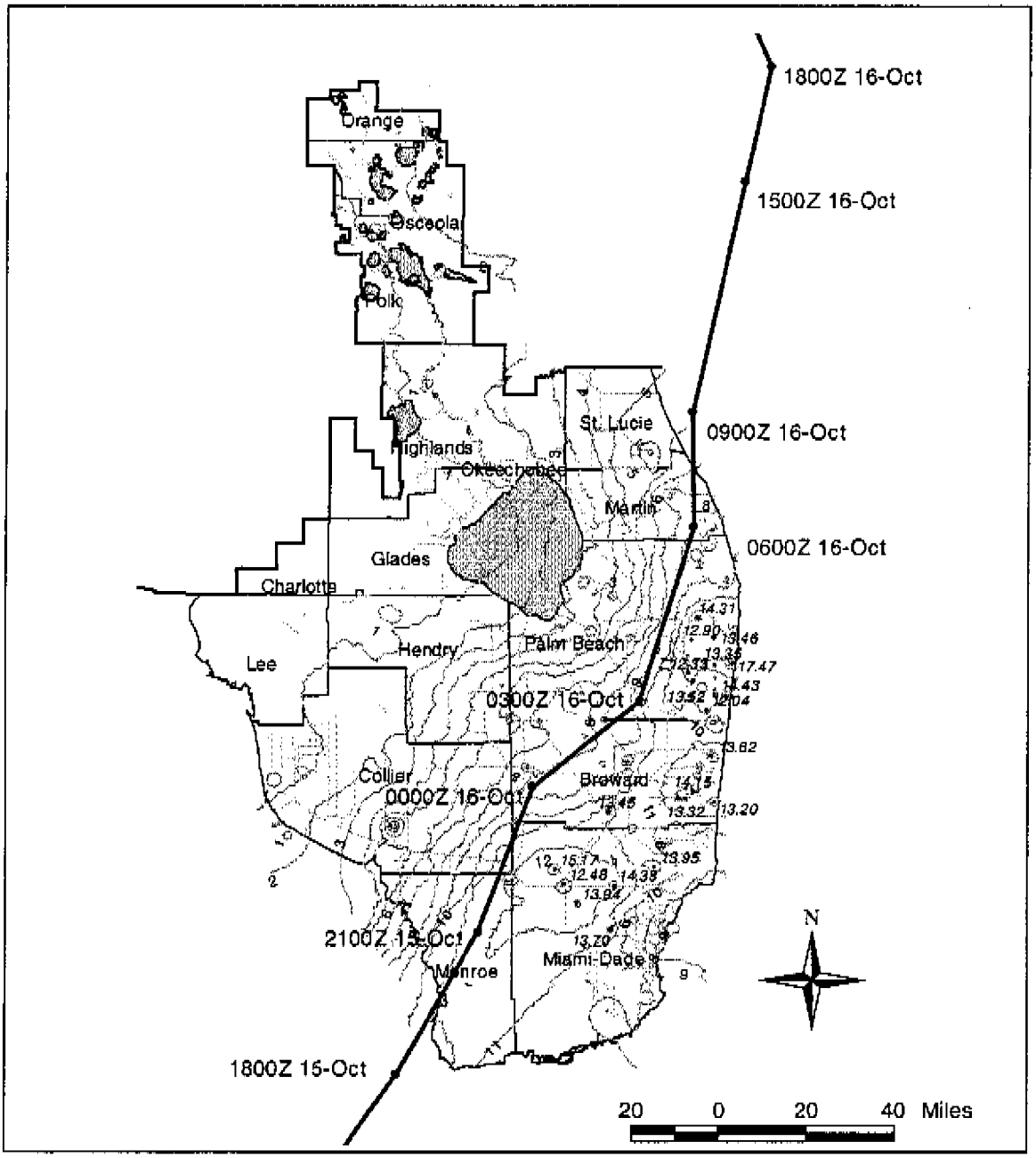


Figure 2. Path of Hurricane Irene in South Florida and Isohyetal Map of Accompanying Rainfall (October 13 through 17, 1999).

RAINFALL ANALYSIS

Rainfall Observations

Rainfall analysis was completed using data from the South Florida Water Management District rainfall monitoring network (**Figure 3**). Rainfall antecedent to Hurricane Irene (October 1 to 12) varied from average to wet in the rain areas (basins) monitored by the South Florida Water Management District. The east coast area had rainfall during the week preceding Hurricane Irene. **Figure 2** presents an isohyetal map with an interval of 1 inch for the rainfall that occurred between October 13 and 17. Rainfall amounts followed the path of the hurricane with most of the rain falling to the east of the path (**Figure 2**). The strongest wind and storm surge is in the right-front quadrant of the hurricane as viewed in the direction of movement (Williams and Duedall, 1997). Although labeled isohyetal lines range from 1 to 12 inches, there are point rainfall measurements that are higher. The maximum rainfall at a site in Palm Beach County was 17.46 inches at station S41_R near the coast in Boynton Beach. The maximum rainfall at a site in Miami-Dade County was 15.17 inches at station Cooper_R in the western part of the County. The maximum rainfall at a site in Broward County was 14.15 inches at station FTL in the eastern region of the County.

Table 3 depicts, by county, statistics of antecedent rainfall in early October, tropical rainfall during the hurricane and rainfall after the hurricane. It is apparent from the data and statistics in **Table 3** that Charlotte, Glades, Highlands, Lee and Polk counties on the average had less than 1 inch rainfall during the hurricane. Broward and Miami-Dade counties had average rainfall of greater than 10 inches from the hurricane and associated tropical system (**Figure 4**). In **Table 3**, low C.V. (coefficient of variation) indicates low variation between observations at rainfall stations in a county. **Figure 5** depicts rainfall observations at each station in each county from October 13 to 17. It is clearly shown that Broward, Miami-Dade and Palm Beach counties had the most rainfall from the hurricane.

Areal average antecedent rainfall in early October, tropical rainfall during the hurricane and rainfall after the hurricane are presented in **Table 4** for rain areas monitored by the District. Rain areas are multiple hydrologic basins grouped together to facilitate operations in managing the District's water resources. Rainfall data were used in conjunction with a program developed by A. Ali and modified by the authors to determine average values of rainfall for each of the rain areas examined in this study (Ali and Abtew, 1999). Using cells that are 0.5 miles long by 0.5 miles wide, the program computes areal average rainfall for each rain area using gages present in that rain area. The local impact of the hurricane and tropical system rainfall is more pronounced in the rain areas. Broward, Dade and Palm Beach counties, Water Conservation Area (WCA) 1 & 2, 3 and the Everglades National Park had average areal rainfall of greater than 9 inches during the tropical system.

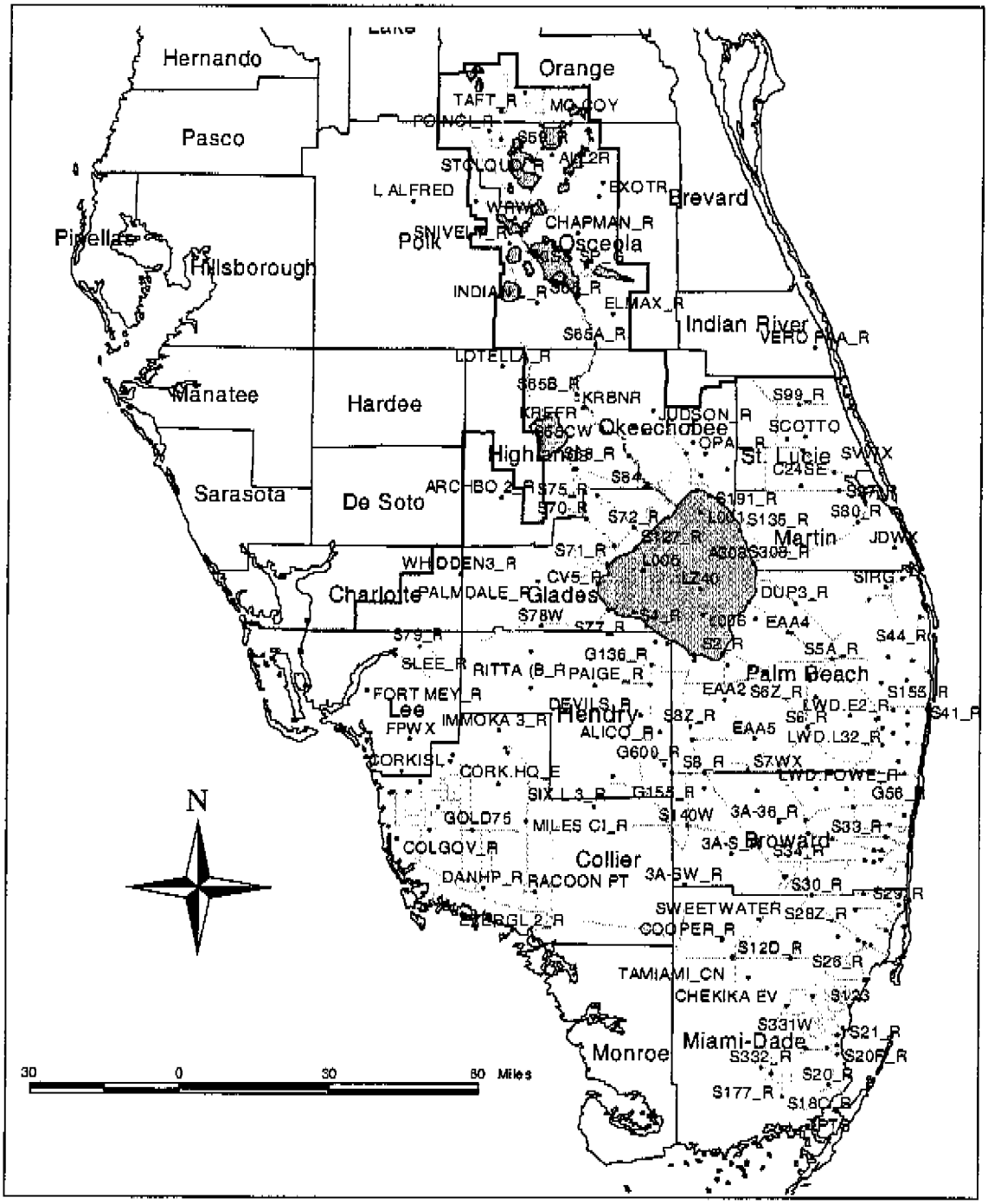


Figure 3. Rainfall Monitoring Locations used in this Study.

Table 3. Antecedent, Hurricane, Monthly and Maximum Rainfall Statistics (inches) for each County.

	10/1/99 to 10/12/99				10/13/99 to 10/17/99				10/18/99 to 10/31/99				October Total			
County	Mean	STD	C.V.	Max.	Mean	STD	C.V.	Max	Mean	STD	C.V.	Max	Mean	STD	C.V.	Max
Broward	2.94	1.27	0.43	6.66	**10.24**	**2.53**	**0.25**	**14.15**	1.47	1.48	1.01	4.52	14.66	4.30	0.29	22.33
Charlotte	2.44	----	----	2.44	**0.24**	**-----**	**-----**	**0.24**	0.46	-----	-----	0.46	3.14	-----	-----	3.14
Collier	1.71	0.80	0.47	2.97	**1.86**	**2.17**	**1.17**	**10.23**	0.50	0.54	1.08	1.41	4.07	2.44	0.60	12.36
Miami-Dade	2.55	1.09	0.43	4.78	**10.23**	**2.58**	**0.25**	**15.17**	0.63	0.82	1.30	3.11	13.41	2.82	0.21	18.25
Glades	2.74	1.20	0.44	4.89	**0.73**	**0.30**	**0.41**	**1.27**	0.47	0.62	1.31	2.36	3.94	1.41	0.36	6.66
Hendry	2.87	1.12	0.39	5.39	**3.01**	**2.25**	**0.75**	**6.84**	1.36	0.82	0.60	2.51	7.26	1.78	0.24	11.06
Highlands	3.21	1.44	0.45	3.64	**0.69**	**0.30**	**0.43**	**0.95**	1.82	0.73	0.40	2.42	5.72	1.39	0.24	8.22
Indian River	3.28	-----	-----	3.28	**4.24**	**------**	**------**	**4.24**	0.45	----	-----	0.45	7.97	-----	-----	7.97
Lee	2.08	0.65	0.31	2.81	**0.45**	**0.26**	**0.58**	**0.68**	0.22	0.32	1.44	0.71	2.75	1.09	0.40	4.04
Martin	3.72	1.38	0.37	5.90	**5.61**	**3.86**	**0.69**	**10.73**	0.70	0.77	1.11	2.09	10.03	5.04	0.50	16.97
Okeechobee	4.65	1.32	0.47	6.21	**1.83**	**0.86**	**0.47**	**3.78**	1.03	0.91	0.89	3.55	7.52	2.05	0.27	10.41
Orange	5.67	0.68	0.12	6.42	**1.72**	**0.88**	**0.51**	**2.97**	0.26	0.05	0.20	0.33	7.64	1.37	0.18	9.12
Osceola	4.25	0.77	0.18	5.63	**1.89**	**0.78**	**0.41**	**3.54**	0.75	0.66	0.88	2.68	6.90	1.70	0.25	9.37
Palm Beach	2.52	0.90	0.36	4.99	**7.95**	**4.00**	**0.50**	**17.47**	1.02	0.87	0.85	3.38	11.50	4.25	0.37	22.38
Polk	3.97	1.19	0.30	6.07	**0.79**	**0.27**	**0.34**	**1.35**	0.90	0.65	0.72	2.11	5.67	1.22	0.22	7.83
St. Lucie	3.93	1.46	0.37	6.80	**5.20**	**1.47**	**0.28**	**7.20**	1.27	0.47	0.37	1.82	10.40	2.36	0.23	12.38

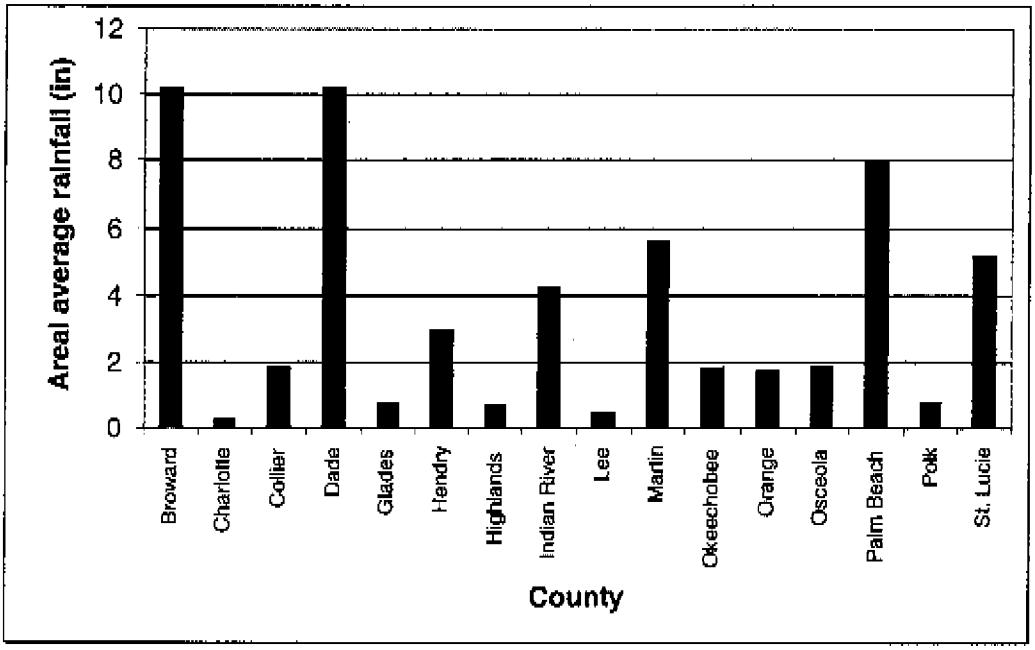


Figure 4. Hurricane Irene Areal Average Rainfall by County (October 13 through 17, 1999).

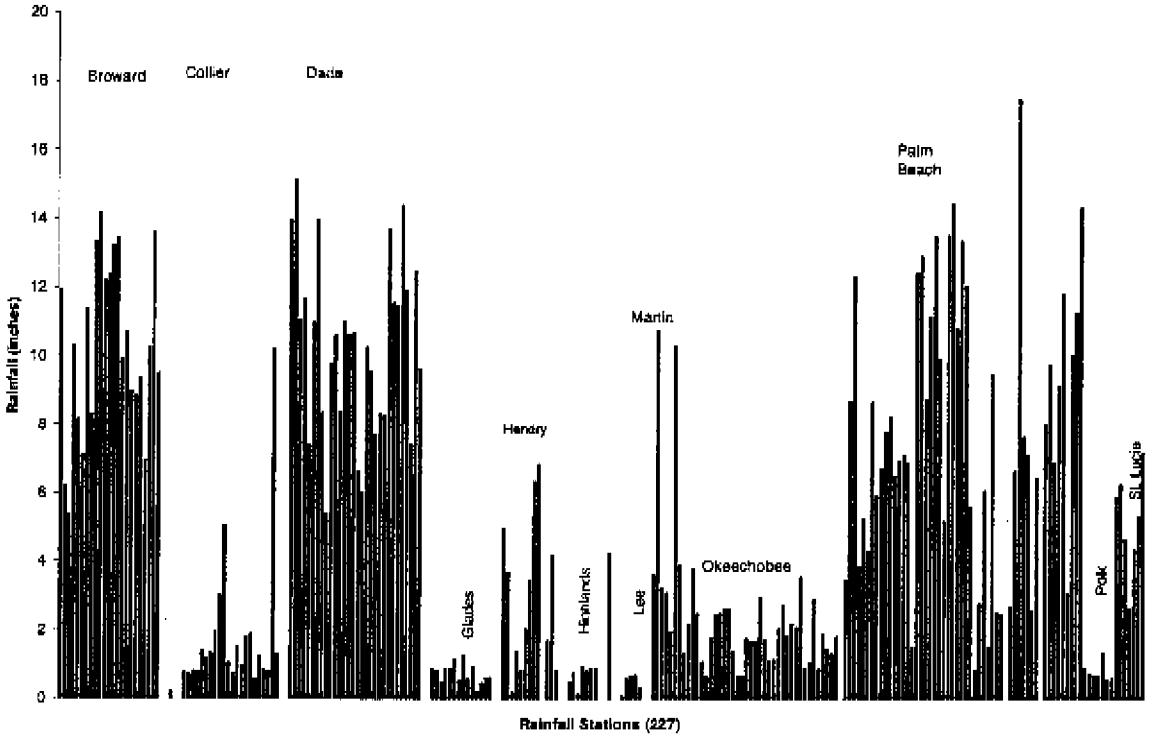


Figure 5. Rainfall Observations at each Station in each County (October 13 through 17, 1999).

Table 4. Antecedent, Hurricane and End-of-Month Rainfall Statistics (inches) for each Rain Area of the South Florida Water Management District.

Rain Area	10/1/99 to 10/12/99 Mean	**10/13/99 to 10/17/99 Mean**	10/18/99 to 10/31/99 Mean
Big Cypress Preserve	1.99	**7.65**	0.32
Broward	3.75	**12.15**	3.04
Caloosahatchee	2.83	**0.87**	1.21
Miami-Dade	2.51	**9.92**	0.66
East EAA	2.47	**5.28**	1.20
Lake Okeechobee	3.07	**1.27**	0.81
Lower Kissimmee	3.55	**1.28**	1.63
Martin/St. Lucie	4.26	**6.57**	1.17
Palm Beach	2.97	**9.74**	0.88
Southwest Coast	1.75	**1.15**	0.53
Upper Kissimmee	2.81	**1.47**	0.53
WCA1 & 2	2.81	**9.35**	0.28
WCA 3	2.19	**9.86**	1.01
West Ag.	2.90	**3.09**	1.44
Everglades National Park	2.58	**12.28**	0.17

Frequency Estimates

Frequency of occurrence of a certain amount of rainfall at a site for a given duration can be estimated using statistical analysis or by comparing the amount to a published frequency analysis. Due to Hurricane Irene, rainfall for October was wetter than average for most of the rain areas. Comparison of historical monthly areal average for each rainfall area to the rainfall of October 1999 provides a measure of the wetness or dryness for the month. Based on a regional rainfall frequency analysis for Central and South Florida (Ali and Abtew, 1999), the probability of occurrence for October 1999 monthly rainfall is given in return periods in **Table 5**. The wettest rainfall area was Broward County. Broward County's October 1999 rainfall had an estimated return period of 32 years. Rainfall in Water Conservation Area 1 and 2 had 20-year (wet-season) return period. Rainfall amounts in the other rain areas had less than 15-year (wet season) return period. The Southwest Coast rain area was drier than average in October 1999.

Table 5. October 1999 Rainfall (inches) and Historical Average Rainfall with Estimated Return Period for each Rain Area of the South Florida Water Management District Area.

Rain Area	Historical Basin Average for October (in)	Monthly Rainfall October 1999 (in)	Return Periods (Years) Wet Season	Dry Season
Big Cypress Preserve	-----	9.96	-----	
Broward	7.39	18.93	~32	
Caloosahatchee	3.78	4.64	~3	
Dade	7.32	13.06	~9	
East EAA	4.29	8.95	~13	
Everglades National Park	-----	15.03	-----	
Lake Okeechobee	3.83	5.15	~4	
Lower Kissimmee	3.07	6.46	~13	
Martin/St. Lucie	6.77	12.01	10	
Palm Beach	7.80	13.14	~9	
Southwest Coast	4.05	3.26		~3
Upper Kissimmee	3.24	6.52	~10	
WCA 1&2	5.04	12.44	~20	
WCA 3	-----	12.88	-----	
West Ag.	3.83	7.43	~10	

Regional, monthly rainfall averages conceal the impact of rainfall events when there is uneven spatial and temporal distribution. The frequency of occurrence would be lower (the return period would be higher) if the area of high rainfall was considered locally as opposed to regionally for a shorter duration (less than a month). This is demonstrated by the frequency of point maximum rainfall measurement at a site. Frequency analysis of one-day, two-day and three-day rainfall maxima for Central and Southern Florida have been published in District Technical Publications (MacVicar, 1981; Trimble, 1990). **Table 6** depicts the maximum 24-hour, 48-hour and 72-hour rainfall at a station in each county with the estimated frequency of occurrence shown as return period. Broward and Miami-Dade counties had sites that received the 100-year, 24-hour, 48-hour and 72 hour rainfall during Hurricane Irene. Palm Beach County had sites that received 25-year, 24-hr rainfall and 100-year, 48-hr and 72-hr rainfall. Although the areal monthly rainfall amounts shown in **Table 5** do not indicate the occurrence of an extreme event, return periods for the 24-hr, 48-hr and 72-hr maximum point rainfall in **Table 6** show the magnitude of the hurricane rainfall on the drainage system. Generally, the flooded areas in each county had rainfall monitoring sites where maximum rainfall was observed (**Table 6**).

Table 6. Maximum 24, 48 and 72-hour Rainfall (inches) at a Station for each County and the Corresponding Return Periods (RP) in Years.

County	Station	24-hr Amount (in)	Return Period (yr)	Station	48-hr Amount (in)	Return Period (yr)	Station	72-hr Amount (in)	Return Period (yr)
Broward	3A-SW	8.97	100	MIRAMAR	12.97	100	FTL	14.08	100
Charlotte	WHIDDEN3	0.18	---	WHIDDEN3	0.24	---	WHIDDEN3	0.24	---
Collier	RACOON PT	8.00	25	RACOON PT	10.23	25	RACOON PT	10.23	10
Miami-Dade	COOPER	10.30	100	COOPER	14.87	100	COOPER	15.17	100
Glades	S129	1.12	---	S129	1.14	---	S4	1.23	---
Hendry	G600	4.30	5	G600	6.82	5	G600	6.84	5
Highlands	S68	0.74	---	MCARTH	0.89	---	MCARTH	1.02	---
Indian River	VERO FAA	1.63	---	VERO FAA	2.43	---	VERO FAA	2.86	---
Lee	S79	0.42	---	FPWX	0.64	---	FPWX	0.64	---
Martin	S80	6.82	10	JDWX	9.42	10	JDWX	10.72	25
Okeechobee	DAVIE2	2.97	---	DAVIE2	3.35	---	DAVIE2	3.78	---
Orange	BEELINE	1.98	---	BEELINE	2.94	---	BEELINE	2.96	---
Osceola	EXOTR	2.15	---	EXOTR	3.51	---	EXOTR	3.54	---
Palm Beach	WPBFS	10.35	25	S41	16.25	100	S41	17.46	100
Polk	INDIAN L	0.74	---	TICK-ISL	0.89	---	S65A	1.17	---
St. Lucie	C24SE	3.17	---	C24SE	5.50	Average	SVWX	7.20	5

--- no significance in terms of wet season frequency of occurrence

FLOWS THROUGH WATER CONTROL STRUCTURES

Pumping

Flows through water control structures and water levels in Lake Okeechobee, the Water Conservation Areas and canals showed significant increases due to Hurricane Irene. A number of flow control structures had a record maximum average daily discharge. Record maximum average daily water levels were also observed in a number of canals. District pumps (**Figure 6**) discharged 646,654 acre-feet (ac-ft) during October with 466,388 ac-ft being pumped from October 13 to 31. The pumping for October 1999 was greater than the combined sum of pumping volumes for October in the previous three years. **Table 7** shows pumping volume for selected pump stations during the hurricane period and following days and the total volume for the month of October. Seventy-seven percent of the pumping was into the Water Conservation Areas through G251, S5A, S6, S7, S8 and S9 pump stations. **Figures 7a to 7c** depict the daily flow distribution for selected pump stations with significant flows. The hurricane related pumping was evident at most pump stations from October 13 to the end of the month. The S9 pump station achieved a historical maximum pumping daily average rate of 2,539 cubic feet per second (cfs) on October 16, 1999. The S332 pump station had a record maximum rate of 539 cfs on October 17, 1999.

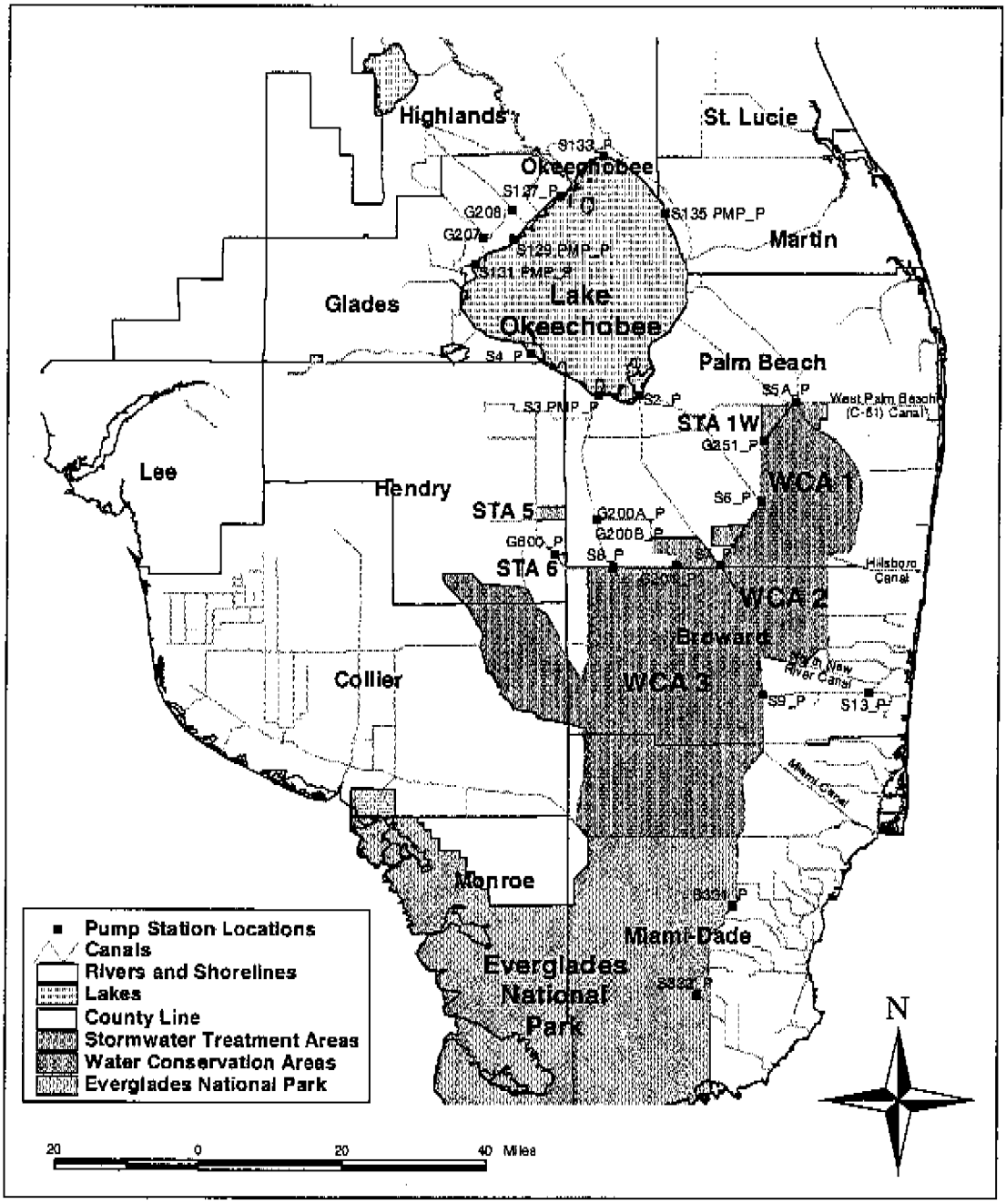


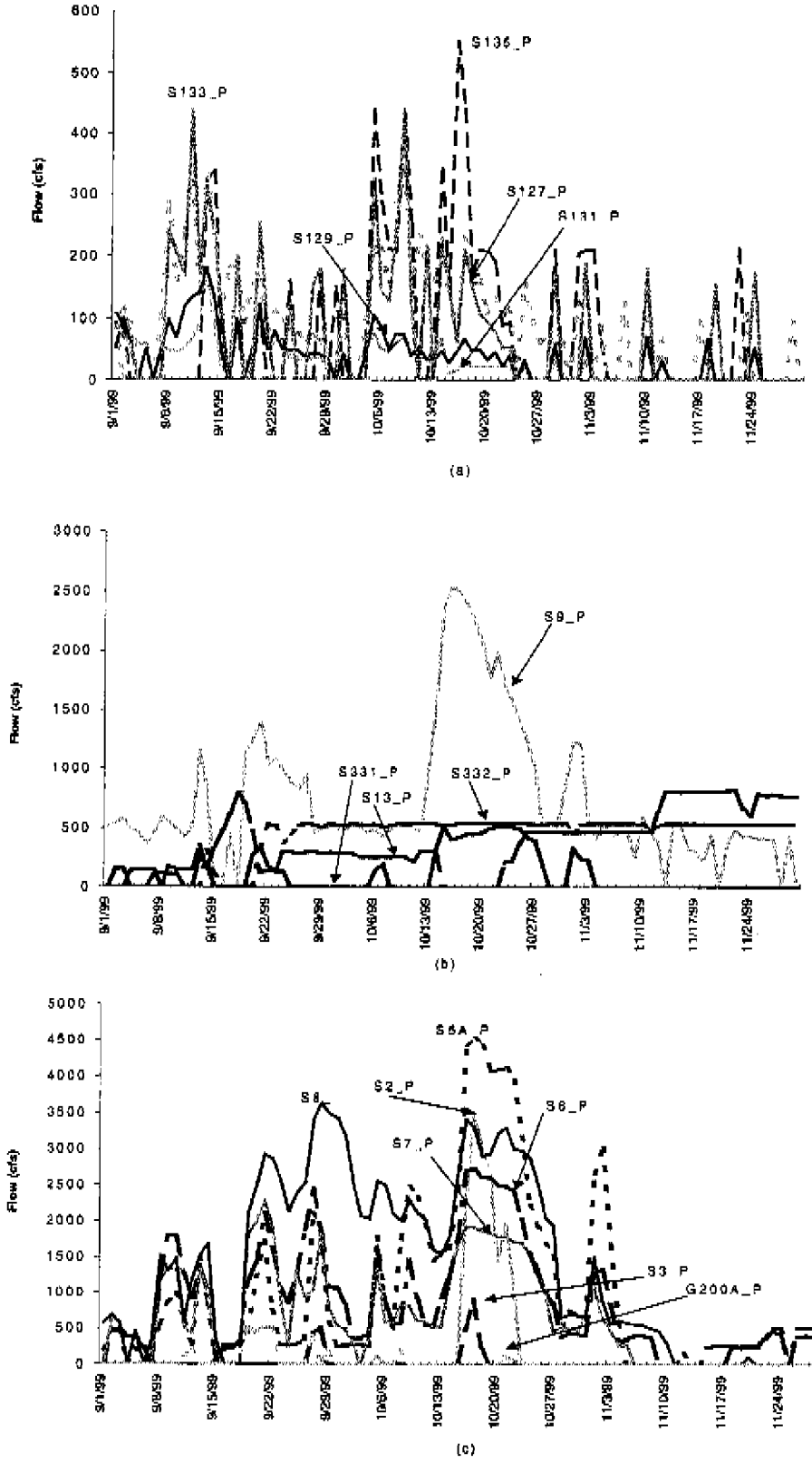
Figure 6. Pump Station Locations used in this Study.

Table 7. October 1999 Pumping Volumes for Selected Pump Stations.

Pump Station	Pumping Volume (ac-ft.)	
	October 13 to 31, 1999	October 1999 Total
S131_P	694	1,721
S135_P	5,410	9,164
S127_P	4,125	8,050
S129_P	1,095	2,300
S133_P	2,705	6,271
G207_P	0	0
G208_P	0	0
G600_P	9,408	14,735
G251_P	10,793	18,830
G201_P	4,421	6,538
G200B	958	1,333
G200A_P	379	790
S2_P	31,669	31,930
S3_P	3,213	3,213
S4_P	1,326	6,578
S5A_P	96,076	124,239
S6	60,075	78,108
S7_P	48,396	62,348
S8_P	85,406	138,880
S9_P	58,705	70,535
S13_P	12,976	13,641
S331_P	8,347	14,645
S332_P	20,211	32,805
Total	466,388	646,654

Lake Okeechobee Flows

Inflow to Lake Okeechobee was 381,065 ac-ft from October 13 to 31, 1999, and outflow was 173,175 ac-ft. The total inflow for October was 565,146 ac-ft and the outflow was 179,346 ac-ft. It is apparent that the storage of the Lake increased during the hurricane. **Table 8** presents inflow and outflow of Lake Okeechobee through each structure. Flow monitoring locations at the structures used in this study are shown in **Figure 8**.



Figures 7a to c. Daily Average Flow for Pump Stations – September 1 through November 30, 1999.

Table 8. Lake Okeechobee Inflows and Outflows (ac-ft).

Pump Station	October 13 to 31, 1999		October 1999 Total	
	Inflow	Outflow	Inflow	Outflow
S131 PMP	694	0	1,721	0
S71_S	17,541	0	32,722	0
S129 PMP	1,095	0	2,300	0
S72_S	5,284	0	12,135	0
S127_P	4,125	0	8,050	0
S84_S	36,908	0	54,491	0
S65E	224,271	0	319,140	0
S154_C	11,322	0	20,700	0
S133_P	2,705	0	6,271	0
S191_S	0	0	0	0
S135 PMP	5,410	0	9,164	0
S308_L	0	40,990	0	40,990
L8.441	58	0	307	1,302
S352_S	0	1,824	0	6,453
C-10	5,265	0	6,354	0
C-12A	2,780	0	4,617	0
C-12	3,111	0	4,177	0
S2_P	31,668	0	31,929	0
S351_S	0	0	0	98
C-4A	1,174	0	1,752	0
S3 PMP_P	3,213	0	3,213	0
S354_S	0	0	0	0
S236_P	1,271	0	2,713	0
INDUST	3	371	3	514
S4_P	1,326	0	6,578	0
S77_S	0	129,989	0	129,989
FISHP_O	21,842	0	36,807	0
Total	381,065	173,175	565,146	179,346

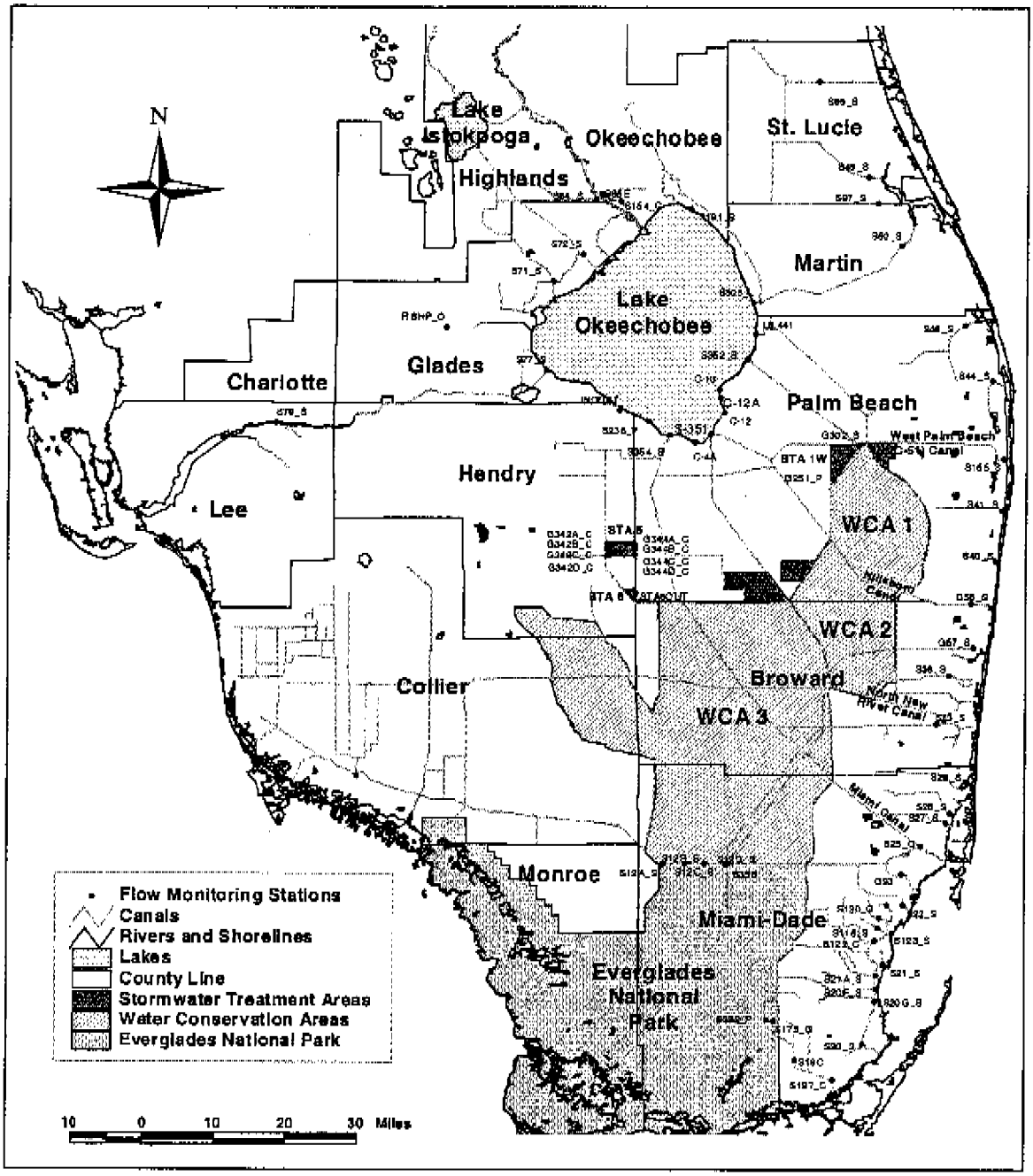


Figure 8. Flow Monitoring Locations used in this Study.

Outflow through Coastal Structures

Outflow through coastal structures was very high due to Hurricane Irene. For October 1999, the total volume of outflow through coastal structures was 1,108,107 ac-ft with 976,757 discharged between October 13 and 31. **Figures 9a to 9e** depict flows through the east coast coastal structures and the Caloosahatchee River on the west, for the period from September 1 to November 30, 1999. High flows due to the hurricane are observable from October 13 through the following days. Ten structures attained historical maximum daily average flow rates in October 1999 due to Hurricane Irene. **Table 9** depicts flow volumes through coastal structures indicating those that achieved maximum discharge. The highest discharge rate was through S79 in the west (7,527 cfs), S155 on C-51 (7,327 cfs), S41 on Canal 16 (4,821 cfs), S99 on Canal 25 (4,555 cfs) and S40 on Canal 15 (3,981 cfs). Except S79, which has higher capacity than the observed maximum flow during the period, the remaining four structures achieved historical maximum daily average discharge rates.

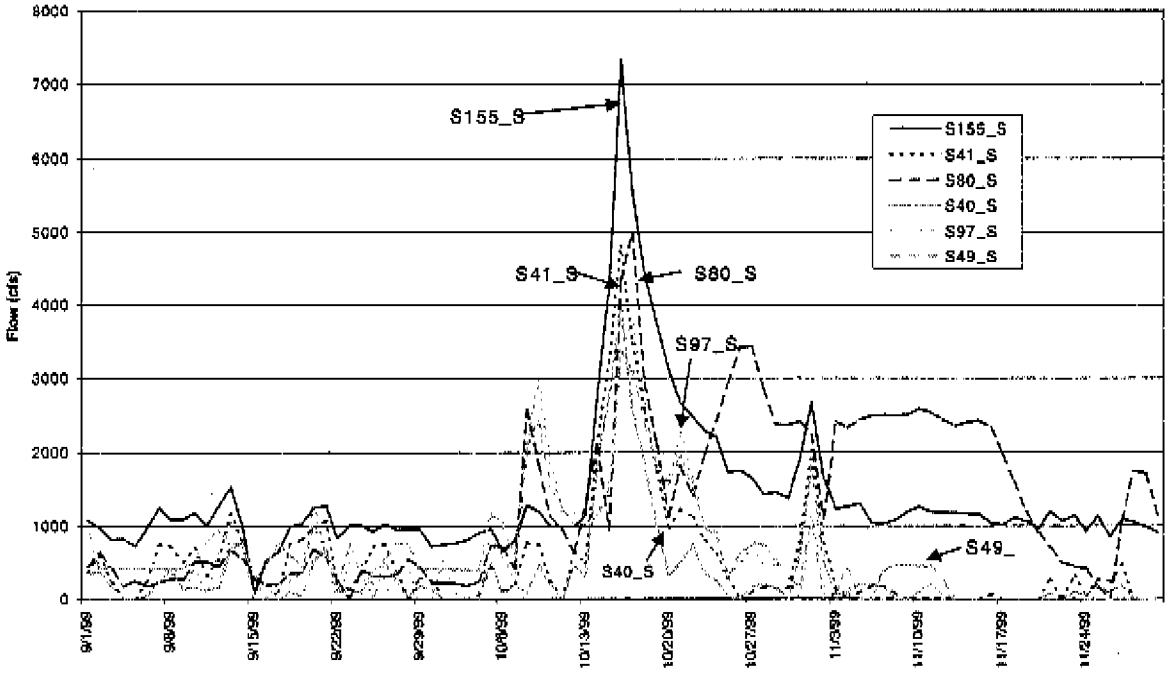


Figure 9a. Daily Average Outflow for Selected Coastal Structures – September 1 through November 30, 1999.

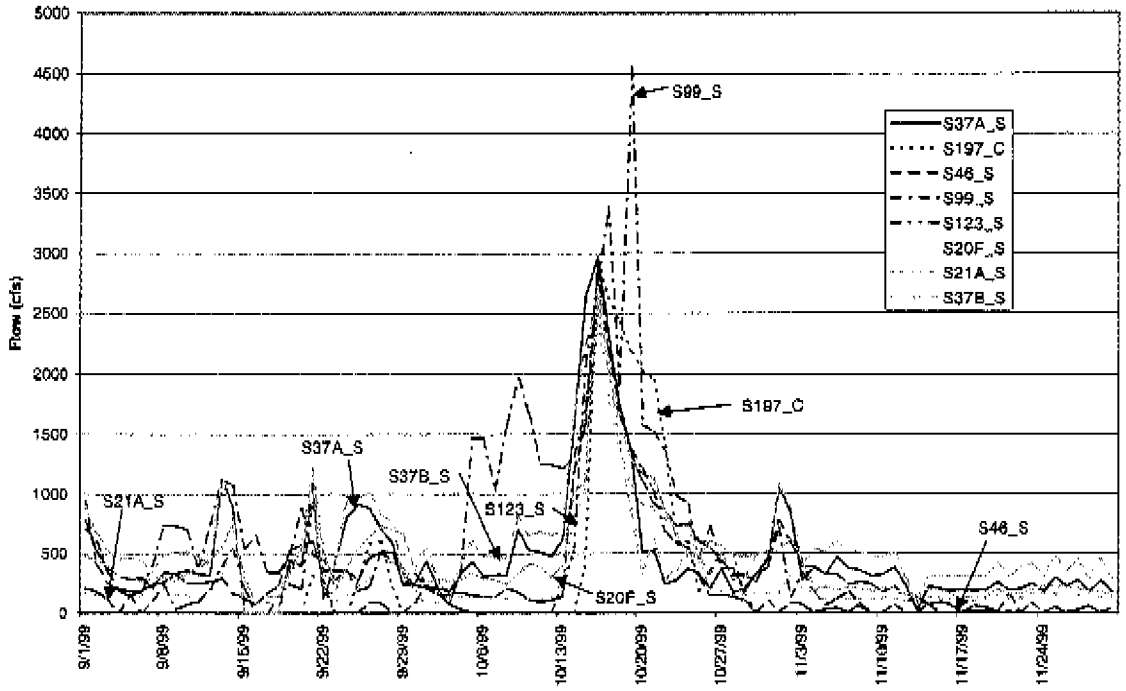


Figure 9b. Daily Average Outflow for Selected Coastal Structures – September 1 through November 30, 1999.

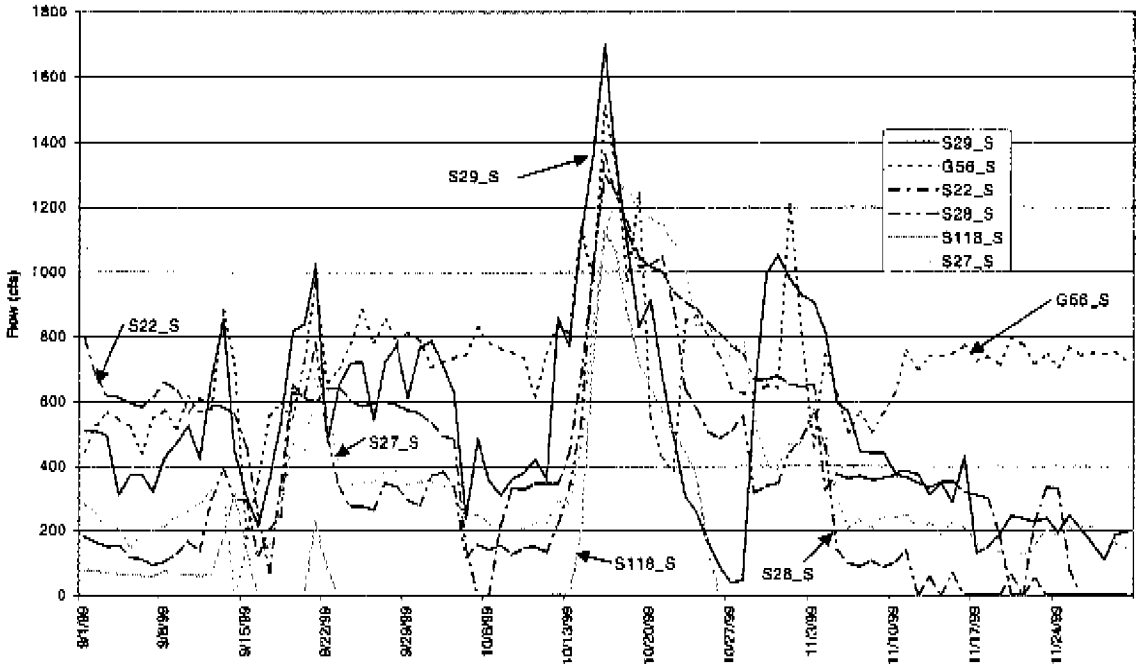


Figure 9c. Daily Average Outflow for Selected Coastal Structures – September 1 through November 30, 1999.

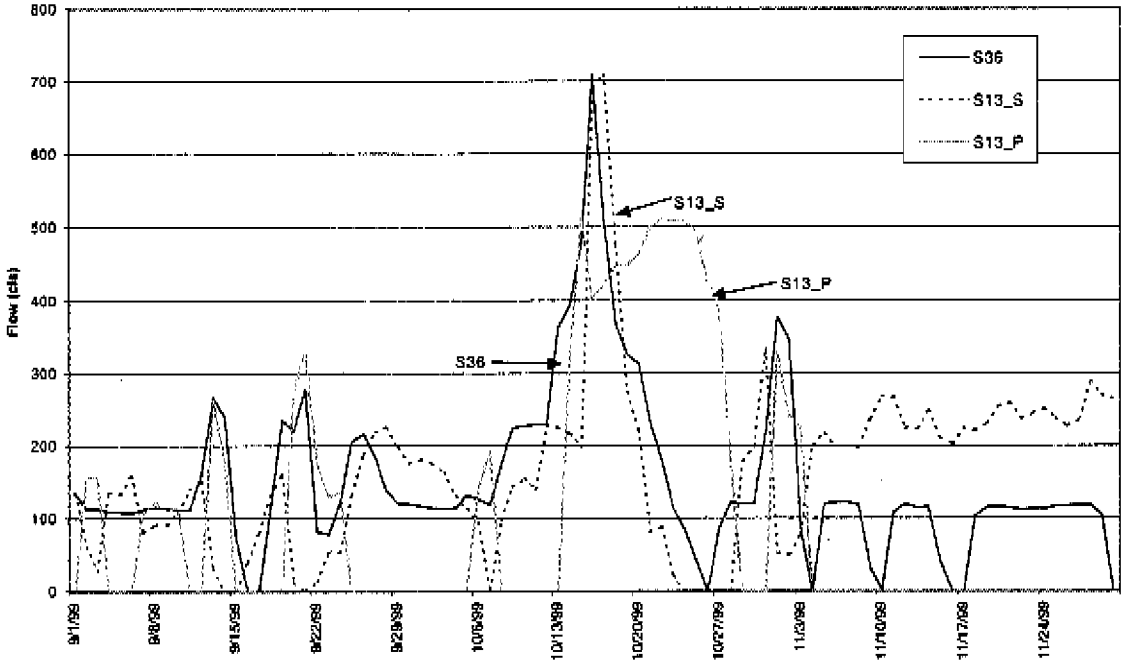


Figure 9d. Daily Average Outflow for Selected Coastal Structures – September 1 through November 30, 1999.

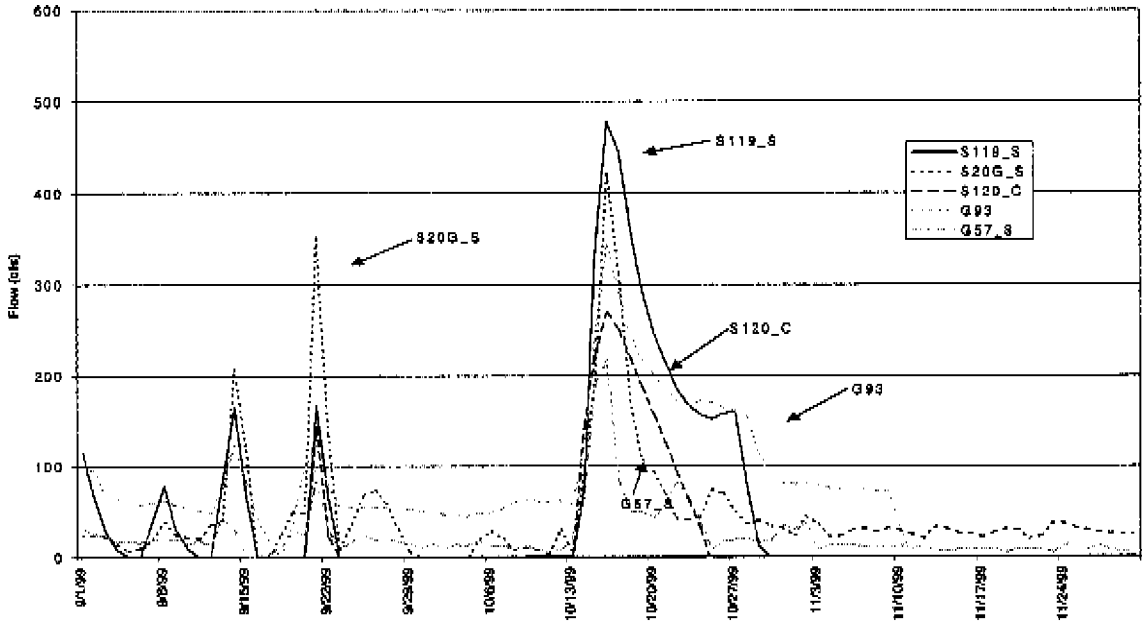


Figure 9e. Daily Average Outflow for Selected Coastal Structures – September 1 through November 30, 1999.

Table 9. Flow through Coastal Structures (ac-ft).

Structure	October 13 to 31, 1999	October 1999 Total
G56_S	31,316	49,117
G57_S*	2,462	2,177
G93	7,919	6,638
S118_S	14,624	14,633
G119_S	6,985	6,985
S123_S	30,997	32,014
S155_S*	105,535	127,655
S197_C*	37,410	37,410
S20_S	5,564	7,345
S20F_S*	36,002	43,243
S20G_S	3,842	4,098
S21A_S	28,428	31,201
S22_S	33,400	40,505
S27_S*	31,820	37,897
S28_S	27,366	32,208
S29_S	27,511	39,222
S36_S	9,487	13,295
S37A_S*	34,199	43,371
S40_S*	34,856	38,952
S41_S*	49,163	55,592
S44_S*	20,418	23,057
S46_S	36,452	40,035
S49_S	48,981	74,304
S79_S	101,884	101,884
S80_S	93,766	113,305
S97_S	50,606	73,740
S99_S*	51,657	76,705
Total	976,757	1,108,107

* indicates record high average daily flow rate in October 1999

Flow to the Everglades National Park

Flows to the Everglades National Park increased during Hurricane Irene similar to most water control structures in the affected areas (**Figure 10**). The total volume of inflow to the Park through structures S12A, S12B, S12C, S12D, S18C, S175, S332 and S333 for October 1999 was 365,785 ac-ft with 276,672 ac-ft occurring between October 13 and the end of the month. **Table 10** depicts structure by structure flows.

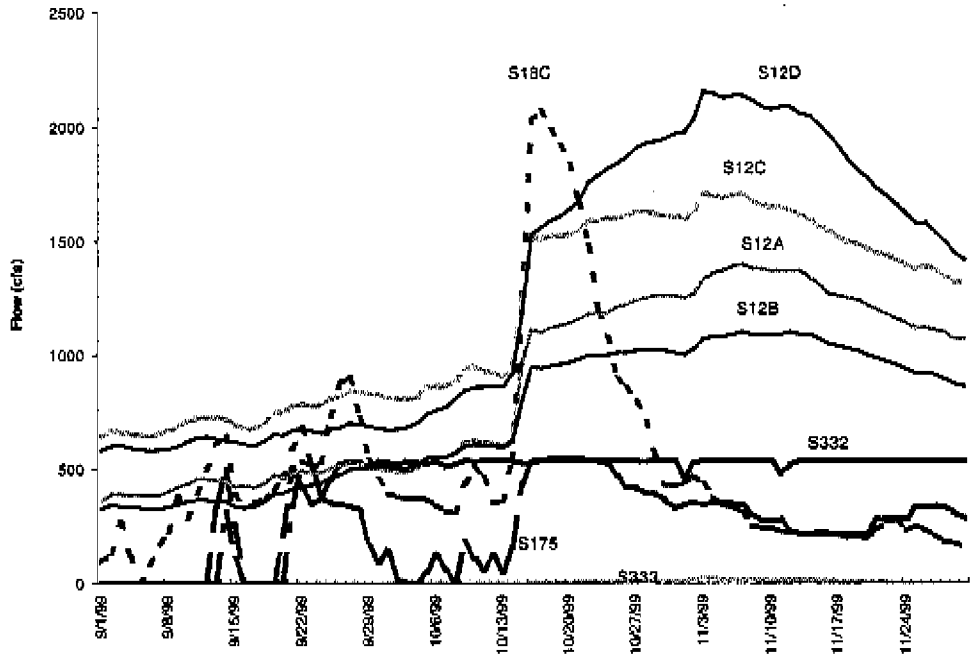


Figure 10. Inflows to Everglades National Park – September 1 through November 30, 1999.

Table 10. Inflows to the Everglades National Park.

Structure	Flow Volume (ac-ft.)	
	October 13 to 31, 1999	October 1999 Total
S12A	42,078	55,310
S12B	35,477	48,717
S12C	56,222	77,047
S12D	62,193	80,560
S18C	43,847	52,955
S175	16,406	18,153
S332	20,211	32,805
S333	248	248
Total	276,672	365,785

Stormwater Treatment Areas (STAs) Flows

Inflow to and outflow through STA-6 increased during the hurricane and following days (**Figure 11**). Between October 13 and 31, inflow was 9,408 ac-ft, while outflow was 11,749 ac-ft. For October, inflow was 14,735 ac-ft and outflow was 18,847 ac-ft. The observed flows show that STA-6 did not contribute to any flood attenuation during the hurricane event. Total outflow and the rate of outflow was higher than inflow most of the time. STA-1W had inflow of 7,945 ac-ft and outflow of 10,793 ac-ft between October13 and 31. For October, inflow was 16,359 ac-ft and outflow was 18,829 ac-ft. Inflow was pulsed while outflow was generally steady. During the hurricane event, no inflows occurred and outflow was zero for a day (**Figure 12**). Almost all the inflow to STA-5 in October was during the hurricane and the following days totaling 7,422 ac-ft (**Figure 13**). The outflow was 17,268 ac-ft and occurred during the hurricane and following days.

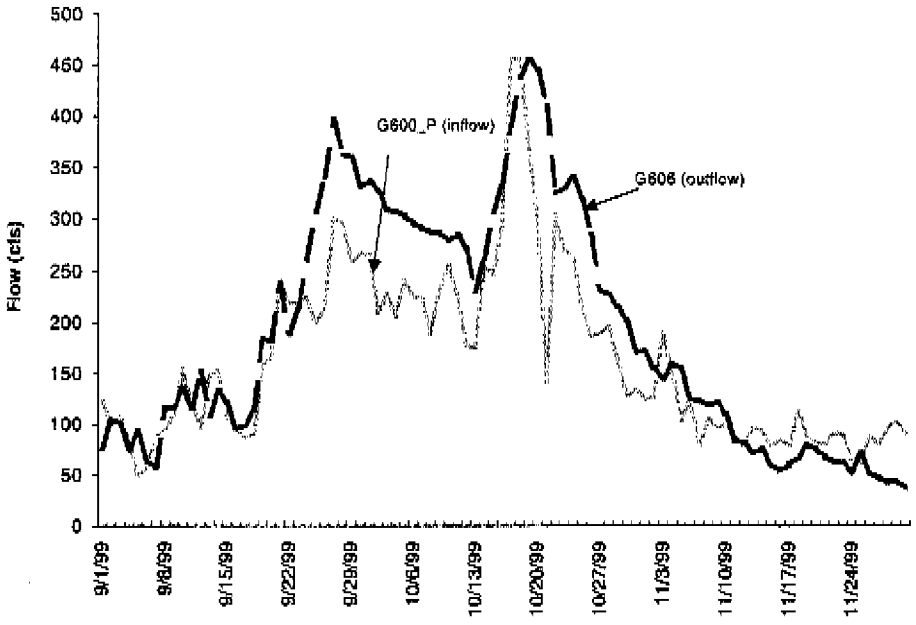


Figure 11. Inflow and Outflow to STA-6 - September 1 to November 30, 1999.

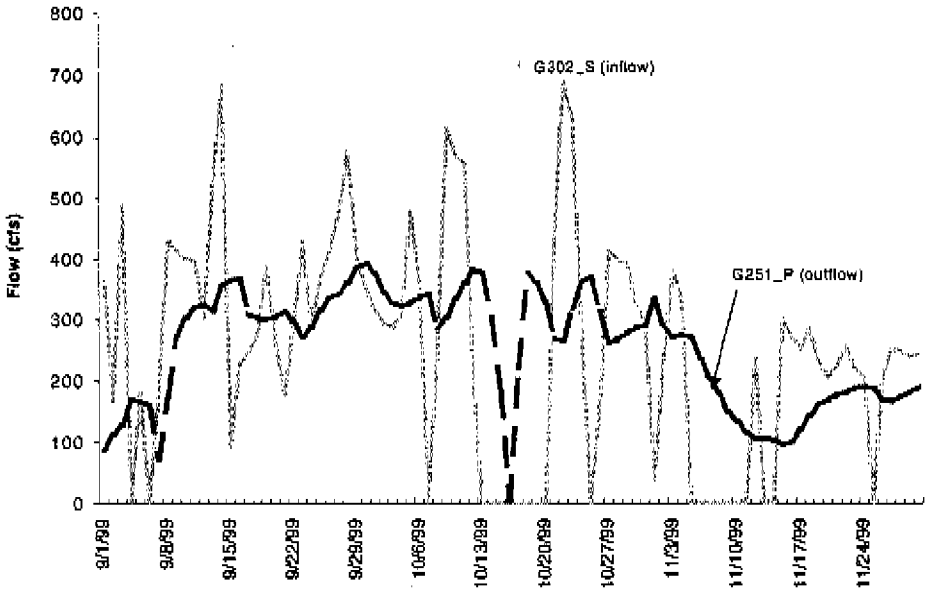


Figure 12. Inflow and Outflow to STA-1W – September 1 through November 30, 1999.

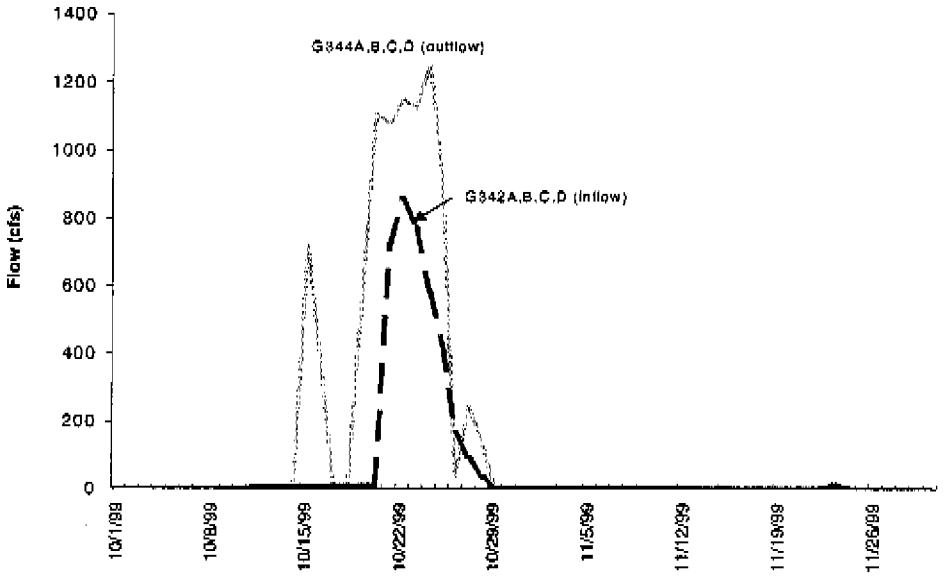


Figure 13. Inflow and Outflow to STA-5 – September 1 through November 30, 1999.

WATER LEVELS

Lake Okeechobee

Water level monitoring sites used in this study are shown in **Figure 14**. Water levels in lakes, water conservation areas and canals rose sharply due to the rainfall and associated flows from Hurricane Irene. There were many instances where historical high water levels were observed. The average daily water levels from September 1, 1999 through November 30, 1999 for Lake Okeechobee and Water Conservation Areas 1, 2 and 3 are depicted in **Figure 15**. Lake Okeechobee's water level was rising before the hurricane impacted, reaching 17.10 ft NGVD on October 13. The Lake achieved its maximum annual water level of 17.80 ft NGVD (National Geodetic Vertical Datum) on October 25, 1999. As shown in **Table 3**, the areal average rainfall from Hurricane Irene on Lake Okeechobee and its northern watershed (Lower Kissimmee and Upper Kissimmee) was not very high (1.27, 1.28 and 1.47 inches, respectively). Otherwise, higher water levels would have resulted.

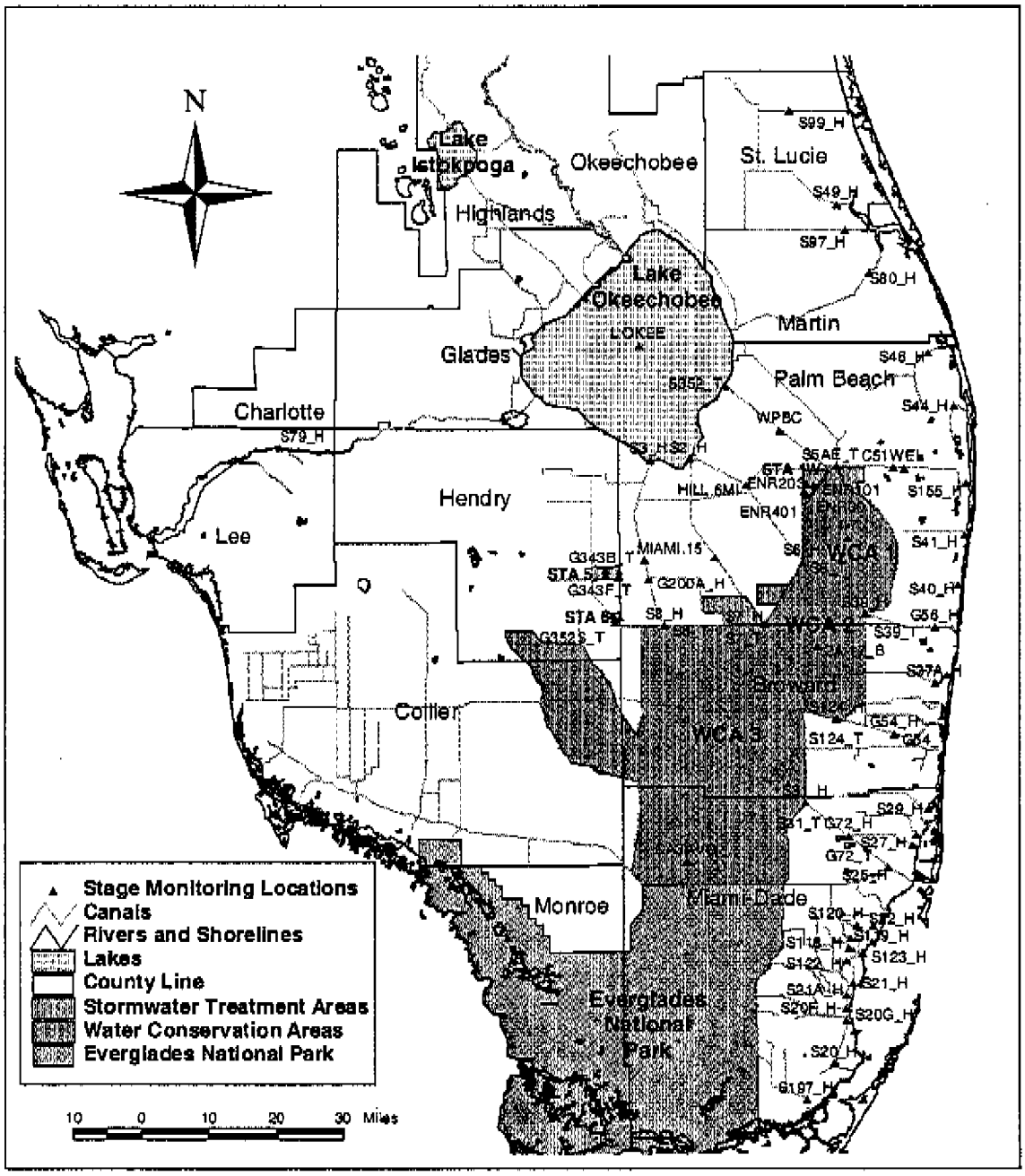


Figure 14. Water Level Monitoring Locations used in this Study.

Water Conservation Area 1

Water Conservation Area 1 water level was rising before Hurricane Irene impacted, attaining 17.28 ft NGVD on October 13, 1999 (**Figure 15**). There was a sharp increase in water level reaching a maximum of 18.12 ft NGVD on October 15, 1999, which was the maximum stage for 1999. The rise is due to high rainfall (**Table 3**) and inflows through pump station S5A and structures G251 and G301 (**Figures 7c** and **12**).

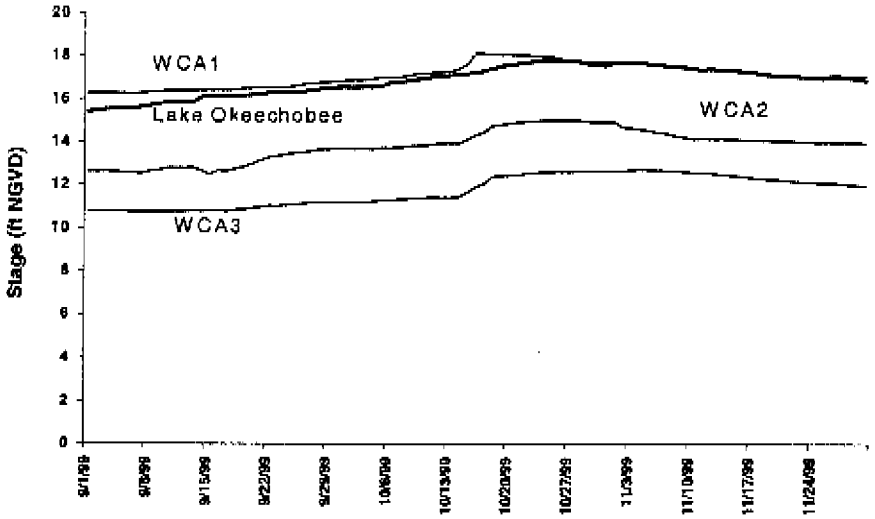


Figure 15. Daily Average Water Level for Lake Okeechobee and Water Conservation Areas 1, 2 and 3 – September 1 through November 30, 1999.

Water Conservation Area 2

Water level in Water Conservation Area 2 was on the rise since the beginning of October 1999 (**Figure 15**). Hurricane Irene's rainfall and associated flows increased the stage from 13.93 ft NGVD on October 13 to a yearly maximum of 15.00 ft NGVD on October 26, 1999. The sharp rise was due to rainfall from the hurricane and inflows.

Water Conservation Area 3

Water level in Water Conservation Area 3 was on the rise beginning October 1, 1999 (**Figure 15**). Due to the rainfall from the hurricane and inflows, the water level rose from 11.39 ft NGVD on October 13, 1999 to 12.62 ft NGVD on October 28, 1999. The maximum stage for the year was attained on November 3, 1999, at 12.70 ft NGVD.

Stormwater Treatment Areas

Water levels in Cells 1, 2, 3 and 4 of STA-1W were high a few weeks before the hurricane. Although outflow was higher than inflow, the stages remained high due to the rainfall (**Figure 16**). There was no contribution from STA-1W in temporarily storing water during the hurricane and following days. Both Cell 3 and Cell 5 of STA-6 showed significant stage rise during the hurricane and gradually drawdown to initial stage by the end of October (**Figure 17**). There was some increase in storage in STA-6 during the hurricane although outflow was higher than inflow. Cell 1A and 2A of STA-5 showed some increase while Cell 1B and Cell 2B declined due to discharge (**Figure 18**). No significant gain in storage was observed.

Figure 16. Daily Average Water Level in Cells 1, 2, 3 and 4 of STA1W – September 1 through November 30, 1999.

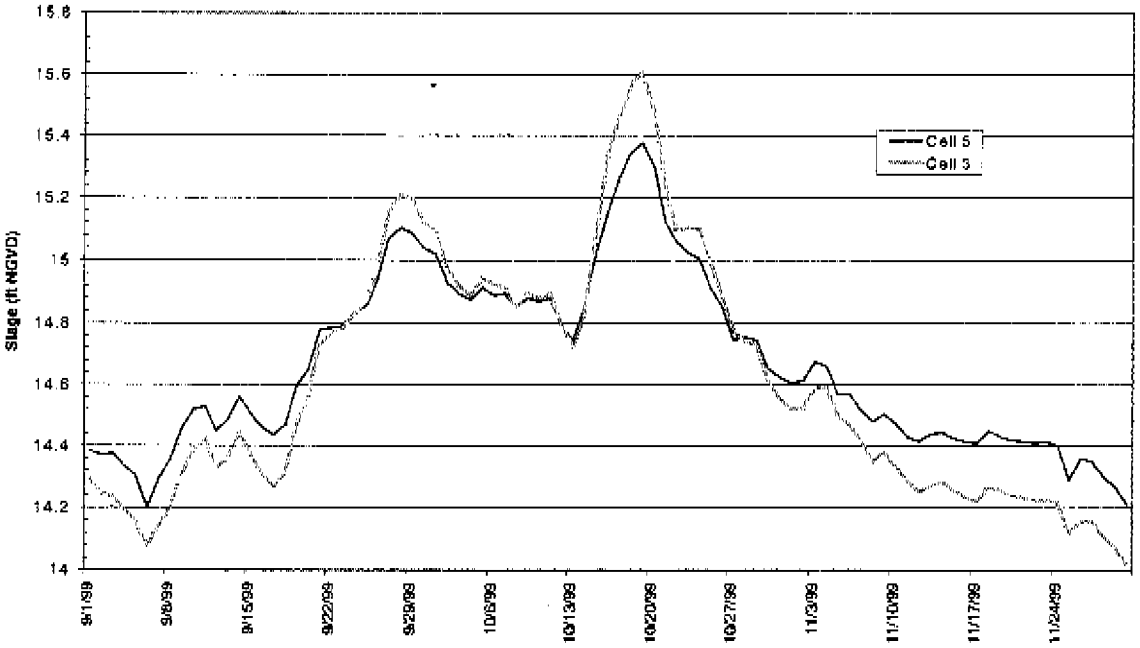


Figure 17. Daily Average Water Level in Cells 3 and 5 of STA6 – September 1 through November 30, 1999.

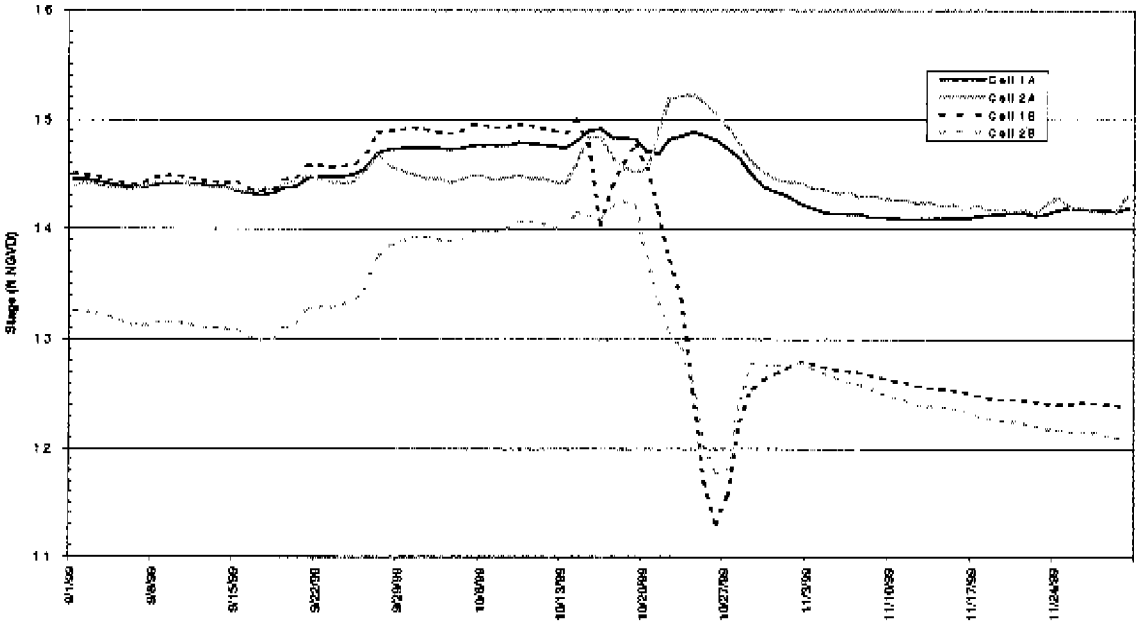


Figure 18. Daily Average Water Level in Cells 1A, 1B, 2A and 2B in STA5 – September 1 through November 30, 1999.

Primary Canals

Water level in the primary canals significantly increased during the hurricane, and several record high water levels were observed. The West Palm Beach (C-51) Canal showed a drastic increase in water level starting at Lake Okeechobee (S352) to its coastal outlet (S155). **Figure 19** shows water levels in West Palm Beach Canal at gaging stations along the flow path from Lake Okeechobee to the coast; S352 at Lake Okeechobee, WPBC at Big Mound Canal, S5AW at S5A pump station, S5AS and S5AE at S5A complex, C51WEL at Wellington, C51SR7 at SR7 and S155 at Atlantic coast (**Figure 19**). The highest recorded water level since 1973 was attained at C51WEL; since 1979 at C51SR7; and since 1968 at S155 head water. The effect of Hurricane Irene is clearly shown along the canal.

The Hillsboro Canal also showed an increase in water level along its path from Lake Okeechobee at (S2_H), the Hillsboro Canal at 6 mile bend (HILL.6MI), the S6 pump station (S6_H, S6_T), the Hillsboro Canal at Conservation Area 1(S39_H, S39_T), and the Deerfield lock on Hillsboro Canal (G56) (**Figure 20**). The highest recorded water level since 1979 was observed at the S39 tailwater and the tailwater of G56. **Figure 20** shows daily average water level along the Hillsboro Canal for the period September 1, 1999 to November 30, 1999. The effect of Hurricane Irene is clearly shown.

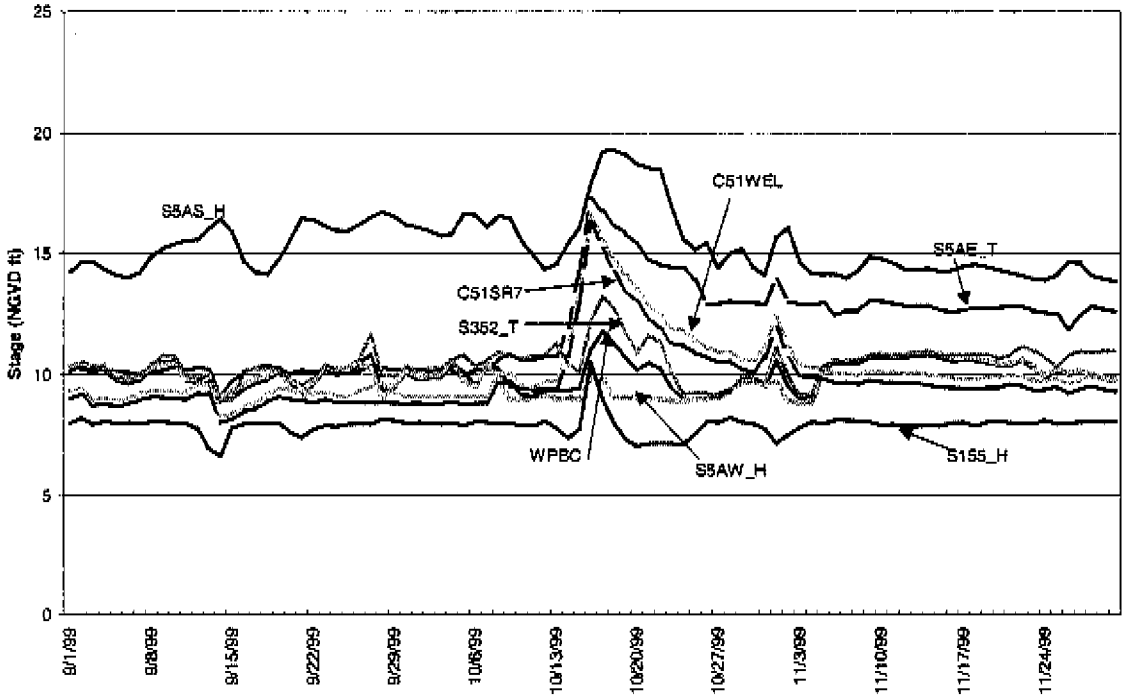


Figure 19. Daily Average Water Level Along the C-51 Canal (West Palm Beach) – September 1 through November 30, 1999.

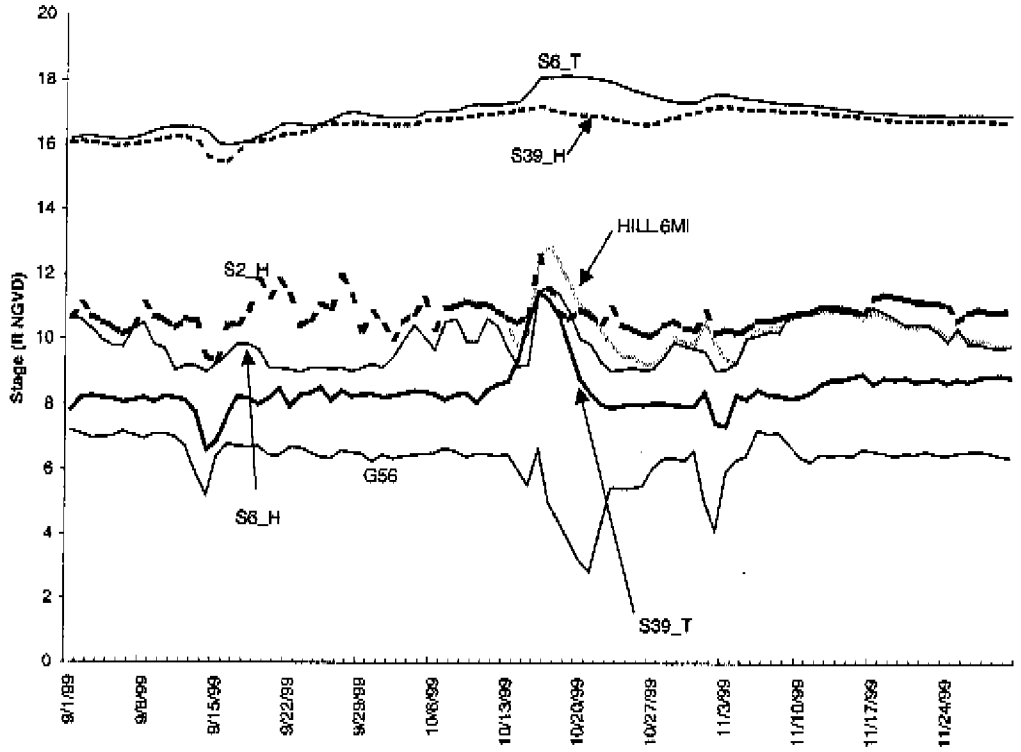


Figure 20. Daily Average Water Level Along the Hillsboro Canal – September 1 through November 30, 1999.

The North New River Canal showed a significant increase in water level along its flow path, as well, starting from Lake Okeechobee (S2_H), North New River at South Florida Sugar (NNRC.SFS), S7 pump station (S7_H, S7_T), Culvert on L-35A on North New River Canal (S124_H, S124_T), and Sewell Locks on North New River (G54_H, G54_T) (**Figure 21**). Maximum historical record high water levels were attained at tail water of G54 (highest since 1969), at North New River at South Florida Sugar (since 1986) and at S124 head water (since 1985). **Figure 21** shows daily average water level along the North New River Canal for the period September 1, 1999 to November 30, 1999. Again, the effect of the hurricane is clearly shown.

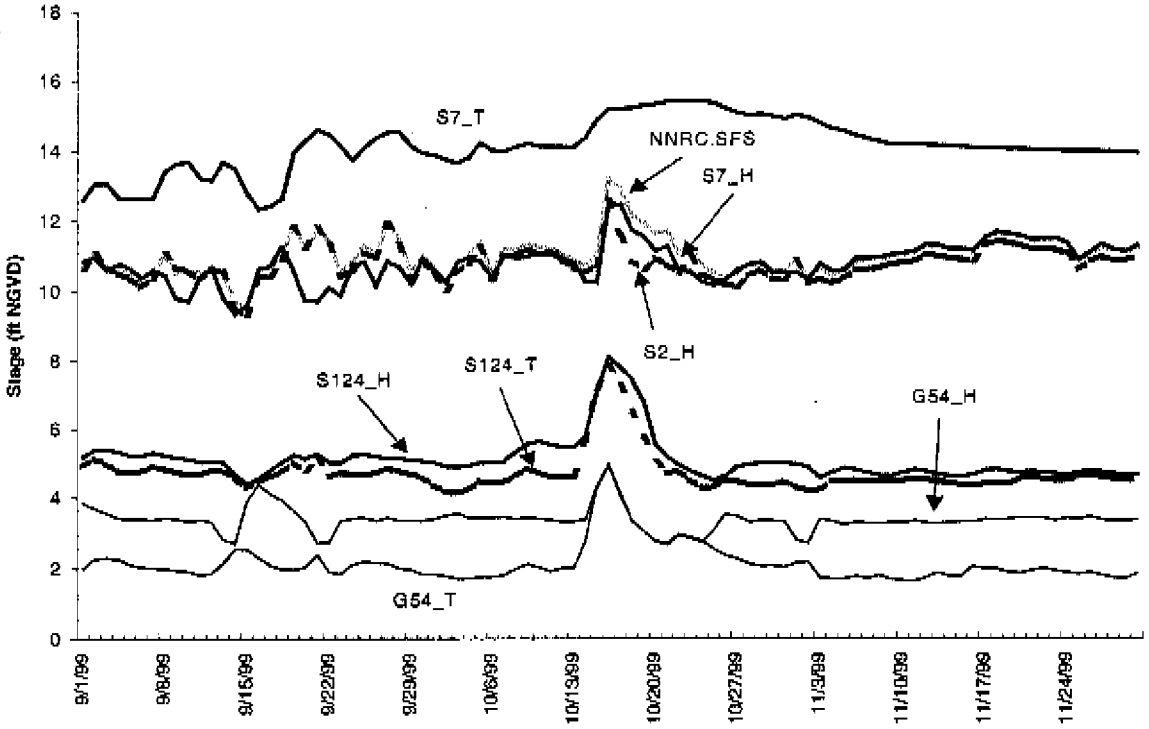


Figure 21. Daily Average Water Level Along the North New River Canal – September 1 through November 30, 1999.

The Miami Canal showed a significant increase in water level along its flow path from Lake Okeechobee (S3_H), the Miami Canal 15 miles below Lake Harbor (MIAMI.15), pump station G200A at the northwest corner of the Holey Land (G200_H), the S8 pump station (S8_H, S8_T), the S-31 culvert on Canal C-6 at Conservation Area 3B (S31_H, S31_T), G-72 on Canal C-7 at N.W. 87th avenue (G72_H, G72_T), and the S-25 culvert on Canal C-5 at tidewater (G72_H, G72_T) (**Figure 22**). Maximum historical record high water level was observed at the G72 headwater (since 1985), the G72 tailwater (since 1985), and the S31 tailwater (since 1985). **Figure 22** shows the daily average water level along the Miami Canal for the period September 1, 1999 to November 30, 1999. The effect of Hurricane Irene is clearly shown.

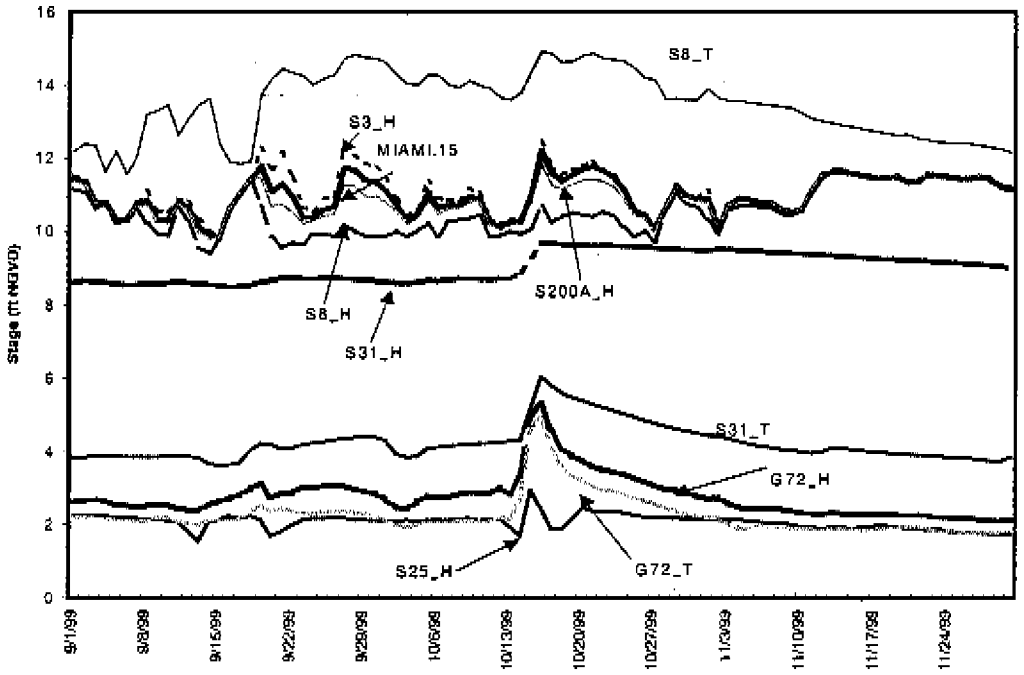


Figure 22. Daily Average Water Level Along the Miami Canal – September 1 through November 30, 1999.

GROUNDWATER LEVELS

Fluctuations of Shallow Water Tables

Data from 168 wells in 12 counties where groundwater levels were monitored was examined to determine the impact of Hurricane Irene on groundwater table elevations. Thirty-seven wells were selected as representative of the response to the hurricane. **Figure 23** shows water levels in three wells in Miami-Dade County and is typical of the response of wells in the surficial aquifer to an extreme rainfall event like Hurricane Irene. Broward and Miami-Dade counties recorded the highest areal average rainfall totals for the five-day period from October 13 to 17, 1999 at 10.24 and 10.23 inches, respectively.

Figure 24 shows changes in groundwater table elevation from October 1, 1999 to October 17, 1999 for the 37 wells examined in this study. Some caution should be exercised when reviewing this figure. The impact of rainfall events on groundwater elevations are subject to site-specific characteristics including antecedent moisture condition, soil type, ground cover, lithology and boundary conditions such as distance to and depth of adjacent surface water bodies and distance to other pumping or injection wells. The variation among the three wells shown in **Figure 23** can, in a large part, be explained by these site-specific characteristics.

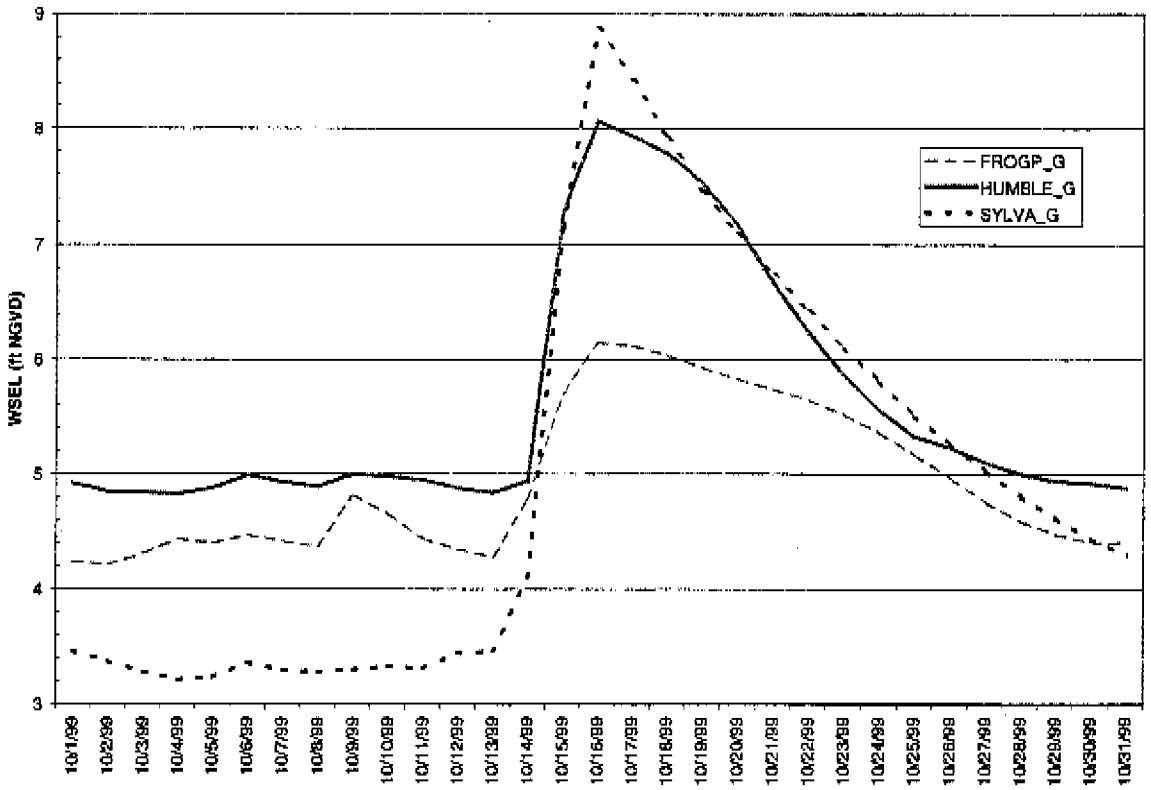


Figure 23. Groundwater Table Elevations at 3 Wells in Miami-Dade County - October 1999.

In addition, groundwater tables usually rise a number of days after water has begun to infiltrate the ground surface as the result of a rainfall event. Typically, groundwater levels in the surficial aquifer show the quickest response. By focusing on wells in the surficial aquifer (all wells are within 40 feet of the ground surface), the relative impact on groundwater elevations of rainfall received during the first part of October 1999 including that from Hurricane Irene, can be seen in **Figure 24**. Some of the greatest increases in groundwater elevations through October 17, 1999 were in wells in counties that received the greatest rainfalls, namely Miami-Dade County (10.23 inches) and Broward County (10.24 inches).

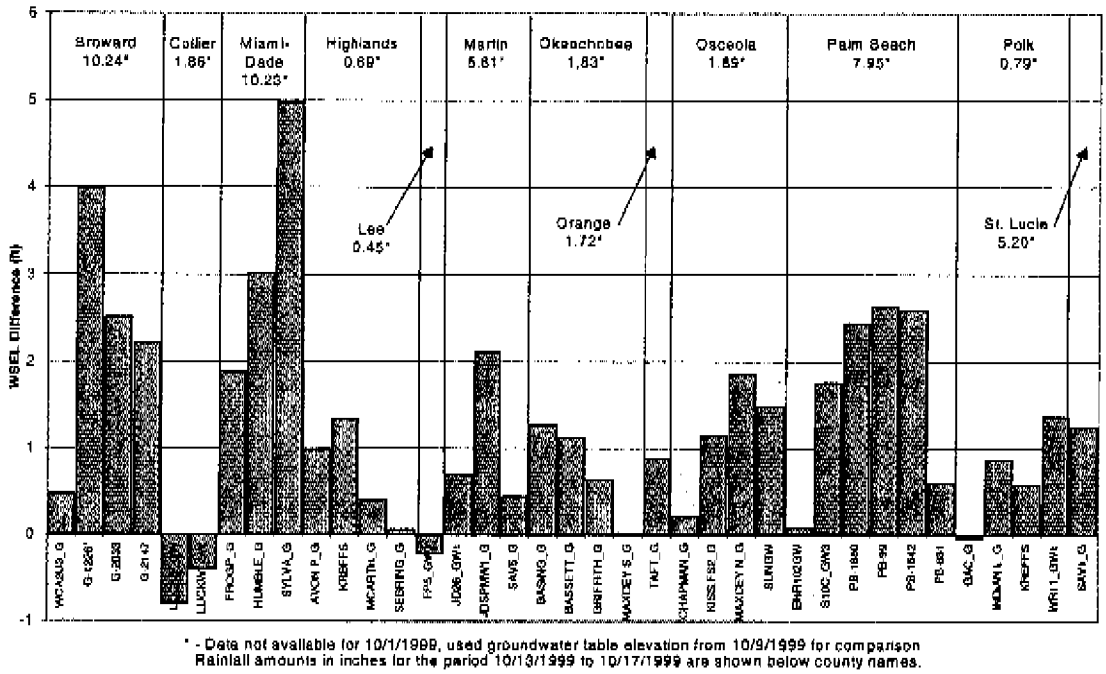


Figure 24. Groundwater Table Elevation Differences at 37 Selected Wells.

SUMMARY

In this study, the fact that hurricanes and tropical storms have high frequency of occurrence in South Florida is referenced. There is general interest in knowing the measure of the magnitude and occurrence of certain high or low rainfall events in order to imply flood or water shortage effects, respectively. The frequency of Hurricane Irene's rainfall, and the spatial and temporal distribution of October 1999 rainfall in South Florida are presented. The determination of frequency of a rainfall event in an area is subject to the approach in analysis. The meaning of the frequency analysis varies with the purpose it is used for. A drainage system with insufficient detention and drainage removal capacity would be affected by intensity of rainfall. In such cases, both total magnitude and intensity of rainfall are important. In this study, frequency estimates for 24-hour, 48-hour, and 72-hour rainfall at a gaging site are presented. Also, county-wide and South Florida Water Management District rainfall basin areal average rainfall is provided.

The amount of pumping and discharge through District structures is presented, and historical structures that achieved historical maximum discharge are identified. Inflow and outflows in major parts of the system are presented. The study also included water level changes in Lake Okeechobee, Water Conservation Areas, Stormwater Treatment Areas and major canals. The effect of Hurricane Irene on the primary water management system is shown. Surficial groundwater table fluctuation is presented. The information in this study will contribute input into the operational decision-making process in regional water management for such events.

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