# Technical Paper

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## Hydrology and Hydraulics of South Florida

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**by**

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**Hydrology and Hydraulics of South Florida**

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***Abstract***

The ecological and physical characteristics of South Florida have been shaped by years of hydrologic variation. South Florida hydrology is driven by continuous balance of rainfall and evapotranspiration reflected in surface water runoff, surface and subsurface storage, flows through the low relief features, dry-outs and wildfires. Generally, the region is a wet region with a regional average annual rainfall of 134 cm. The general hydraulic gradient is north-to-south, where under the natural system excess surface water flows from Upper Kissimmee Basin in the north to the Everglades in the south. The current hydraulic and hydrologic system is composed of lakes, impoundments, wetlands, canals and numerous water control structures that are managed under various water management schedules and operational decisions, based on flood control, water supply, water quality and environmental restoration objectives. Lake Okeechobee is the center of the South Florida hydrologic system with the largest storage and it plays a critical role in flood control during wet seasons and water supply during dry seasons. Hydrologic extremes are exemplified by flooding and excess water during wet years and wildfires and water shortage during drought years. The development of the region required a complex water management system to manage flooding, occasional drought, and hurricane impacts. Excess water is stored in lakes, detention ponds, wetlands and impoundments or discharged to the coast. Currently, as part of a major environmental restoration program, reservoirs are planned and are under construction to increase storage for water quantity and water quality improvements.

***Introduction***

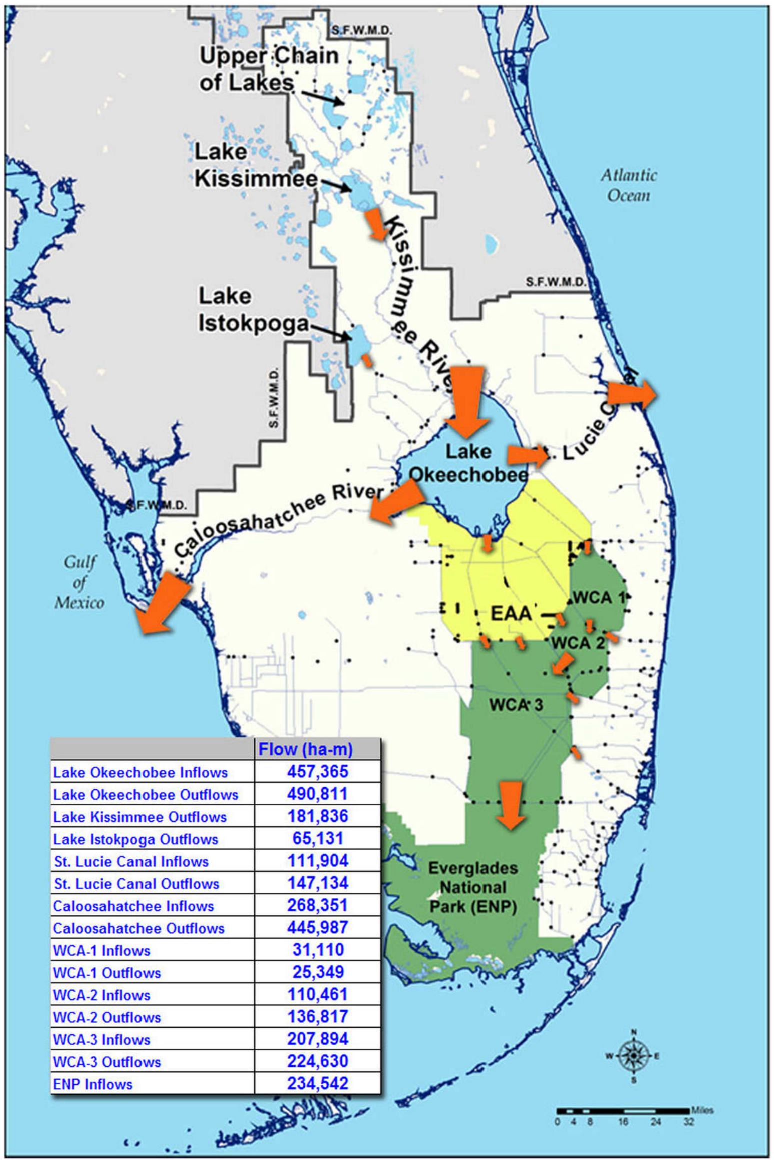
The South Florida Water Management District (District or SFWMD) area extends from Orlando to the north to the Florida Keys to the south (Figure 1). It covers an area of 46,400 square km extending across 16 counties. The District manages the region's water resources for flood control, water supply, water quality and natural systems needs. The District's water management system consists of lakes, impoundments, wetlands, and canals that are managed under a water management schedule based on flood control, water supply, and environmental restoration. The general surface water direction is from the north to the south, but there are also water supply and coastal discharges to the east and the west. The major hydrologic components are the Upper Kissimmee Chain of Lakes, Lake Okeechobee, Lake Istokpoga, the Everglades Agricultural Area (EAA), the Caloosahatchee Basin, St.

Lucie Basin, the Lower East Coast and the Everglades Protection Area (EPA). The Upper Kissimmee Chain of Lakes (Lake Myrtle, Lake Alligator, Lake Mary Jane, Lake Gentry, Lake East Tohopekaliga, Lake Tohopekaliga, and Lake Kissimmee) are a principal source of inflow to Lake Okeechobee. Lake Kissimmee is a 142 sq. km area lake draining into the Kissimmee River (C-38 Canal) through the S-65 spillway. The major source of inflow into Lake Okeechobee is the Kissimmee River (C-38 Canal) draining the Upper Kissimmee (4,194 sq. km); Lower Kissimmee (1,882 sq. km) and part of the Istokpoga water management basins (Abtew et al., 2007). Other inflows into Lake Okeechobee are inflows from Lake Istokpoga and Lake Istokpoga Surface Water Management Basin (1,082 sq. km) through C-40, C-41 and C-41A canals, Fisheating Creek, the Taylor Creek-Nubbin Slough Basin, reverse flows from the Caloosahatchee River, the St. Lucie Canal, and the Everglades Agricultural Area (EAA) from the south (Abtew et al., 2007). Lake Istokpoga is a 112-sq. km shallow lake, with outflow through structure S-68 into the Surface Water Management Basin.

Lake Okeechobee is the center of the South Florida hydrologic system, with an area of 1,792 sq. km and a mean depth of 2.7 m. Since 1931, the average water level elevation is 4.4 m National Geodetic Vertical Datum (NGVD) with a maximum 5.72 m NGVD set on November 2, 1947 during a hurricane season. The lowest water level on record for the lake was 2.73 m NGVD, set on May 24, 2001, during the drought of 2000–2001. The annual average inflow to Lake Okeechobee (1972–2006) is 266,286 ha-m, while the average outflow is 187,707 ha-m. Outflows are mainly through the south, southeast, and southwest structures (Abtew et al., 2007). The Everglades Agricultural Area is the main source of surface water inflow into the EPA. On the average, about 111,018 ha-m of water is discharged from the EAA to the south and southeast, mostly discharging into the EPA (Abtew and Khanal, 1994; Abtew and Obeysekera, 1996). About 10 percent of the discharge from the EAA is Lake Okeechobee water flow-through, with most of it reaching the EPA (Abtew and Khanal, 1994; Abtew et al., 2002).

The Everglades Protection Area begins at the southern and eastern edges of the EAA and extends south to Florida Bay. The EPA consists of several defined regions: Water Conservation Area 1 (WCA-1) (572 sq. km), which contains the Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge); Water Conservation Areas 2A and 2B (WCA-2A and 2B) (544 sq. km); Water Conservation Areas 3A and 3B (WCA-3A and 3B) (2,369 sq. km); Everglades National Park (Park or ENP) (5,566 sq. km); and Florida Bay, as shown in Redfield et al. (2003). The extent and components of the EPA are depicted in Figure 1. The EPA receives additional surface water inflows from the urban areas in the east, the southeast and the northwest; these sources are identified as non-Everglades Construction Project (non-ECP) stormwater flows. Surface water flow into and out of the EPA is determined by weather-related factors and multi-objective water management decisions that include fixed regulation schedules, deviations, commitments, and emergency management. Emergency management includes flood control during high rainfall events, water supply during drought periods, saltwater intrusion, and environmental issues. The major hydrologic components of the District are depicted in Figure 1 with water year 2006 major surface water flows.

The hydraulic components of the water management system are composed of storage and conveyance systems. The major storage components are lakes, impoundments, ponds and wetlands. The conveyance system is composed of a network of canals and water control structures. Water is moved throughout the water management system by gravity and pumps. The average volume of water pumped by the District for the last ten years was 331,697 ha-m per year.




| | Flow (ha-m) |
|---|---|
| Lake Okeechobee Inflows | 457,365 |
| Lake Okeechobee Outflows | 490,811 |
| Lake Kissimmee Outflows | 181,836 |
| Lake Istokpoga Outflows | 65,131 |
| St. Lucie Canal Inflows | 111,904 |
| St. Lucie Canal Outflows | 147,134 |
| Caloosahatchee Inflows | 268,351 |
| Caloosahatchee Outflows | 445,987 |
| WCA-1 Inflows | 31,110 |
| WCA-1 Outflows | 25,349 |
| WCA-2 Inflows | 110,461 |
| WCA-2 Outflows | 136,817 |
| WCA-3 Inflows | 207,894 |
| WCA-3 Outflows | 224,630 |
| ENP Inflows | 234,542 |

**Figure 1. Major hydrologic components of the South Florida water management system and surface water flows for WY2006 (May 1, 2005 to April 30, 2006).**

South Florida experiences hydrologic variation that ranges from extreme drought to flood. The hydrology of the area is driven by rainfall, rainfall generated runoff, groundwater recharge and discharge, and evapotranspiration. Surface water runoff is the source for direct and indirect recharge of groundwater, lake and impoundment storage, and replenishments of wetlands. Excess surface water is discharged to the coast. Most of the municipal water supply is from groundwater that is sensitive to surface recharge through direct rainfall, runoff or canal recharge.

***Rainfall***

Rainfall in South Florida varies temporally and spatially with a seasonal pattern. South Florida is a high-rainfall region, with frontal, convective, and tropical system-driven rainfall events. The heaviest rains in South Florida are produced by mesoscale convective systems; extra-tropical in the dry season and tropical in the rainy season (Rosenthal, 1994). The regional annual average rainfall is 134 cm. The dry season extends from November through May and, on average, 35 percent of District rainfall occurs in this season. The percentage of dry season rainfall varies from rainfall area to rainfall area (Figure 2) with the highest in the Palm Beach rainfall area (39 percent) to the lowest in the Southwest Coast (29 percent) as presented in Ali and Abtew (1999a).

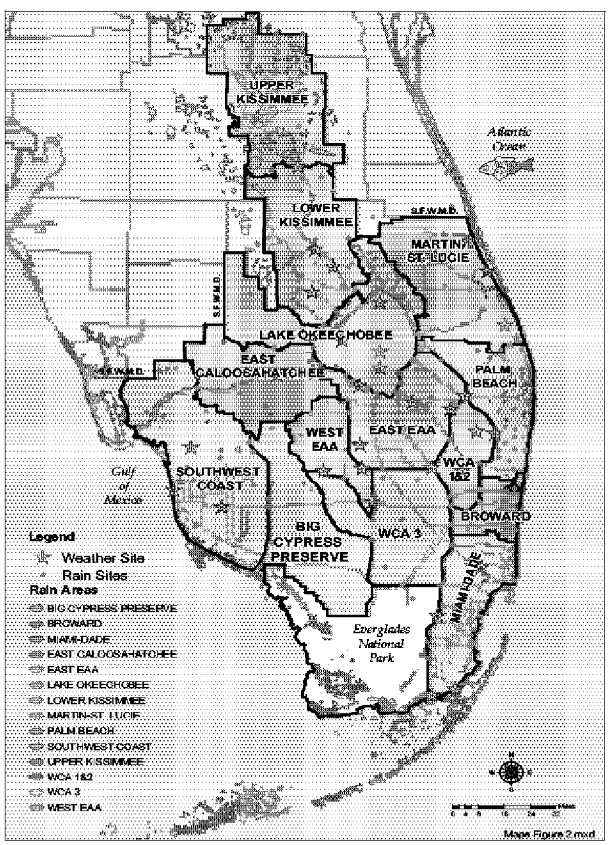



**Figure 2. Rainfall areas of the South Florida Water Management District.**

In Central and South Florida (excluding the Florida Keys), 57 percent of total summer rainfall falls on undisturbed sea breeze days, 39 percent on disturbed days, and 4 percent on highly disturbed days (Burpee and Lahiff, 1984). Point rainfall measurement at a rain gauge station could fluctuate from 75 cm to 250 cm annually, although areal rainfall fluctuation is relatively smaller. Figure 3 depicts annual rainfall in Miami, Florida from 1914 to 2005. The range is 86 cm to 227 cm with a mean of 150 cm and standard deviation of 32 cm. Statistical measures of year-to-year variation of monthly regional rainfall, average of multiple gauges over the District, are shown in Table 1 (Ali et al., 2000). Currently, the District rainfall monitoring has 279 active rain gauges supplemented with NEXRAD radar rainfall from OneRain, Inc (Pathak, 2006).

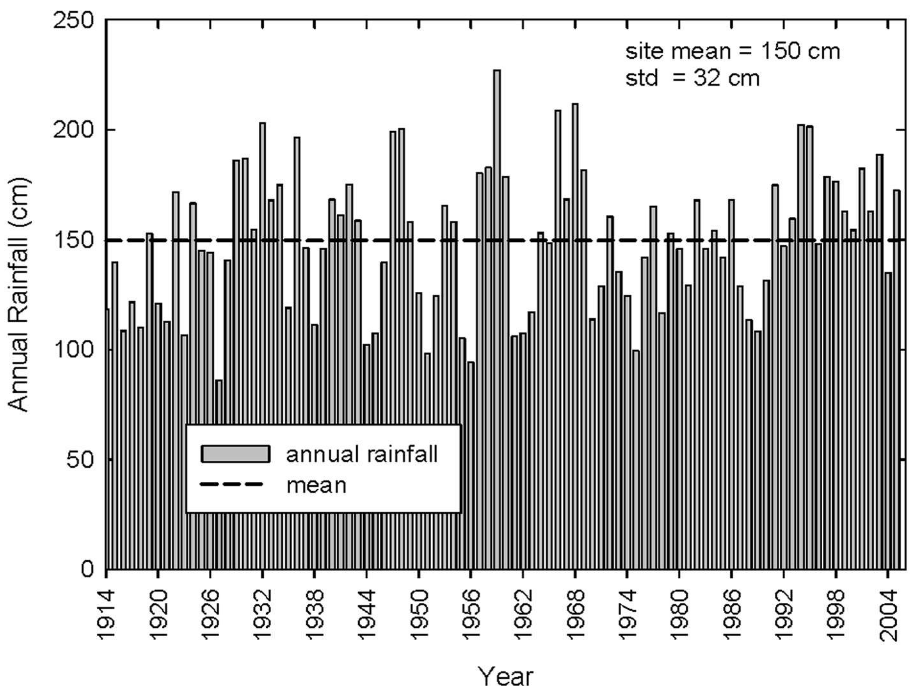



**Figure 3. Annual rainfall variation at a site, Miami.**

In the District, June is generally the wettest month and December is the driest. The wet season runs from June through October and accounts for 65 percent of annual rainfall (Abtew et al., 2002). During El Niño years, high rainfall events occur in the dry season resulting in water level rises and discharge through canals (Huebner, 2000). Extreme hydrometeorological and related events have significant effects on the region. El Niño conditions, hurricanes, and tropical systems are associated with high-rainfall events or seasons, and La Niña conditions and drought events result in dry conditions. El Niño occurs about once every three to four years (Huebner, 2000). Tropical systems are a frequent occurrence.

**Table 1. Monthly regional rainfall over the SFWMD area.**

| | Rainfall statistics (cm) | | |
|---|---|---|---|
| | Average | Standard deviation | Coefficient of variation |
| January | 5.1 | 5.2 | 2.4 |
| February | 6.0 | 4.7 | 2.0 |
| March | 7.5 | 6.5 | 2.2 |
| April | 6.6 | 5.9 | 2.3 |
| May | 11.8 | 8.0 | 1.7 |
| June | 19.9 | 10.6 | 1.3 |
| July | 17.7 | 8.1 | 1.2 |
| August | 17.9 | 8.1 | 1.1 |
| September | 18.4 | 9.6 | 1.3 |
| October | 12.0 | 9.7 | 2.1 |
| November | 5.8 | 6.0 | 2.6 |
| December | 4.8 | 4.6 | 2.4 |

The general area of the District has been affected by 42 hurricanes, 32 tropical storms, and 9 tropical cyclones (a term used before modern hurricane categories were established) from 1871–1999 (Abtew and Huebner, 2000). Since 1999, nine hurricanes and remnants of a tenth hurricane have affected the District area (Abtew et al., 2006). Other conditions, such as local convective systems and regional frontal systems, have also been associated with high rainfall events.

The annual average rainfall on the entire region managed by the SFWMD is 134 cm (Ali and Abtew, 1999a). The SFWMD area is divided into 14 rainfall areas for operational purposes. Spatial variation of annual rainfall over the District area is shown in Figure 4 by region (rainfall area). The source of annual rainfall statistics are Ali and Abtew (1999a) and Sculley (1986).

Historically, Palm Beach County rainfall area has the highest annual rainfall, followed by Broward County and Miami-Dade rainfall areas. The Lower Kissimmee and Lake Okeechobee rainfall areas have the lowest rainfall. The District's east coast receives higher rainfall levels than the inland and west coast areas. Even during drought years, there were cases where the coastal rainfall in these areas was close to the average. Because there are no large impoundments in the eastern coastal rainfall areas, runoff is discharged to the Atlantic Ocean.

Extreme hydrologic events contribute to variation in the temporal and spatial distribution of the hydrology of South Florida. Droughts are extreme hydrologic events categorized as moderate, severe, and extreme droughts. Generally, droughts are regional or have significant spatial coverage and corresponding impacts. In South Florida, a minimum of one severe drought occurs every 10 years. In Central and South Florida, severe droughts were reported in 1932, 1955-1957, 1961-1963, 1971-1972, 1973-1974, 1980-1982, 1985, 1988-1989, 1990, and 2000-2001 (Abtew et al., 2002). Tropical systems as tropical depressions, tropical storms, and hurricanes result in high rainfall and contribute to rainfall variation in South Florida. The general area of the South Florida Water Management District has experienced tropical systems at a rate of two every three years (Abtew and Huebner, 2000). Tropical systems contribute an estimated 15 to 20 percent of South Florida rainfall.

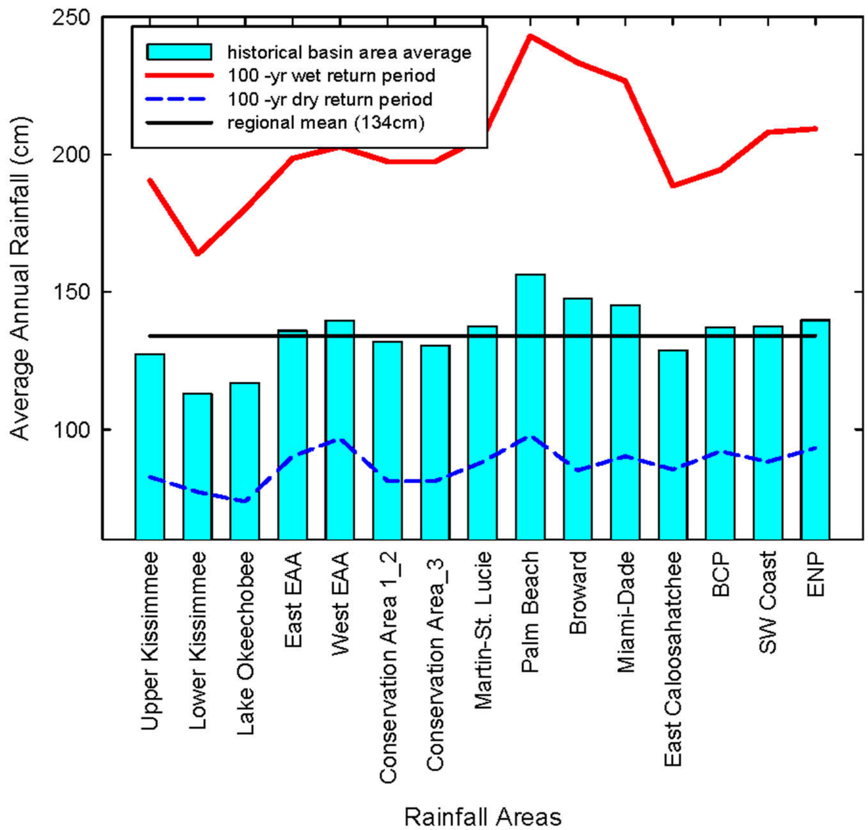



**Figure 4. Historical average, 100-year wet and 100-dry return period rainfall for each rain area**.

Other frontal or convective rainfall systems have resulted in major rainfall events resulting in sub-regional and local flooding. Extremely high local or sub-regional rainfall events also occur in the dry season. Such events include the January 15–17, 1991 high rainfall events in Palm Beach County (SFWMD, 1991), the January 2–3, 1999 extreme high rainfall event on Northeast Palm Beach County (Ali and Abtew, 1999b); the March 28-29, 1982 high rainfall events on Palm Beach, Martin, and St. Lucie counties' coast (SFWMD, 1982a); the April 23–26, 1982 high rainfall events on Palm Beach, Broward and Miami-Dade counties (SFWMD, 1982b); the May 22–23, 1984 high rainfall events on Palm Beach coast (SFWMD, 1984a); and the November 21–26, 1984 high rainfall events on Palm Beach coast (SFWMD, 1984b).

*Evapotranspiration*

Evapotranspiration (ET) varies spatially and temporally over South Florida with seasonal trends. A significant area of South Florida is covered by lakes, wetlands, and impoundments. These areas have evapotranspiration losses equal to potential evapotranspiration. Areas which have permanent or seasonal limitation to moisture have reduced evapotranspiration. Spatial variation of potential evapotranspiration or evaporation from wetlands and lakes over South Florida, as estimated by Abtew et al. (2003), is depicted in **Figure 5**. Generally, evapotranspiration increases from north to south. Temporal variation in annual evapotranspiration in South Florida is slight compared to annual variation in rainfall. Seasonal variation of evapotranspiration over South Florida is depicted in **Figure 6** (Abtew et al., 2003). Currently, evapotranspiration is computed at 21 weather stations.


**Figure 5. Estimated potential evapotranspiration isohyetal lines for the South Florida Water Management District area.**

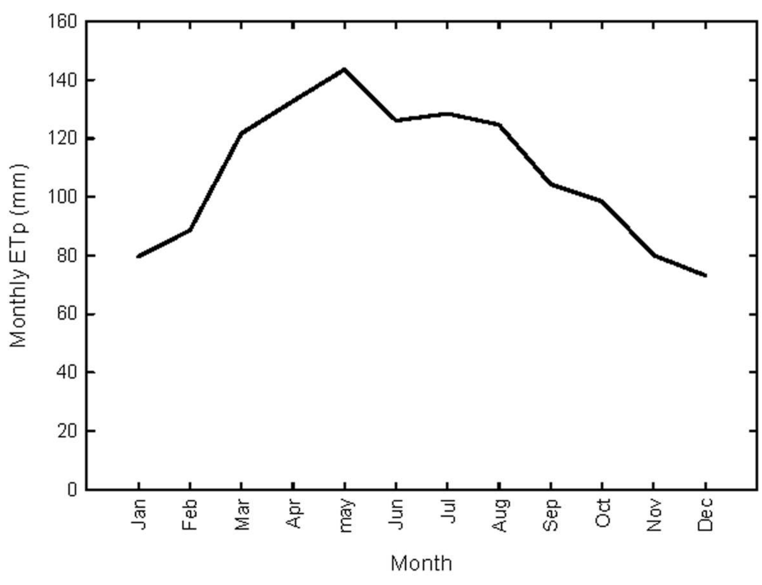



**Figure 6. Seasonal variation of monthly potential evapotranspiration in South Florida.**

### *Hydraulics and Operation*

Generally, South Florida is low relief and the hydraulics of the system requires large storage capacity, a network of canal conveyance, numerous hydraulic structures and a complex water management system. The general hydraulic gradient is from the north to the south. From Lake Tohopekaliga in the Upper Kissimmee to Florida Bay in the south, the elevation drop is 16.5 m in 400 km distance. Elevation drop from Lake Tohopekaliga to Lake Okeechobee is 13.4 m in about 130 km distance. On the average, the water level drop from Lake Okeechobee to the Caloosahatchee Estuary, 113 km to the west, and to the St. Lucie Estuary, 56 km to the east, is 4.4 m. As a result, South Florida is a low relief area. The drainage system is a three layer system, Primary, Secondary and Tertiary. The Tertiary System is mainly composed of residential and business area retention ponds, drainage canals and water control structures. These systems are maintained privately by entities such as home owner association managements. The Secondary System is operated by local drainage districts which drain excess water from the Tertiary System into their secondary system and discharge into the Primary System. The Primary System is managed by the South Florida Water Management District. This system is comprised of vast surface water storage areas as lakes, impoundments and wetlands; 3000 km of canals and more than 400 water control structures. The District has an extensive hydrometeorology and hydraulics monitoring network that complements the real-time water management decision making.

#### Storage

Major lakes and impoundments in the system are interconnected into the conveyance system of canals with flows and water levels regulated with water control structures with operation guidelines. The combined average storage of the major lakes and impoundments is over 637,000 ha-m with about 72 percent being that of Lake Okeechobee. During wet conditions and high flow periods, storage between the actual stage and the maximum regulatory stage is limited. The stage-storage curve for Lake Okeechobee is shown in Figure 7. The successful operation of the system depends on timely water management decisions and constant movement of water. Excess water is mainly discharged to the Gulf of Mexico, the St. Lucie Estuary, the Atlantic Ocean and the Florida Bay.

#### Conveyance

The Upper Kissimmee and the Lower Kissimmee drain into Lake Okeechobee through the Kissimmee River (C-38 Canal). Lake Istokpoga and the Lake Istokpoga water management basin drain into Lake Okeechobee through three major canals (C-40, C-41 and C-41A). Lake Okeechobee discharge and local runoff flows into the Gulf of Mexico through the Caloosahatchee River (C-43 Canal) to the west and to the St. Lucie estuary to the east through the St. Lucie River (C-44 Canal). Also, water supply and Lake regulatory releases are made to the south, to the EAA, EPA and the Lower East Coast. Major canals connecting Lake Okeechobee, the Everglades

Agricultural Area, the Water Conservation Areas and the east coast are the Miami Canal, North New River Canal, Hillsboro Canal and the West Palm Beach (C-51) Canal. Drainage from the EAA and a portion of the outflows from Lake Okeechobee are discharged to the south mainly to the Stormwater Treatment Areas (STAs) which are 16,000 ha of constructed wetland treatment systems designed to remove phosphorus. STAs discharge into the Water Conservation Areas to the south and the Water Conservation Areas discharge to Everglades National Park and to the east coast. These major canals also deliver groundwater recharge for the urban east coast water supply. The Upper East Coast and the Lower East Coast have numerous water drainage and water supply canal networks.

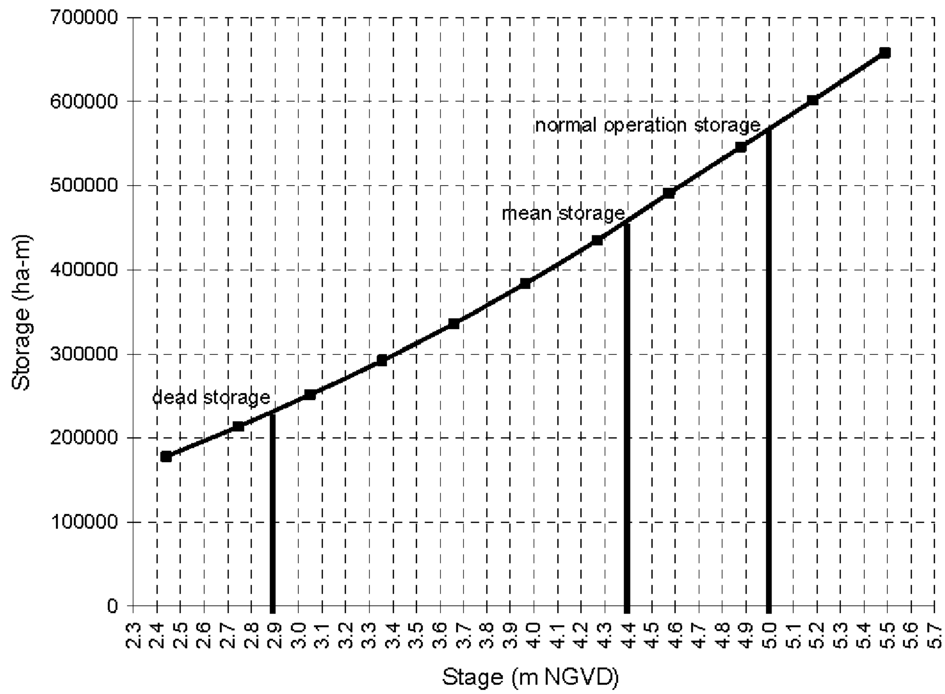



**Figure 7. Stage-storage curve for Lake Okeechobee.**

## Water Control Structures

Due to the low relief of South Florida, water movement is complex with bi-directional flows in many canals and it is aided with over 400 flow control structures. Major water control structure types include spillways, pump stations, gated culverts, and weirs. There are 425 flow control structures where flow is monitored; and 27 percent are spillways, 14 percent are pump stations, 55 percent are culverts and 4 percent are weirs. Although most water is moved by gravity, pumping is a critical part of the water management system. In FY2006, 444,000 ha-m of water was moved by pumping stations.

## Water Levels and Surface Water Flows

Water level and surface water flow data along with rainfall are the basis for water management decision making. An extensive network of water level gauges (1,195) and surface water flow monitoring sites (425) is supplemented with 975 wells for groundwater monitoring (Pathak, 2006). Real-time data are collected and water control structures are operated remotely, automatically with onsite preprogramming and manually. In general, water levels rise with significant rainfall and surface water transfer and decline with drier conditions and surface water withdrawal. High water levels can lead to flooding and low water levels can lead to water shortage and salt water intrusion into coastal aquifers. Water level fluctuations of lakes and impoundments (Figure 8) are indicators of hydrologic variation in the region.

Each year large volumes of water are handled in the South Florida water management system. Figure 1 illustrates how much water is moved through the major systems in one year. Generally, drainage from the coastal cities is discharged into the ocean. Most discharge to the ocean is by gravity, but high tide limits discharge capacity. From the north to south, a massive volume of water moves and continuous operation of moving water is needed as there is not sufficient storage. Under the Consolidated Everglades Restoration Plan, expansion of the storage capacity is underway with building of reservoirs. The Upper Kissimmee Basin discharges south through Lake Kissimmee at an annual average of 92,601 ha-m with an annual maximum of 187,901 ha-m since 1972 (Abtew et al., 2007). Lake Okeechobee inflows ranged from a minimum of 81,921 ha-m and a maximum of 457,365 ha-m with an average inflow of 266,286 ha-m since 1972.

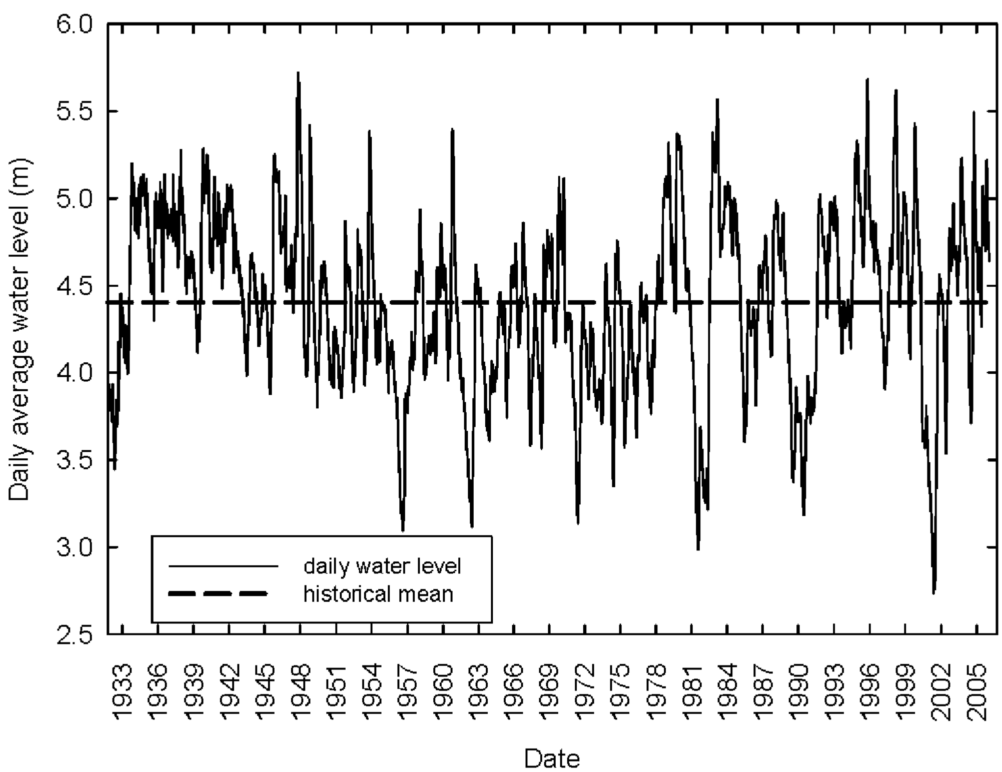



**Figure 8. Lake Okeechobee water level fluctuations (1931 to 2006).**

### *Summary*

South Florida has a wet and humid hydrology with infrequent drier periods. Meteorologically wet and dry season impacts are mitigated by water management decision making. The area's high hydrologic variation, low physical relief, limited storage and conveyance capacities make water management challenging. Water quality impacts on discharge receiving systems are part of water management decision making and are influenced by hydrologic variation. The area hydrology is influenced by tropical systems. The threat of hurricane impact on the water management infrastructure, such as dikes and potential flooding, influences water management decision. Hydrologic variation and uncertainties impact wet season water storage levels for the following dry season.

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