Appendix 2-1: Hydrological Monitoring Network of the South Florida Water Management District

Edited by Chandra S. Pathak

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EXECUTIVE SUMMARY

The acquisition of hydrologic and hydraulic data is a critical and key component of the South Florida Water Management District's (SFWMD or the District) mission. The District is responsible for the collection and validation of hydrologic data for real-time water management as well as for data analysis that results in archival hydrologic records that are used to evaluate and assess the current status of water resources systems. Data collection is accomplished via the District's hydrologic monitoring network, which has evolved over the years but was not specifically designed or optimized for any single purpose. This report provides status and inventory of the network as of April 30, 2007, and includes progress on the District's network optimization or design studies that began in 2002.

The hydrologic monitoring network is divided into five parts: rainfall, meteorological, surface water stage, surface water flow, and groundwater. The network is spatially distributed over the geographic areas of the District with sensors that record time varying data, i.e., rainfall, meteorological, stage, flow, and groundwater data. Description of each network part presents the history and evolution of the network; information on sensors/instrument(s) used; number and location of instruments; frequency of data collection; time interval of the available data; and optimization or design.

The District actively operates and maintains an extensive network of 287 rain gauges to obtain rainfall data. Since 2002, the District has been acquiring radar rainfall NEXRAD data coverage. The District has a meteorological monitoring network that includes 45 active weather stations. Meteorological data, such as air temperature, barometric pressure, humidity, solar radiation, wind speed, and water temperature, are collected and are available on breakpoint and daily time intervals. In addition, daily potential evapotranspiration (PET) data are available for 19 weather stations that were estimated using "the Simple Method".

A network of 1,265 active surface water stage gauges provides the surface water stage data for various water bodies. Additionally, the District owns a network of 446 active surface water flow monitoring sites that provide instantaneous flow data in 15-minute intervals and mean daily flow data. The groundwater monitoring network contains a total of 907 active groundwater wells that are monitored on 15-minute continuous, monthly, or greater than 1-month interval basis. The District is responsible for monitoring, maintenance, quality assurance/quality control (QA/QC), data archival, and funding for 568 of these wells. The U.S. Geological Survey is responsible for the remaining 339 wells.

Hydrologic data management includes processing the data collected, summarizing, deriving and analyzing, storing, and publishing. Processed data are archived into two different databases, namely, Data Collection/Validation Pre-Processing (DCVP) and DBHYDRO. Instantaneous (breakpoint) data are stored in the DCVP database, while daily summary and 15-minute interval datasets are published in the DBHYDRO database. End users can retrieve data from either of these two databases.

I. INTRODUCTION

By Chandra Pathak

A. Background

The South Florida Water Management District (SFWMD or the District) is responsible for managing and protecting water resources in a 46,439-square kilometer (17,930-square mile) region of South Florida. This area extends from Orlando in the north to Key West in the south and from the Gulf Coast in the west to the Atlantic Ocean in the east and includes Lake Okeechobee, the country's second-largest freshwater lake. This region is also the focus of an $8 billion environmental restoration program, known as the Comprehensive Everglades Restoration Plan (CERP). The District operates approximately 3,000 kilometers (1,800 miles) of canals and more than 500 water control structures across 16 counties to serve a population of over six million people.

Water flows from the northern part of the District south from the Upper Chain of Lakes near Orlando, along the Kissimmee River, through Lake Okeechobee, and finally to canals that release surface water to estuaries along the east and west coasts. Lake Okeechobee is at the center of this system and is the primary source of supplemental water supply for the Everglades Agricultural Area (EAA) to the south, the Caloosahatchee Basin to the west, the St. Lucie Basin to the east, and several other basins around the lake (**Figure 1**).

Lake Okeechobee receives the majority of its inflow from large tributary basins to the north, including the Kissimmee River and Fisheating Creek. The tributary basin area is more than five times the surface area of the lake. During normal climatic conditions, inflow volumes offset the large water needs to the south of the lake. However, when the climate remains abnormally dry for an extended period (for one or two seasons), inflows may diminish to very low levels during the same period that demands on the lake water increases. Consequently, lake stages may fall very quickly to extremely low levels. Conversely, when climatic conditions are wetter than normal, large volumes of water enter the lake, coinciding with periods when water use to the south may be minimal. These wet events cause lake stages to rise very quickly and require large volumes of water to be discharged to the Water Conservation Areas (WCAs) or to oceans through the St. Lucie and Caloosahatchee estuaries. Abrupt changes in flow and/or very large releases through the estuaries are harmful to these ecosystems.

The WCAs are the primary source of supplemental water for the highly developed urban areas along the southeast coast of Florida, with the lake being the alternate source. The WCAs were built as large water storage impoundments in the Everglades to provide both water supply and flood protection for the urban areas. In addition to agricultural and municipal water consumptive needs, water releases from the lake are required to meet the needs of the Everglades and the numerous related coastal ecosystems. The WCAs and Everglades National Park (ENP) are known today as the remnant Everglades. Water held in and released from the WCAs effectively recharges the Biscayne aquifer in some areas.

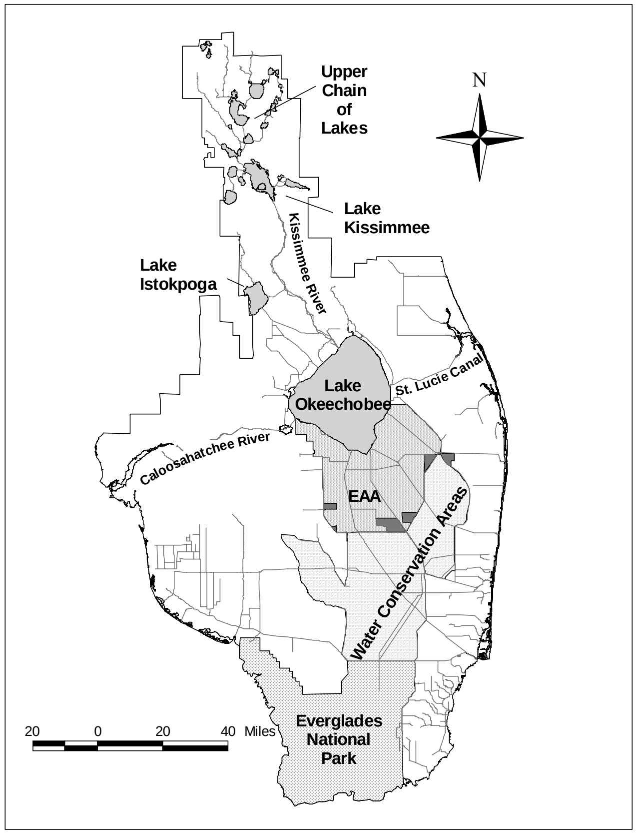

Figure 1. Map of the water resources area the District is responsible for managing and protecting.

The Florida Everglades — one of the world's largest freshwater wetlands — has changed dramatically over the past century. Historically, hundreds of lakes once flowed into the Kissimmee River, which runs south through 16,187 hectares (40,000 acres) of marsh to Lake Okeechobee. The lake in turn flowed into the Everglades, which extended over 1.2 million hectares (3 million acres) from the south shore of Lake Okeechobee to the Florida Bay and the Gulf of Mexico. The Everglades consisted of a continuous, shallow river flowing through grass-like plants, bordering expanses of cypress swamp, mangrove forest, and tropical hardwood hammocks on aquatic deep-water sloughs that extended nearly 50 miles (80 kilometers) wide and more than 100 miles (160 kilometers) long. These marshes and swamps acted as natural filters that recharged underground aquifers in the South Florida region.

B. Hydrologic Monitoring Network

1. Technical Background

Hydrologic variables such as rainfall, evapotranspiration (ET), surface water and ground water stages, and surface water and ground water flow, which are components of the hydrologic cycle, are multi-dimensional, continuous fluxes or fields (very often assumed to be smooth functions even though in reality that may not be the case) or fields — dynamic functions in space and time. These dynamic hydrologic variables are either mathematically estimated or directly measured at a specific point and for a discrete time segment. Subsequently, based on estimates or measurements at several points and various time segments for a given domain, effort is expended to represent and characterize the actual continuous flux or fields in space and time. In order to represent this continuous flux or fields of a variable in a domain, space is discretized into mesh of geometric elements, mostly linear regular or irregular rectangular/triangular shape grids/cells (prism/solid). This representation in space leads to estimation of the variable at certain relevant locations along those geometric elements (for example at vertices or grid/cell-centroids) by using simple to complex interpolation schemes among the measured points or numerical models. When there are many points of measurement, more accurate values of hydrological variables would be available for relatively better spatial representation of the flux or fields. The interpolated estimation comes with estimation errors that are generally understood to increase in proportion with increasing distance among the point of measurement. Hence, more points of measurement would lead to superior representation and characterization of the continuous flux or fields (assumed to be smooth functions) of a variable by reducing errors associated with interpolation. However, obtaining a large number of point measurements is not only expensive, but also in many cases is not very practical.

Similarly, to represent changes of the variable on a time continuum, various frequencies of measurement (or sampling) at selected time intervals (from seconds to hours; and/or at discrete time steps when there is change in the state of variable detected) are performed. Once again, some interpolation is needed when the time intervals between measurements increase and the measurements are used to represent a variable along a certain time continuum. This necessitates the selection of a variable-based sampling frequency. Typically, the limitation on the frequency of measurement/sampling for hydrologic variables depends on the type of sensors and dataloggers used for their measurements.

The character of the continuous flux or fields in space and time that is developed from the measurement differs significantly from variable to variable in a given domain based on spectral content. For example, the character of rainfall flux is significantly different from the character of solar radiation flux. The understanding and knowledge gained from past datasets for the spatial and temporal characterization of variables can be very useful. This experience, in turn, would provide the information needed to design and or optimize the monitoring network for a given variable. The analytical methods used for designing and/or optimizing the network are highly dependent on the variable-of-choice, and may not be interchangeable. Therefore, one should be very careful in generalizing the methods used to design and or optimize the monitoring network for each variable. For example, the methods used for designing a rain monitoring network would not be appropriate for designing a surface water stage monitoring network; similarly, the methods used for designing a wind monitoring network would not be appropriate for designing a solar radiation monitoring network. Therefore, the authors believe that the network for each variable should be designed independently. Each variable's network should be evaluated and assessed in an integrative fashion, as suggested by a peer reviewer, to further optimize the networks to take advantage of co-location of measuring sites, combining data transmission equipment and other infrastructure requirements with the intent of minimizing cost, improving efficiency and achieving economies of scale.

2. District's Hydrologic Monitoring Network

The District requires accurate data collection, processing and archival of the data collected by the hydrologic monitoring network for many purposes. There is a constant need to add new stations/sites with instrumentation for hydrologic data collection within the District, and this need will grow faster as the CERP and Acceler8 (i.e., certain CERP projects are on accelerated design and construction schedule) projects are implemented. The District's hydrologic monitoring network is divided into five parts:

1. Rainfall Monitoring Network
2. Meteorological Monitoring Network
3. Surface Water Stage Monitoring Network
4. Surface Water Flow Monitoring Network
5. Groundwater Monitoring Network

All of the monitoring networks at the District have evolved over the last several decades. Until 2002, these networks were not designed and/or optimized for any single purpose. During the last three to four years, the District has begun studies on the optimization and design of these networks. The optimization and/or design of the network involve consideration of the following elements:

- Purpose or objective of monitoring
- Total optimal number of monitoring stations (or points) needed
- Locations of the monitoring stations (spatial distribution)
- Sensor(s) needed for the monitoring station
- Frequency of data sampling needed at the monitoring station (temporal distribution)

Criteria for optimal locations for sampling would vary with the hydrologic parameter that is under consideration. For example, the criteria used for rain gauge location would be different than the criteria used for locating flow sites. Further details on these subjects are provided in the report related to the Rain-Gauge Network Optimization Study and the Flow and Stage Network Optimization Studies.

Traditional monitoring network design and or optimization studies are based on data collection purpose and usage (or objective of monitoring) for which variables are measured. However, in District's design and optimization studies, the District focused on obtaining the best possible data quality from the network for hydrologic variables that are financially affordable and most relevant for the District's mandated objectives. It is to be noted that the present monitoring network has evolved and is currently meeting most of the requirements of the District mission and goals. In addition, the District's staff is proposing to develop data accuracy requirements based on the data collection purpose. Currently, in the absence of these formal requirements, it has become important for the design/optimization studies to develop relationships among the numbers of sensors, distribution of sensors and estimated errors in measurements. Based on this information, the District can make decisions about a set of number of sensors and their distribution needed for measurement of each variable and the measurement errors and related risks associated with that decision.

Presently, the current flow monitoring network is the most efficient network of the five networks including rain, meteorological, surface water stage, surface water flow and ground water stage networks. This is due to where flow data are derived at a water control structure by using dynamic data from upstream and downstream surface water stage sensors and gate/pump operation. Where possible, some stage sensor data could be shared between two water control structures for computing flow depending upon the relationship and accuracy of the measured and estimated stage data; but this procedure would need to be performed on a structure-by-structure basis which is time consuming, expensive and may not lead to improved efficiency.

The District's remaining monitoring networks do require improvement in efficiencies. However, due to budget constraints, the network efficiencies need to be improved while holding current maintenance costs level. This would be best accomplished by maintaining the current total number of sensors. However, some increase in the current total number of the sensors may be scientifically necessary and would be considered and permitted by the District on a case-by-case basis. These cases would then require using some optimization scheme to improve the spatial distribution of sensors by removing certain dense clusters of sensors, and at the same time, adding sensors in other areas where very few sensors are present and additional sensors are needed. Specifically, these sensor relocations are being considered for the rainfall network, meteorological network, and surface water stage network. It is to be noted that the network design would be (and were) performed not on a project-by-project basis, but by using a regional approach that considered homogenous areas (polygons) with similar spatial characteristics of a variable for a selected time interval (daily or hourly) and season (dry or wet). However, in some cases, project requirements (for some specific projects) would be considered in design and or implementation of the network when available.

In addition, the District staff will be investigating the possibility of using simulation and sensitivity analysis procedures by utilizing the regional hydrologic models that would integrate a set of monitored variables and hence, further improve the efficiencies of monitoring networks, as recommended by peer reviewers.

The District is continuing to invest in the state-of-the-art monitoring technologies such as new field flow measurement instruments including Acoustic Doppler Current Profilers (ADCPs), Acoustic Doppler Flow Meters (ADFMs), Acoustic Doppler Velocimeters (ADVs), (these instruments are based on the acoustic Doppler principle and provide much more detailed and accurate flow data than other traditional mechanical instruments); actual evapotranspiration (ET) measurements at a field-scale level are performed utilizing a set of Eddy correlation instrumentation that includes a single-axis sonic anemometer, a fine wire, chromelconstantan thermocouple, and a krypton hygrometer; radar (NEXRAD) based rainfall estimation and satellite based ET estimation.

The District has been expending efforts in developing methodologies and procedures to estimate uncertainties associated with various monitored variables including flow measurements for a specific set of instruments. A project is under consideration to develop procedures for classifying the data quality under categories such as excellent, good, fair and poor for the monitoring data that are collected from rainfall, ET, surface water stages, surface water flow and groundwater monitoring network.

In recent years, the District has made advances in improving the maintenance cycles of sensors in the field; these advances significantly reduce the quantity of missing or bad quality data. Also, when it is discovered that certain sensors are not functioning or are providing bad quality data, then the appropriate information is provided to field crews to repair the instrument. This prompt responsiveness further reduces acquisition of missing or poor-quality data from the sensors. Additionally, the District's electronic data transmission and acquisition network (hardware and software) have been improved to increase reliability of the data transmission, which further reduces data loss between the field sensors and data acquisition system.

3. Purpose of Hydrologic Monitoring

Hydrologic monitoring is critical for water resources management. Hydrologic data on real-time or near real-time are needed for operation of various water control structures. The hydrologic data developed from the hydrologic monitoring network is used for various purposes and details on major purposes are shown below.

a. <u>Operation of water control structures (pumps, gated spillways and culverts)</u>: Water management is accomplished by operating hundreds of water control structures across the District. It is complicated by many factors including surface water–groundwater interaction, rainfall-runoff relationships, topography, errors in measurements, and/or estimates of hydrologic components such as flow, rainfall, evapotranspiration, storage and seepage, multiple competing objectives, and the uncertainty of forecasting meteorological events and climatic outlook. In addition, there are significant spatial and temporal variations of hydrologic components across the District. Water management is performed for various purposes by using previously established regulation schedules that integrate these different purposes. Regulation schedules are rule curves designed to manage the regional storage available. In order to satisfy flood control and water supply needs on a long-term basis, water level regulation schedules for each of the water bodies were developed by the District and USACE in cooperation with other agencies and stakeholders. One of the major purposes for the hydrologic monitoring is water management for the District by operating water control structures on real-time basis. Water managers who operate these structures require real-time and near-real-time data on rainfall, surface water stages, gate openings of the structures, and pump operation information from the hydrologic monitoring network.

The operation of structures is regulated on an hourly basis by examining existing conditions and following a set of previously established operating rules as guidelines. Water managers pay strict attention to the safety of people and property during the operation of the control structures, especially during extreme storm events. This requires knowing and understanding the physical capacity and capability of water control structures, levees and canals.

Operation of the water control structures includes adjustment of gate openings for gated spillways and gated culverts and the starting and stopping of pumps. Gated structure operations are classified into three groups. The first consists of Derived Data Set Point sites, which are computer controlled and operated from the Operations Control Center (OCC). The second consists of automatic sites, which are operated by computers or mechanical devices at the structure site not controlled from the OCC. The third group consists of manually operated gated structures.

Field staff are dispatched by the OCC operator from the appropriate field station to open or close manually operated gated structures. Pumps are controlled by the operators housed at the respective pump stations, while some of the unmanned pump stations are operated by the dispatched field station. Although these stations are typically operated during regular work hours, some must be operated after hours during extreme weather events and during most of the wet season.

b. Hydrologic and hydraulic analyses and modeling: The District performs many hydrologic and hydraulic analyses for various projects. For these analyses, the hydrologic time-series data (including rainfall, ET, surface and ground water stages, and surface water flows) collected from the hydrologic monitoring network are needed. In addition, these data are used in developing, calibration and validation of the regional, basin and/or sub-basin level hydrologic simulation model for the District.

c. Design of new hydraulic structures, levees, canals, storage facilities and others: Hydrologic data collected from the network are used for development of different design criteria such as 100-year 24-hour storm rainfall depths. Then, these criteria are used in design of the hydraulic structures, levees, canal and storage facilities.

d. Regulatory and/or permit compliance: Hydrologic data are used to develop regulatory criteria that regulatory permit applicants are required to follow. The data from the network are also used to monitor the permit compliance of the permit recipients.

e. Evaluation and assessment of various water-resources infrastructure facilities: The District has been constructing water resources infrastructure facilities over last several decades. These facilities require periodic evaluation and assessment of performances for which hydrologic data from the network are used.

4. Consistency of Historical Hydrologic Data

Over long periods of time (20-30 years), different technologies have been used to measure the same hydrologic parameter due to advances in measuring technology. Typically, improved technology, when implemented properly, has resulted in the improved quality of the data (with lower uncertainty). Essentially, the error band in the measurements is reduced. This does not necessarily translate to needing to adjust the data in the database. However, the hydrologic data user and data analysts should note that various sensors were used over time in measurement of these data.

Currently, the information on the measuring sensors is recorded in various separate databases, including District's corporate scientific database − DBHYDRO. For example, for field flow measurements that are used to calibrate flow computation equations, the instrument used to collect the measured flow data are recorded in the QMEAS database (a subset of the DBHYDRO database).

The District believes that it is not appropriate to "correct" past data. However, whenever possible, all the available additional information should be shared with data users. One peer reviewer recommended that the District research past equipment changes, learn the specifications of the old equipment, obtain any old-new comparison data from other agencies, compute bias that may be attributed to equipment changes, and develop new long-term data records that account for the equipment changes. These are excellent recommendations. However, due to fiscal limitation, the District has no plans to implement this retro-analysis.

5. Hydrological Data Quality and Uncertainty

Currently, the District has divided the quality of the measured hydrologic data into three broad and basic groups: (1) acceptable quality data, (2) bad quality data, and (3) missing data. The acceptable quality data is not quantitatively defined. The exclusion of bad quality data is considered an acceptable quality-control process. The data are processed to screen bad quality data values and these are flagged with a "?" tag/code in the database. These bad quality data values stand out when time series are graphically plotted and reviewed. Data values are considered missing when the measurements are not available from the sensors in the field for various reasons. Missing data values are tagged with "M" code in the database.

The missing data due to equipment malfunction including sensor malfunction and malfunction of data communication (or data transmission) system (such as CR10, RACU, MOSCAD, LoggerNets) can be obtained from the time-series datasets that are available in DBHYDRO database. The time-series data that are missing are tagged with code "M". On a given year, missing data vary between 2 and 5 percent depending upon measured parameter. For example, during 2005, approximately 3.2 percent daily mean flow data were missing, whereas approximately 4.2 percent daily rainfall data were missing due to malfunction of equipment that included both sensor and communication systems. In many cases, missing data values are estimated using various methods and are tagged with code “E” (estimated) and then stored in the database.

The District has been developing methodologies to estimate uncertainties of measurements and classify (i.e., quantitatively or qualitatively) data quality of the collected data that are “acceptable quality data”. These efforts are currently underway but are not ready to be included at this time in the report.

C. Objective and Scope

This report provides a status of the hydrologic monitoring network as of April 30, 2007, at the District. The information presented herein is a prerequisite to expanding and refining the District’s hydrologic network to meet the needs of CERP and non-CERP projects. The objective of this report is to describe the hydrologic monitoring network of the District. The hydrologic monitoring network is divided into five parts:

1. Rainfall Monitoring Network
2. Meteorological Monitoring Network
3. Surface Water Stage Monitoring Network
4. Surface Water Flow Monitoring Network
5. Groundwater Monitoring Network

In this report, the network is defined as the collection of sensors that are spatially distributed and record time varying data, i.e., rainfall, meteorological, stage, flow, and groundwater data. For each network, the report includes the history and evolution of the network; information on sensor(s)/instrument(s) used; number and location of instruments; frequency of data collection; time interval of the available data; optimization or design studies of the network completed and in progress; and relevant references used.

In addition, the report briefly describes data-related processes that are common to all the networks. These include data collection, data acquisition system, data processing, storage and retrieval, and data quality assurance/quality control.

D. Approach Used in the Report

The hydrologic monitoring network at the District is dynamic in nature and is constantly being expanded due to the needs of District initiatives such as Acceler8 and CERP. Rainfall and meteorological monitoring networks are not expanding that often and are relatively stable because of the adequacy of the data already provided. However, stage and flow networks are expanding at a faster pace as new Acceler8 and CERP projects that change stage and flow data are implemented. The groundwater monitoring network is also growing.

The approach used for this report includes the compilation of a group of stations and their respective “x” and “y” coordinates (based on the Florida state plane coordinate system). These datasets were retrieved from the DBHYDRO database using pl/sql scripts. This report uses active monitoring stations that are only archived in DBHYDRO. The stations were considered “active” if time-series data was available before and after April 30, 2007. The station names and their respective locations were plotted on maps using ArcGIS software. Microsoft Excel spreadsheets and ArcGIS data files are available in electronic format of this report on a CD-ROM.

The intent of this report is to provide a comprehensive overview of the hydrologic monitoring network of the District. It includes a high-level description of all the essential elements of the hydrologic monitoring that has evolved over the last five decades. The majority of the information presented here is available at an exhaustive level of detail in over 50 District publications such as technical reports, notes, and papers that are referenced throughout this appendix. For relevant and detailed information on any subject presented in the report and readers are referred to acquire more detailed information on each subject from these in-depth reference publications from the District’s Reference Center.

II. HYDROLOGIC DATA MANAGEMENT

By John Raymond and Chandra Pathak

The District has an extensive data collecting and monitoring network. The Supervisory Control and Data Acquisition (SCADA) and Hydro Data Management (SHDM) Department is responsible for data collection and management (**Figure 2**). The Department is made up of two divisions: SCADA and Instrumentation Management (SIM), which is responsible for designing, installing, maintaining and repairing environmental data recording instrumentation; and Operations and Hydro Data Management (OHDM), which is responsible for producing, managing and maintaining the highest quality operational and hydrometeorological data.

A. Data Collection

The data collection network supports the District's mission and goals by using acquired information on the state of water resources for multipurpose objectives. The District's critical mission includes: flood control, water supply, environmental deliveries and ecosystem restoration. The data collection network addresses (1) legal mandates, such as hydrologic documentation of the Central and South Florida (C&SF) Control Project Operations; (2) key resource issues, such as wellfield protection; and (3) general purpose and restoration needs, such as the Kissimmee River and Everglades restoration efforts.

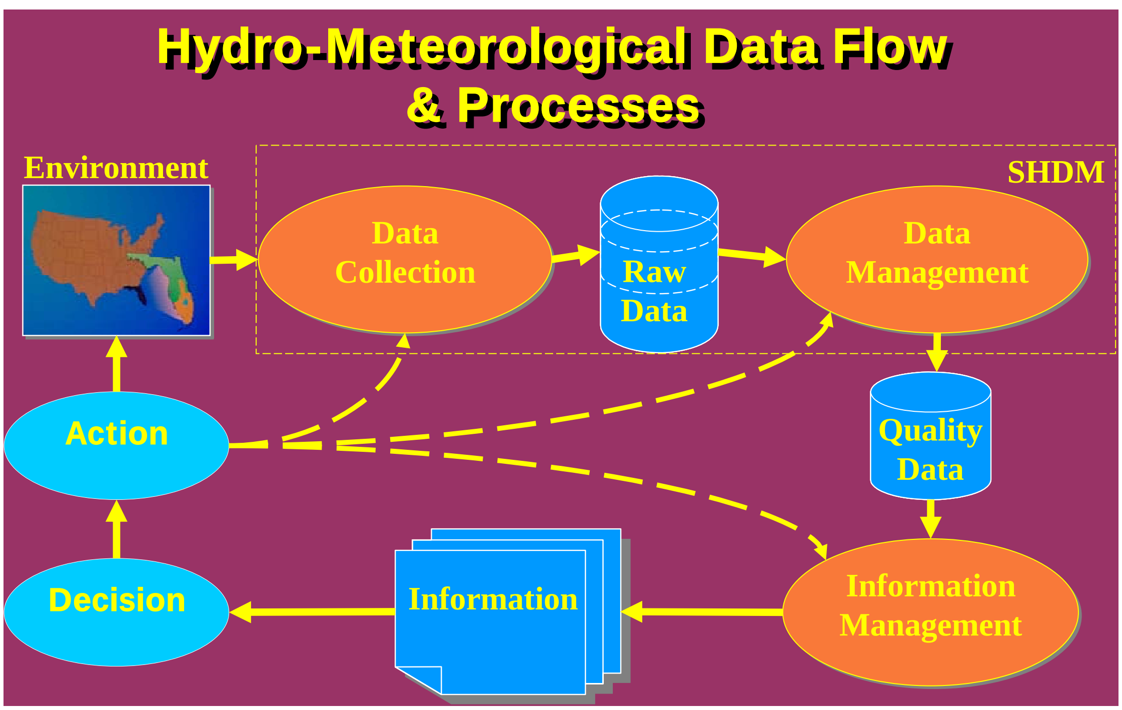

Figure 2. The hydrometeorological data flow and process.

Construction, installation and maintenance of these data collection sites follow strict quality control practices and procedures to ensure that the best quality data will be collected. The accuracy of the entire data collection network depends upon the site selection; equipment selection and proper installation; data collection methodology; recorder and sensor maintenance; data processing and verification; data storage, database management; and quality control.

The District's hydrologic data collection and management program is focused on a controlled expansion of its data collection networks through modernization, consolidation, and enhancement of current monitoring practices. As a result of controlled expansion, the data acquisition networks are evaluated for redundancy and increased coverage areas to meet current needs.

Data collection involves three major processes: observation, recording, then transferring and loading the raw data (**Figure 3**). The District collects data through telemetry or remote-access technology, remote terminal units (RTUs), manual measurements, analog graphic recorders, and mechanical punch-tape recorders. The main data acquisition systems are SCADA, ARDAMS (Automatic Remote Data Acquisition and Monitoring System), and LoggerNet. The RTU devices include Motorola SCADA (MOSCAD), Remote Acquisition Control Unit (RACU), and Campbell Scientific, Inc. data logger (CR10).

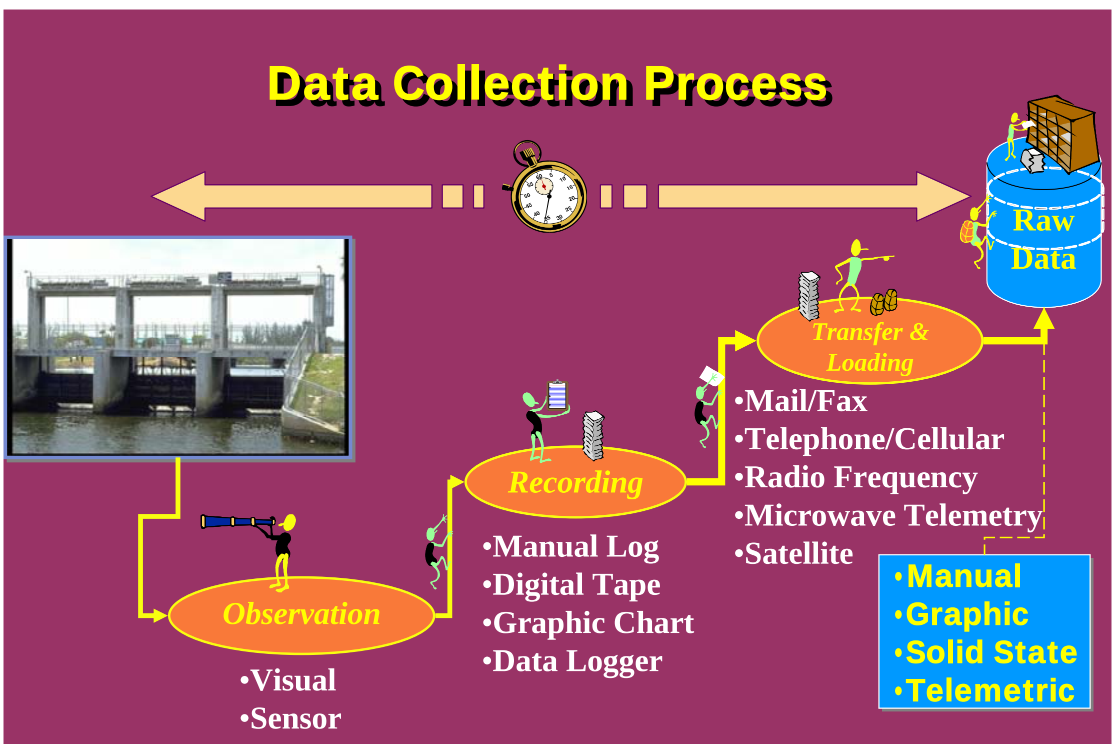

Figure 3. Data collection process.

The District's SCADA system transmits and receives information on water stages (or levels), wind velocities, rainfall, water temperature, salinity levels, and other data. The system operates 24 hours and uses wireless communication to monitor and control water levels, water control gate positions, and pumping. The SCADA system provides an early warning mechanism to anticipate flood problems by observing water level and rainfall trends. This computerized data collection system comprises the cornerstone of the District's data collection through a District-wide network of real-time and near-time data collection stations.

The District also obtains manually observed readings of water level (stage), pump operations, gate openings, flashboard changes, rainfall, and evaporation data at various cooperative sites. The field observer records the daily observations onto a log sheet. The log sheets are collected from the sites at timed intervals and delivered for data processing.

B. Data Management

Data management includes processing the data collected, summarizing, deriving, storing and publishing into the DBHYDRO database (**Figure 4**). During the processes of deriving and publishing, two major groups are required to support data processing: engineering and hydraulics; and post-processing QA/QC (quality assurance/quality control). The engineering and hydraulics group provides support in deriving, computing flow at water control structures or open channels, and evapotranspiration at weather stations; the post-processing QA/QC evaluates the processed data and assembles single time series for a subset of the database as baseline in modeling and as required by legal mandates.

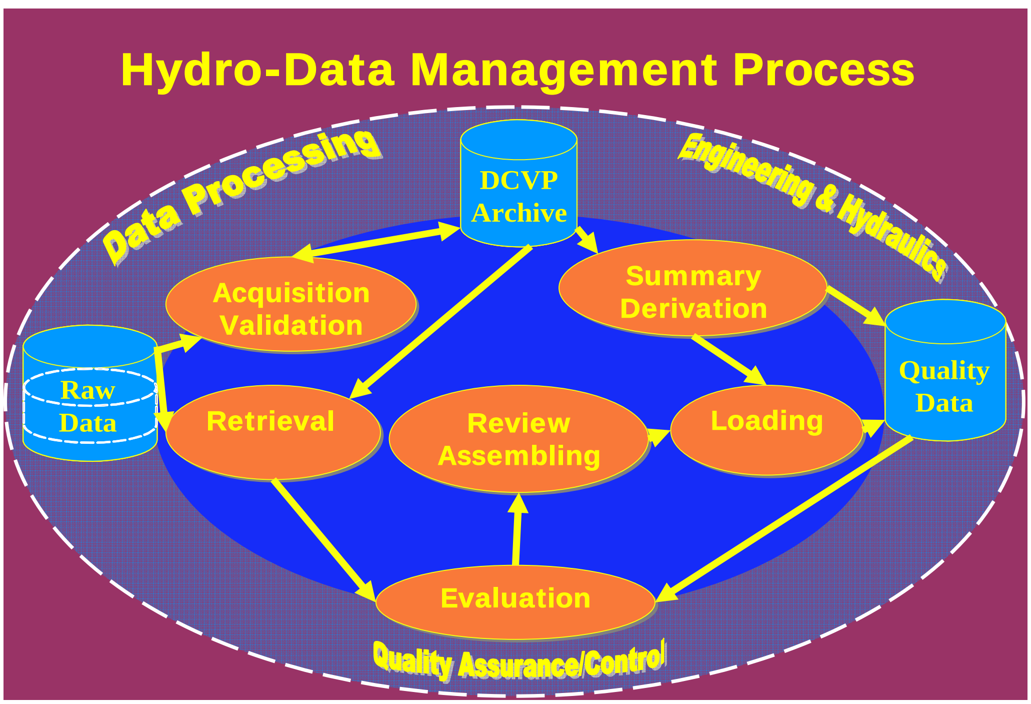

Figure 4. Hydro data management process.

1. Data Processing

Data processing involves the review, interpretation, processing, analysis, and validation of hydrologic data in support of environmental monitoring and assessment activities. Data processing includes a set of activities performed on raw time-series data collected within the District's monitoring networks. The raw data are reviewed through various validation procedures and processes to assure the quality of the data values.

Several standard operating procedures (SOPs) were developed for data processing by the District (Bachand et al., 2002; Bachand et al., 2003; Bachand et al., 2003a; Bachand and Dawkins, 2004; Bazell et al., 2004; Burkhardt and Dawkins, 2003; Carlton and Dawkins, 2002; Carlton and Dawkins, 2003; Danz and Dawkins, 2002; Danz et al., 2004; Hanson and Dawkins, 2003; Smelt and Dawkins, 2002; and Smelt and Dawkins, 2002a). Many of these procedures and processes are automated. The Data Collection/Validation Preprocessing System (DCVP) database provides for the storage and extraction of preliminary time-series data for further inspection. Once data is extracted from DCVP, it is subjected to an initial QA/QC check in order to ascertain or improve data quality. This is accomplished through the use of the Graphical Verification Analysis (GVA) Program, a software tool which provides analysts with a graphical user interface in which to plot, edit, and apply quality tags and comments to data. The GVA application is used for the validation of the data. Once data has undergone analysis in GVA, it is uploaded into the DBHYDRO database, finalizing the preprocessing stage (Bachand et al., 2002; Bachand et al., 2003; Bachand et al., 2003a; Bachand and Dawkins, 2004; Bazell et al., 2004; Burkhardt and Dawkins, 2003; Carlton and Dawkins, 2002; Carlton and Dawkins, 2003; Danz and Dawkins, 2002; Danz et al., 2004; Hanson and Dawkins, 2003; Smelt and Dawkins, 2002; Smelt and Dawkins, 2002a; Damisse et al., 2005; Sangoyomi et al., 2005a; Sangoyomi and Dawkins, 2005; Sangoyomi et al., 2005b; and Sangoyomi et al., 2006).

2. Data Storage

Processed data are archived into two different databases (**Figure 5**). Breakpoint data are stored in the DCVP Archive database, while daily summary and 15-minute data are published into the WREP or DBHYDRO database.

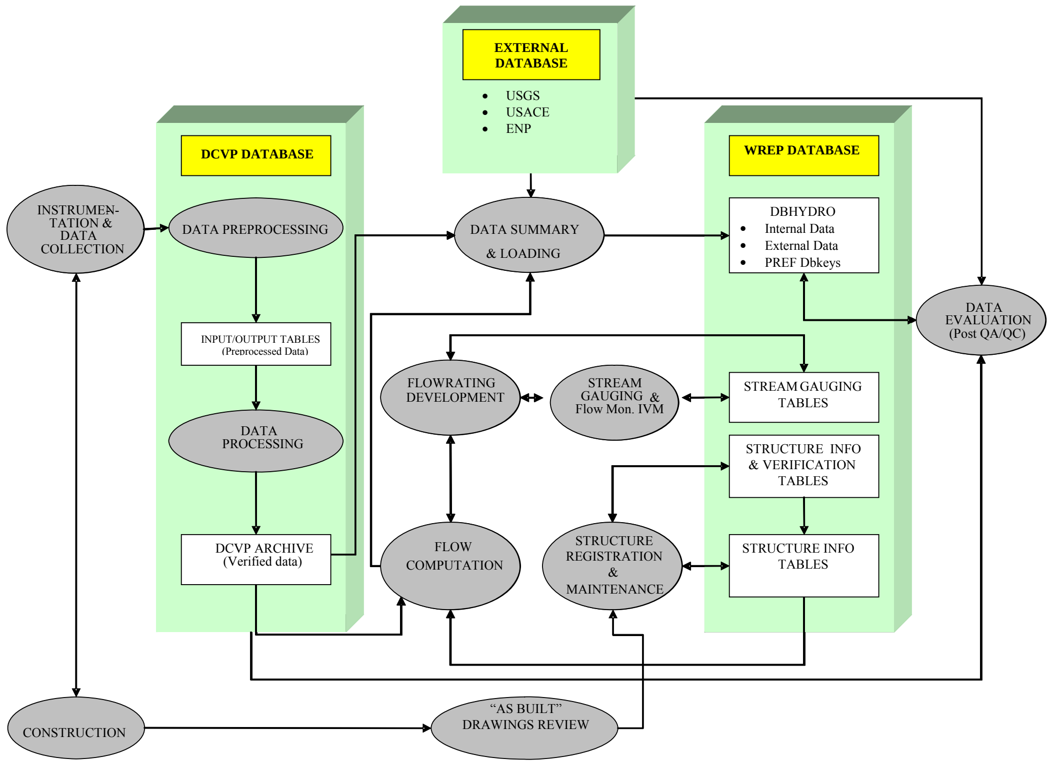

Figure 5. Hydro Data Management System

The District stores data received from its gauge stations in the DBHYDRO database. The DBHYDRO database contains meteorological, hydrologic and water quality data collected from District monitoring stations, available as public domain and accessible in a variety of different time-series formats. Some external data from U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA) and ENP are also available in DBHYDRO. Current and historic data are stored in DBHYDRO, allowing for the generation of specialized analyses relating to water control issues, as well as providing data necessary for use in operations, hydrologic models, and generating statistics.

3. Data Retrieval

DBHYDRO data are accessible to users through a Web browser. Internal users can also retrieve information from the DCVP archive using the Web. **Figure 6** shows the DBHYDRO web browser. DBHYDRO can be accessed via the Internet at http://glades.sfwmd.gov/pls/dbhydro_pro_plsql/show_dbkey_info.main_page. However, some functionality of the DBHYDRO is not publicly available.

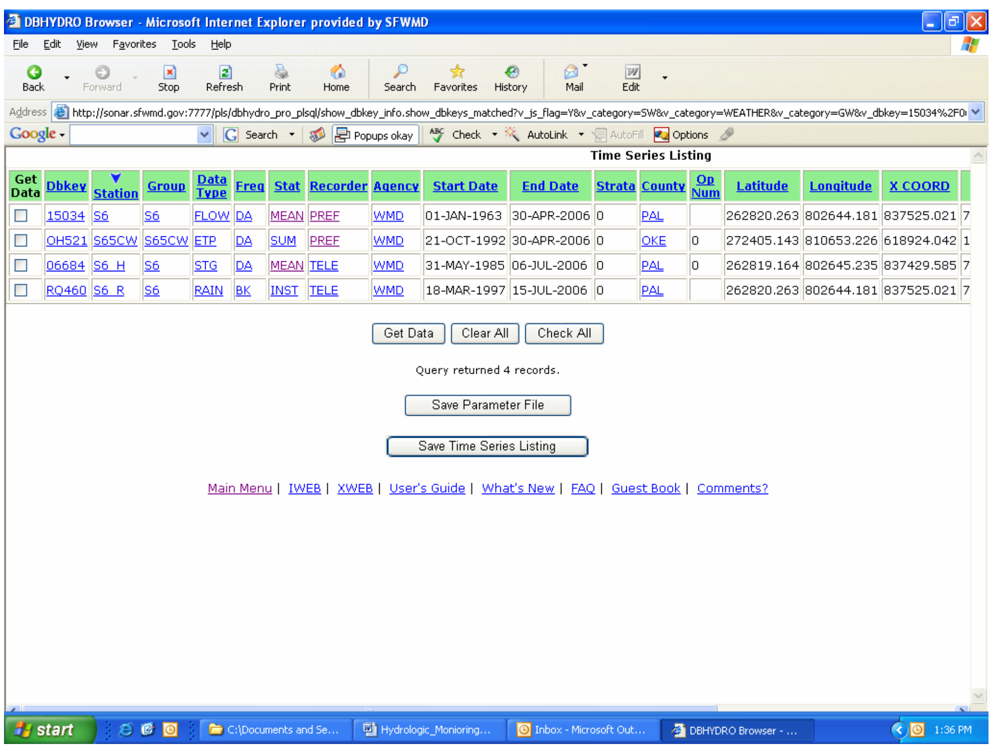

Figure 6. Screenshots of the DBHYDRO — main page and output.

DBHYDRO contains identification information for all District monitoring stations and associated instrumentation, as well as geographic location information. For every time-series data, the records include the station name, a database unique identifier (Dbkey), latitude, longitude, basin, county, state plane coordinates, section, township, range, data type (flow, rain, water level), and sampling frequency. Dbkeys change when (1) sensors have been upgraded, (2) when gauges are moved at District sites or become obsolete, (3) when gauges are removed from the gauge network altogether or, (4) a different combination of sensors are used in flow computation.

Data are stored within DBHYDRO for the period of record for each station and includes breakpoint and non-breakpoint data. Breakpoint data are accessible in 15-minute, 30-minute, hourly, and daily time intervals, while non-breakpoint data is available only as daily accumulation totals (rainfall) or daily mean (water level and flow). Daily datasets are used most often at the District and represent the preferred time interval for the support of many operations, such as hydrologic modeling. This is because the daily time interval makes use of the entire data available through the network, and also because daily data take up less storage volume in computer applications than data of smaller time increments.

Data codes, or tags, accompany daily data within DBHYDRO in order to provide data users and analysts with an indication of data quality and processing status. A "null value" in the data code field corresponds to data that are missing. The "M" tag designates that data are missing, a code indicative of gauge equipment malfunction. The "X" data code for rain designates that data are unknown. Data demonstrating the "X" tag are eventually followed with an "A" code, meaning that an accumulative amount of data (rainfall) was measured over the time period indicated by an "X" tag. The complete record of DBHYDRO data codes used for rainfall and associated definitions are in **Table 1**.

Table 1. DBHYDRO data tags and associated definitions.

Data Tag	Meaning	Description
A	Accumulated	Reserved for rainfall data accumulated over a period exceeding 24 hours
E	Estimated	Designate estimated data. "E" tags are converted to "M" codes when data cannot be reasonably estimated.
M	Missing	Reserved for missing data
X	Included in Next Amount Marked "A"	Indicate days where manually observed rainfall has accumulated. "X" tags precede "A" tags, where the accumulation total is given.
!	Normal Limits Exceeded	Indicate instances when normal data values have been exceeded
?	Questionable (Do Not Use)	Indicate questionable data, not to be used
<	Less Than	Less Than
>	Greater Than	Greater Than
N	Not Processed	Not Yet Available
P	Partial	Computed from Partial Record

4. Data Quality Assurance and Quality Control

The District maintains a structured QA/QC procedure to ensure that data collected is of the best possible quality before it is further published. Preprocessing is the first stage of operations applied to “raw” time series data collected within the District’s monitoring network. The initial step of preprocessing involves the import of data collected manually and electronically from the field and data formatting for subsequent entry into the DCVP database. These tasks are accomplished through a series of software applications, which also perform validation checks on the data (Damisse et al., 2005; Sangoyomi et al., 2005a; Sangoyomi and Dawkins, 2005; Sangoyomi et al., 2005b; Sangoyomi et al., 2006).

Millions of data records are collected and posted to the District’s database DBHYDRO after data processing. Data quality assurance is normally performed during data processing. However, for some select legally mandated sites and for baseline data used in regional modeling and CERP, some post-processing QA/QC is also performed. Some of these mandates include Everglades Agricultural Area (EAA) Rulemaking, Chapter 40E-63 of the Florida Forever Act; Stormwater Treatment Areas (STAs); and the Everglades Construction Project (ECP).

The QA/QC post-processing analysis is a second set of operations that extract preprocessed data from DBHYDRO for select stations to undergo further examination. Post-processing QA/QC provides the opportunity to visualize and analyze current data with historical time-series data. Presently, data from approximately 216 District gauge stations receive additional processing due to legal mandates under the Florida Forever Act. Data that have received the additional scrutiny of the QA/QC post-processing analysis are known in DBHYDRO as “preferred data” (PREF) or “modeling data” (MOD) and represent the “best available single time series data” at the District.

The initial step of QA/QC post-processing entails graphical plotting to show general data trends, gaps and overlapping portions (some of these are handled at the data-processing level). Statistical analyses are then performed in order to compare historical trends and identify suspect data (Damisse et al., 2005; Sangoyomi et al., 2005a; Sangoyomi and Dawkins, 2005; Sangoyomi et al., 2005b; Sangoyomi et al., 2006). In post-processing, missing data may be estimated with data estimation techniques and processes such as spatial and temporal interpolation, and statistical or simulation-model applications. Erroneous data can be replaced with higher quality data, be deleted, or qualified and tagged. The level of scrutiny and data selection will correspond to the data’s usage or application. The post-processing QA/QC is conducted monthly, quarterly, or yearly according to pre-established and published schedules.

III. METEOROLOGIC MONITORING NETWORK

Gary Wu and Chandra Pathak

According to the *Guide to Meteorological Instruments and Methods of Observation* published by the World Meteorological Organization (1996), "meteorological (and related environmental and geophysical) observations are made for a variety of reasons. They are used for the real-time preparations of weather analyses and forecasts, for the study of climate, for local weather-dependent operations (such as operation of the water control structures), for hydrology and agro-meteorology, and for research in meteorology and climatology."

The climate in South Florida is subtropical, humid, and prone to severe conditions. The variability in rainfall is often characterized by multiple wet and dry cycles with severe droughts from time to time. Evapotranspiration in South Florida has been estimated to be from 70 to 90 percent of the rainfall in undisturbed wetlands. Tropical cyclones (hurricanes and tropical storms) produce the most severe weather conditions in South Florida. The high tides and heavy rains — often in excess of 5 inches — associated with these storms can produce coastal and inland flooding, and strong winds can cause extensive damage. Tropical cyclones have repeatedly passed through the region, most frequently in late summer or early fall (USGS, Circular 1134).

Several meteorologic parameters (such as barometric pressure, solar radiation, air temperature, relative humidity, and wind speed) are measured at the weather stations that form the District's meteorologic monitoring network. Typically, these parameters also include rainfall measurements — one of the most important meteorologic parameters that is used at the District for water management, hydrologic analyses, and other purposes. Because of the importance of rainfall measurements, the District has a large number of rain gauge stations (seven-to-eight times more than the total number of weather stations). However, because of its large size, the rainfall monitoring network is excluded from this section and is presented separately in section IV of this report.

The District's weather stations are valuable in providing monitoring and prediction in the following three areas: evapotranspiration; hurricanes/tropical storms; and soil dryness and associated wildfire conditions.

Evapotranspiration (ET)

Evapotranspiration is a major component of the hydrologic cycle. This hydrometeorological parameter is needed for various water budgeting purposes, which accounts for surface and groundwater. Potential evapotranspiration (PET), and reference evapotranspiration, are the hydrologic parameters needed to estimate evapotranspiration from the given soil and vegetation surfaces in an area. Potential evapotranspiration is the rate at which water loss to the atmosphere occurs from well-watered soil and specific plant surfaces. Reference evapotranspiration is the PET specific to either short grass or alfalfa crop. Actual evapotranspiration can either be measured or derived by applying crop or vegetation coefficients to the PET. There are many methods that have been used to estimate PET, provided that adequate input data are available. These methods are generally classified into three groups: energy balance methods, mass balance methods, and combination methods (such as Penman, Corrected Penman, and Penman-Monteith) which include both energy and mass balance approaches. The District developed historical and current daily PET datasets for wetlands using "the Simple Method" (Abtew et al., 2002).

Hurricanes and tropical storms

The hurricane seasons in 2004 and 2005 inflicted severe damage and economical loss on South Florida. To better understand the strong winds created by hurricanes, the National Hurricane Center has identified the weather stations operated by the District as good sources for information. The debate over Hurricane Wilma's strength of either Category 2 or 3 [based on the Saffir-Simpson Hurricane Scale of the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center] has called for better monitoring schemes and measurement methods.

Soil dryness and associated wildfire conditions

The Keetch-Byram Drought Index was designed specifically for fire-potential assessment. The index number represents the net effect of evapotranspiration and precipitation in producing a cumulative moisture deficiency in deep duff and upper soil layers. It is a continuous index, relating to the flammability of organic material in the ground. The rainfall measured and PET calculated from a weather station determines the Keetch-Byram Drought Index for a site.

A. Development of the Meteorological Monitoring Network

1. History

The meteorological monitoring of Central and South Florida can be traced back to the early 20th century. In 1912, the then-named Everglades District conducted pan evaporation observation. Before the Central and Southern Florida Flood Control District was established in 1949, meteorological monitoring was conducted by NOAA, the U.S. Army Corp of Engineers (USACE), and local drainage districts. In 1972, the Central and Southern Florida Flood Control District was renamed the South Florida Water Management District (SFWMD or the District), which took over most of these monitoring responsibilities for the South Florida region. However, in addition to the agencies mentioned above, there are meteorological data obtained from other organizations including the U.S. Department of Agriculture (USDA), United States Geological Survey (USGS), and the University of Florida. The historical meteorological data are stored in DBHYDRO; the lists of pan evaporation and weather stations are shown Tables 2 and 3.

2. Evolution of the Network

The meteorological monitoring network at the District measures various weather parameters. The weather parameters that are measured include the following:

- Air Temperature (AIRT)
- Barometric Pressure (BARO)
- Relative Humidity (HUMI)
- Solar Radiation (Net) (RADN)
- Solar Radiation (Photoactive) (RADP)
- Solar Radiation (Total) (RADT)
- Wind Scalar Direction @ 10 meters (WNDD)
- Wind Scalar Speed @ 10 meters (WNDS)
- Wind Vector Direction @ 10 meters (WNVD)
- Wind Vector Speed @ 10 meters (WNVS)
- Water Temperature (at different depths) (H2OT)

Table 2 summarizes the number of meteorological monitoring sites from 1950 to the present (in calendar years). Pan evaporation observation reached its peak in the 1980s with 38 sites. It is also seen that most meteorological monitoring of atmospheric quantities such as air temperature, barometric pressure, humidity, solar radiation, wind speed, and water temperature were conducted after the 1990s.

Table 2. Number of meteorological monitoring stations at the District from 1950 to the 2005.

	Before 1/1/1950	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2005
Pan Evap	12	21	24	32	38	24	**12**
AIRT	0	0	0	2	6	26	**30**
BARO	0	0	0	0	2	23	**43**
HUMI	0	0	0	1	5	26	**30**
RADN	0	0	0	0	1	13	**20**
RADP	0	0	0	0	4	27	**32**
RADT	0	0	0	0	4	25	**30**
WNDD	0	0	0	1	6	22	**28**
WNDS	0	0	0	0	7	30	**32**
WNVD	0	0	0	0	3	26	**31**
WNVS	0	0	0	1	4	26	**31**
H2OT	0	0	0	0	3	11	**9**

B. Existing Meteorological Network

1. Field Instrumentation at Weather Stations

To measure the different weather parameters, the District uses several types of sensors at weather stations. The most commonly used sensors are as follows:

a. National Weather Service (NWS) Class A evaporation pan
b. Vaisala WS425 ultrasonic wind sensor
c. HMP45C temperature and relative humidity probe
d. PTA-427 barometric pressure transducer
e. LI-COR LI200S pyranometer
f. Q-7.1 net radiometer
g. LI-COR LI190SB Quantum sensor
h. CS 107-108 temperature probes

a. NWS Class A Evaporation Pan

The standard NWS Class A evaporation pan is the most widely used sensor at District weather stations. It is made of unpainted galvanized steel or stainless steel, is 4 feet in diameter by 10 inches deep, and sits on a raised wood frame exposed beneath to let air circulate (**Figure 7**). The pan is filled to a depth of 8 inches, and is refilled when the depth falls to 7 inches. Water surface level is measured daily with a hook gauge in a stilling well. Evaporation is computed as the difference between observed levels, adjusted for any precipitation measured in a standard rain gauge. Alternatively, water is added each day to bring the level up to a fixed point in the stilling well. This method assures proper water level at all times (Kinsman et al., 1994).

Depending on the water level measurement method and how water is supplied to the pan, the measurement accuracy can be varied. The following are technical specifications for the Automatic Evaporation Monitoring System Model 6529, found online at (http://www.geneq.com/catalog/en/auto_evap_mon_sys.html, July 2006).

Figure 7. Fort Pierce (FTPIER) pan evaporation station.

Range	30 (empty) to 250 millimeter (mm) (full)
Resolution	0.2 mm of evaporation or rainfall
Accuracy	± 0.4 mm
Level Reset	Programmable default reset to 200 mm (± 1 mm) at a preset time each day
Water Level	6541 Water Level Instrument with 128k Micrologger
Power Supply	0.3 Ah/day
Battery	Model 6907B 12V 7Ah sealed lead acid
Charger	Model 6904B 12V 2W solar panel mounted on aluminum enclosure
Pan Type	ID 1208 mm OD 1290 mm Depth 250 mm US Class A compatible
Pan Mounting	Timber frame; treated plantation softwood 1300 mm × 1300 mm
Pan Bird Guard	12 mm square steel mesh Hot dip galvanized
Control Enclosure	Aluminum 320 mm × 300 mm × 750 mm (W × D × H)
System Weight	Approximately 52 kilograms (kg)

b. Vaisala WS425 Ultrasonic Wind Sensor

According to the User's Guide, the WS425 has an on-board microcontroller that captures and processes data and performs serial communications. The wind sensor has three, equally spaced ultrasonic transducers on a horizontal plane. The sensor measures the time that it takes an ultrasound acoustic signal to travel from one transducer to another (transit time) in both directions (**Figure 8**).

The transit time depends on the wind velocity along the ultrasonic path. For zero wind velocity, both the forward and reverse transit times are the same. With wind along the sound path, the up-wind transit time increases and the down-wind transit time decreases. The microprocessor of the microcontroller calculates the wind speed from the transit times using the following formula:

$$V_W = 0.5\ L\ (1/t_f - 1/t_r)$$

where

V_W = Wind velocity
L = Distance between two transducers
t_f = Transit time in the forward direction
t_r = Transit time in the reverse direction

Measuring the six transmit times allows wind velocity to be calculated for each of the three ultrasonic paths, which are offset to each other by 120 degrees. The calculated wind speeds are independent of altitude, temperature, and humidity because these factors cancel out with the six measurements (even though the velocity of sound affects individual transit times).

Incorrect readings may occur when a large raindrop or ice pellet strike a transducer. These incorrect readings are eliminated by a proprietary signal processing technique. For example, a wind velocity figure most affected by turbulence error is eliminated to calculate the wind speed and wind direction from the best two values. The following are some of the specifications of the WS425:

Wind Speed: Resolution of reported values of average speed and vector speed are accurate to sensor accuracy.

Range	0–144 mph
Accuracy	± 3 percent < 110 mph
	± 8 percent > 110 mph

Wind Direction: Reported values of vector direction are accurate to sensor accuracy.

Range	0–360 degrees
Accuracy	± 2 degrees
Resolution	1 degree

Figure 8. A Vaisala WS425 ultrasonic wind sensor at weather station L006.

c. HMP45C Temperature and Relative Humidity Probe

The HMP45C Temperature and Relative Humidity probe contains a Platinum Resistance Temperature (PRT) detector and a Vaisala HUMICAP 180 capacitive relative humidity sensor (**Figure 9**).

Temperature:

Range	-33 degrees Celsius (°C) to 48 °C
Accuracy	± 0.4 °C over full range

Relative Humidity:

Range	0–100 percent
Accuracy	at 20 °C, including nonlinearity and hysteresis
	± 2 percent relative humidity at 0–90 percent
	± 3 percent relative humidity at 90–100 percent

Figure 9. An air temperature and relative humidity probe at weather station L006.

d. PTA-427 Barometric Pressure Transducer

The PTA-427 uses silicon capacitive pressure sensors patented by Vaisala (**Figure 10**). It is temperature-compensated and produces a linear voltage output over the full operating range.

Range	600.35–795.47 millimeters mercury (mm Hg)
Accuracy	± 0.375 mm Hg

Figure 10. A typical Vaisala barometric pressure sensor.

e. LI-COR LI200S Pyranometer

A pyranometer is an instrument for measuring solar radiation received by an entire hemisphere. It is suitable for measuring the amount of global sun plus sky radiation (**Figure 11**). The LI-COR LI200S pyranometer utilizes a silicon photodiode which has a spectral response in the wavelength band from 0.4 micrometer (µm) to 1.2 µm.

Linearity	Maximum deviation of 1 percent up to 3,000 watts per meters squared (Wm^{-2})
Typical Sensitivity	0.2 kilowatts per meters squared per millivolt ($kWm^{-2}mV^{-1}$)
Accuracy	± 5 percent maximum (absolute error in natural daylight) ± 3 percent typical
Stability	< ± 2 percent change over a one-year period

Figure 11. An LI-COR LI200S pyranometer.

f. Q-7.1 Net Radiometer

The Q-7.1 is a high-output thermopile sensor that measures the algebraic sum of incoming and outgoing all-wave radiation (i.e., short- and long-wave components). Incoming radiation consists of direct (beam) and diffuse solar radiation plus long-wave irradiance from the sky (**Figure 12**). Outgoing radiation consists of reflected solar radiation plus the terrestrial long-wave component.

Range	Approximately -0.5 (during darkness) to approximately 1.500 (during sunny conditions, full sky)
Spectral response	0.25–60 µm
Uncorrected wind effect	Up to 6 percent reduction at 7 meters per second (ms^{-1}) for positive fluxes Up to 1 percent reduction at 7 ms^{-1} for negative fluxes
Reported values	Kilowatts per meter squared (kWm^{-2})
Accuracy	± 0.075 kWm^{-2}

Figure 12. An Q-7.1 net radiometer at weather station Belle Glade.

g. LI-COR LI190SB Quantum Sensor

The LI190SB accurately measures Photosynthetic Photon Flux Density (PPFD) in both natural and artificial light (**Figure 13**). PPFD is the number of photons in the 400–700 nanometer (nm) waveband incident per unit time on a unit surface, which plants can use for photosynthesis.

Linearity	Maximum deviation of 1 percent up to 10,000 micromoles per second per meters squared ($\mu ms^{-1}m^{-2}$)
Sensitivity	Typically 5 microamps (µA) per 1,000 $\mu ms^{-1}m^{-2}$
Stability	< ± 2 percent change over a 1 year period
Calibration	± 5 percent traceable to the U.S. National Institute of Standards Technology (NIST)

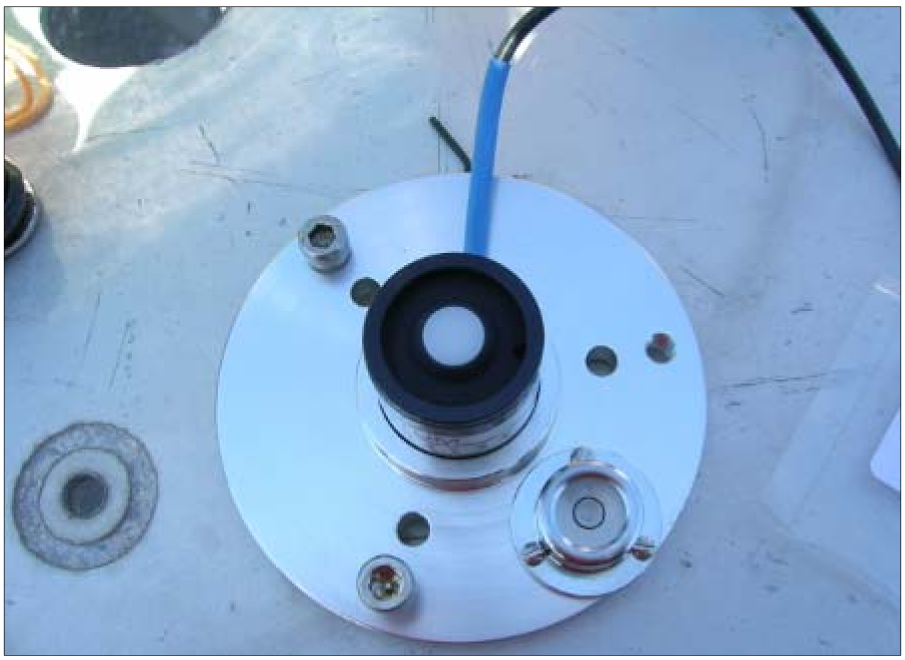

Figure 13. An LI-COR LI190SB Quantum Sensor.

h. CS 107/108 Temperature Probes

Campbell Scientific Models 107 and 108 are rugged, accurate temperature probes that measure air, soil, and water temperature in a variety of applications. These probes consist of a thermistor encapsulated in an epoxy-filled housing (**Figure 14**). The housing protects the thermistor, allowing the probes to be buried or submerged.

Campbell Scientific Model 107 Specifications

Temperature measurement range	-35 °C to 50 °C
Polynomial linearization accuracy	Typically less than ± 0.5 °C over -38 to 50 °C range less than ± 0.1 °C over -24° to +48°C range
Interchangeability error	Typically less than ± 0.2 °C over 0 to 50 °C range increasing to ± 0.4 °C at -40 °C

Campbell Scientific Model 108 Specifications

Temperature measurement range	-5 °C to 95 °C
Polynomial linearization accuracy	Typically less than ± 0.5 °C at the -5 to 90 °C range
Interchangeability error	Typically less than ± 0.2 °C over 0 to 70 °C range increasing to ± 0.3 °C at 95 °C

Figure 14. A Campbell Scientific thermistor temperature probe at weather station L006.

2. Active Meteorological Stations

Tables 3 and **4** show 11 active pan evaporation stations and 45 weather stations at the District as of April 30, 2007. **Table 4** also shows 19 stations where PET data are estimated from meteorological data using “the Simple Method”. **Table 5** shows the major climatic indices measured at active meteorological stations.

Table 3. Active pan evaporation monitoring stations.

No.	Station	Freq	Stat	Recorder	Agency	Start Date	Latitude	Longitude
1	S65_E	DA	SUM	APAN	WMD	1-Oct-83	274814.088	811153.228
2	FT. PI 2_E	DA	SUM	APAN	WMD	1-Nov-69	272616.135	802059.167
3	FT. PIER_E	DA	SUM	APAN	WMD	1-Mar-82	272202.353	803052.906
4	EVP376NE	DA	SUM	DWR	WMD	1-May-05	271512.4	804708.6
5	OKEE FIE_E	DA	SUM	APAN	WMD	1-Oct-83	271505.16	804720.202
6	WPB.EEDD_E	DA	SUM	APAN	EDD	1-May-83	264254.229	800344.141
7	WWTP_E	DA	SUM	COMP	WMD	1-Jan-99	264254	800345
8	S5A	DA	SUM	CPAN	WMD	1-Mar-90	264104.231	802203.172
9	S7_E	DA	SUM	APAN	WMD	8-Mar-60	262009.283	803212.191
10	BCBNAPLE_E	DA	SUM	APAN	WMD	31-Dec-90	261331.318	814829.304
11	S140 SPW_E	DA	SUM	APAN	WMD	18-Jun-85	261019.308	804938.221

Table 4. Active atmospheric monitoring stations.

No.	Station	Recorder	Agency	Latitude	Longitude	Start Date	County	Profile*	PET DBKEY
1	S61W	CR10	WMD	280824.05	812105	20-Oct-92	OSC	Full	
2	WRWX	CR10	WMD	280254.06	812358	16-Apr-97	POL	Full	OU852
3	S65CW	CR10	WMD	272405.14	810653	20-Oct-92	OKE	Full	OH521
4	S65DWX	CR10	WMD	271851.30	810120	23-Feb-00	OKE	Full	OH511
5	SVWX	CR10	WMD	271725.15	801513	14-May-97	STL	Full	OH509
6	S75WX	CR10	WMD	271130.76	810741	1-Sep-02	GLA	Full	
7	L001	CR10	WMD	270822.62	804720.522	4-Aug-94	OKE	Full	
8	ACRAWX	CR10	WMD	270712.88	802555.608	26-May-06	MAR	Full	
9	JDWX	CR10	WMD	270143.19	800955	12-Sep-97	MAR	Full	OH512
10	L005	CR10	WMD	265724.23	805820.586	5-Aug-88	GLA	Full	
11	LZ40	CR10	WMD	265406.21	804720	25-Apr-90	PAL	Full	
12	L006	CR10	WMD	264918.31	804700.314	27-Jan-89	PAL	Full	OH519
13	S78W	CR10	WMD	264723.23	811810	21-Oct-92	GLA	Full	RW483
14	CFSW	CR10	WMD	264406.23	805343	21-Oct-92	HEN	Full	OU851
15	BELLE GL	CR10	WMD/UF	263925.24	803747	16-Apr-96	PAL	Full	OH518
16	FHCHSX	CR10	WMD	263914.56	800405.696	17-May-07	PAL	Full	
17	ENR308	CR10	WMD	263721.24	802620	7-Apr-94	PAL	Full	
18	WCA1ME	CR10	WMD	263038.26	801837.167	12-Feb-96	PAL	Partial	
19	LOXWS	CR10	WMD	262956.26	801320	29-Jun-93	PAL	Full	RW485
20	STA5WX	CR10	WMD	262651.08	805325	17-Sep-02	HEN	Full	UK534
21	FPWX	CR10	WMD	262557.29	814324	3-Sep-97	LEE	Full	OH520
22	S7WX	CR10	WMD	262009.28	803212	12-Jan-98	PAL	Full	RW484
23	ROTNWX	CR10	WMD	261955.23	805248	23-Dec-97	BRO	Full	RW486
24	BCSI	CR10	WMD	261917.00	810404	25-Jun-93	HEN	Full	OU850
25	WCA2F4	CR10	WMD	261901.28	802306.178	1-May-97	BRO	Partial	
26	S140W	CR10	WMD	261016.65	804933.561	21-Oct-92	BRO	Full	OH516
27	SGGEWX	CR10	WMD	260843.34	813432	18-Sep-02	COL	Full	
28	3AS3WX	CR10	WMD	255106.22	804559	3-Apr-00	DAD	Full	OH515
29	BBCW1	CR10	WMD	254035.07	801923.678	18-May-05	DAD	Partial	
30	S331W	CR10	WMD	253639.38	803035	21-Jul-94	DAD	Full	OH514
31	BBCW7GW2	CR10	WMD	253605.50	801834.219	18-May-05	DAD	Partial	
32	BBCW7GW1	CR10	WMD	253605.42	801834.258	18-May-05	DAD	Partial	
33	BBCW8GW2	CR10	WMD	253604.52	801820.763	18-May-05	DAD	Partial	
34	BBCW8GW1	CR10	WMD	253604.46	801820.775	18-May-05	DAD	Partial	
35	BBCW2	CR10	WMD	253015.01	802051.36	17-May-05	DAD	Partial	
36	BBCW9GW2	CR10	WMD	252821.26	802048.805	17-May-05	DAD	Partial	
37	BBCW9GW1	CR10	WMD	252821.18	802048.791	17-May-05	DAD	Partial	
38	BBCW10GW2	CR10	WMD	252819.82	801955.607	18-May-05	DAD	Partial	
39	BBCW10GW1	CR10	WMD	252819.77	801955.615	18-May-05	DAD	Partial	
40	BBCW4	CR10	WMD	252720.47	802202.673	17-May-05	DAD	Partial	
41	BBCW5	CR10	WMD	252626.66	802246.68	17-May-05	DAD	Partial	
42	MDTS	CR10	WMD	251643.43	802342.205	1-Jan-91	DAD	Partial	
43	MBTS	CR10	WMD	251526.43	802520.208	31-May-96	DAD	Partial	
44	JBTS	CR10	WMD	251328.44	803224	23-May-91	DAD	Full	OH513
45	TPTS	CR10	WMD	251223.44	802229.204	1-Jan-91	DAD	Partial	

* The "Full" designation under the Profile column means that wind, radiation, humidity, and air temperature measurements are collected at those sites. The "Partial" designation does not contain all of the above parameters.

Table 5. Major climatic indices measured at active meteorological stations.
Table key follows on next page.

No.	Station	Start Date	AIRT	BARO	HUMI	RADN	RADP	RADT	WNDD	WNDS	WNVD	WNVS	TWAT
1	S61W	20-Oct-92	X	X	X		X	X	X	X	X	X	
2	WRWX	16-Apr-97	X	X	X	X	X	X	X	X	X	X	
3	S65CW	20-Oct-92	X	X	X		X	X	X	X	X	X	
4	S65DWX	23-Feb-00	X	X	X	X	X	X	X	X	X	X	
5	SVWX	14-May-97	X	X	X	X	X	X	X	X	X	X	
6	S75WX	1-Sep-02	X	X	X	X	X	X	X	X	X	X	
7	L001	4-Aug-94	X	X	X		X	X	X	X	X	X	X
8	ACRAWX	26-May-06	X	X	X	X	X	X	X	X	X	X	
9	JDWX	12-Sep-97	X	X	X	X	X	X	X	X	X	X	
10	L005	5-Aug-88	X	X	X		X	X	X	X	X	X	X
11	LZ40	25-Apr-90	X	X	X		X	X	X	X	X	X	X
12	L006	27-Jan-89	X	X	X		X	X	X	X	X	X	X
13	S78W	21-Oct-92	X	X	X		X	X	X	X	X	X	
14	CFSW	21-Oct-92	X	X	X		X	X	X	X	X	X	
15	BELLE GL	16-Apr-96	X	X	X	X	X	X	X	X	X	X	
16	FHCHSX	17-May-07	X	X	X	X	X	X	X	X	X	X	
17	ENR308	7-Apr-94	X	X	X	X	X	X		X	X	X	X
18	WCA1ME	12-Feb-96					X						
19	LOXWS	29-Jun-93	X	X	X	X	X	X		X	X	X	
20	STA5WX	17-Sep-02	X	X	X	X	X	X	X	X	X	X	
21	FPWX	3-Sep-97	X	X	X	X	X	X	X	X	X	X	
22	S7WX	12-Jan-98	X	X	X	X	X	X		X	X	X	
23	ROTNWX	23-Dec-97	X	X	X	X	X	X	X	X	X	X	
24	BCSI	25-Jun-93	X	X	X		X	X	X	X	X	X	
25	WCA2F4	1-May-97		X									
26	S140W	21-Oct-92	X	X	X	X	X	X	X	X	X	X	
27	SGGEWX	18-Sep-02	X	X	X	X	X	X	X	X	X	X	
28	3AS3WX	3-Apr-00	X	X	X	X	X	X	X	X	X	X	
29	BBCW1	18-May-05		X									
30	S331W	21-Jul-94	X	X	X	X	X	X	X	X	X	X	
31	BBCW7GW2	18-May-05		X									
32	BBCW7GW1	18-May-05		X									
33	BBCW8GW2	18-May-05		X									
34	BBCW8GW1	18-May-05		X									
35	BBCW2	17-May-05		X									
36	BBCW9GW2	17-May-05		X									
37	BBCW9GW1	17-May-05		X									
38	BBCW10GW2	18-May-05		X									
39	BBCW10GW1	18-May-05		X									
40	BBCW4	17-May-05		X									
41	BBCW5	17-May-05		X									
42	MDTS	1-Jan-91											X
43	MBTS	31-May-96					X		X	X	X	X	X
44	JBTS	23-May-91	X	X	X		X	X		X	X	X	X
45	TPTS	1-Jan-91											X

TABLE 5 COLUMN LABELS KEY:

AIRT	Air Temperature
BARO	Barometric Pressure
HUMI	Relative Humidity
RADN	Solar Radiation (Net)
RADP	Solar Radiation (Photoactive)
RADT	Solar Radiation (Total)
WNDD	Wind Scalar Direction @ 10 meters
WNDS	Wind Scalar Speed @ 10 meters
WNVD	Wind Vector Direction @ 10 meters
WNVS	Wind Vector Speed @ 10 meters
TWAT	Water Temperature (measurements at different depths of a site may exist)

Figures 15 and **16** are the location maps of active pan evaporation monitoring and atmospheric monitoring stations. **Figure 17** is the location map of 19 active PET stations. **Figure 18** shows a photograph of a typical weather station.

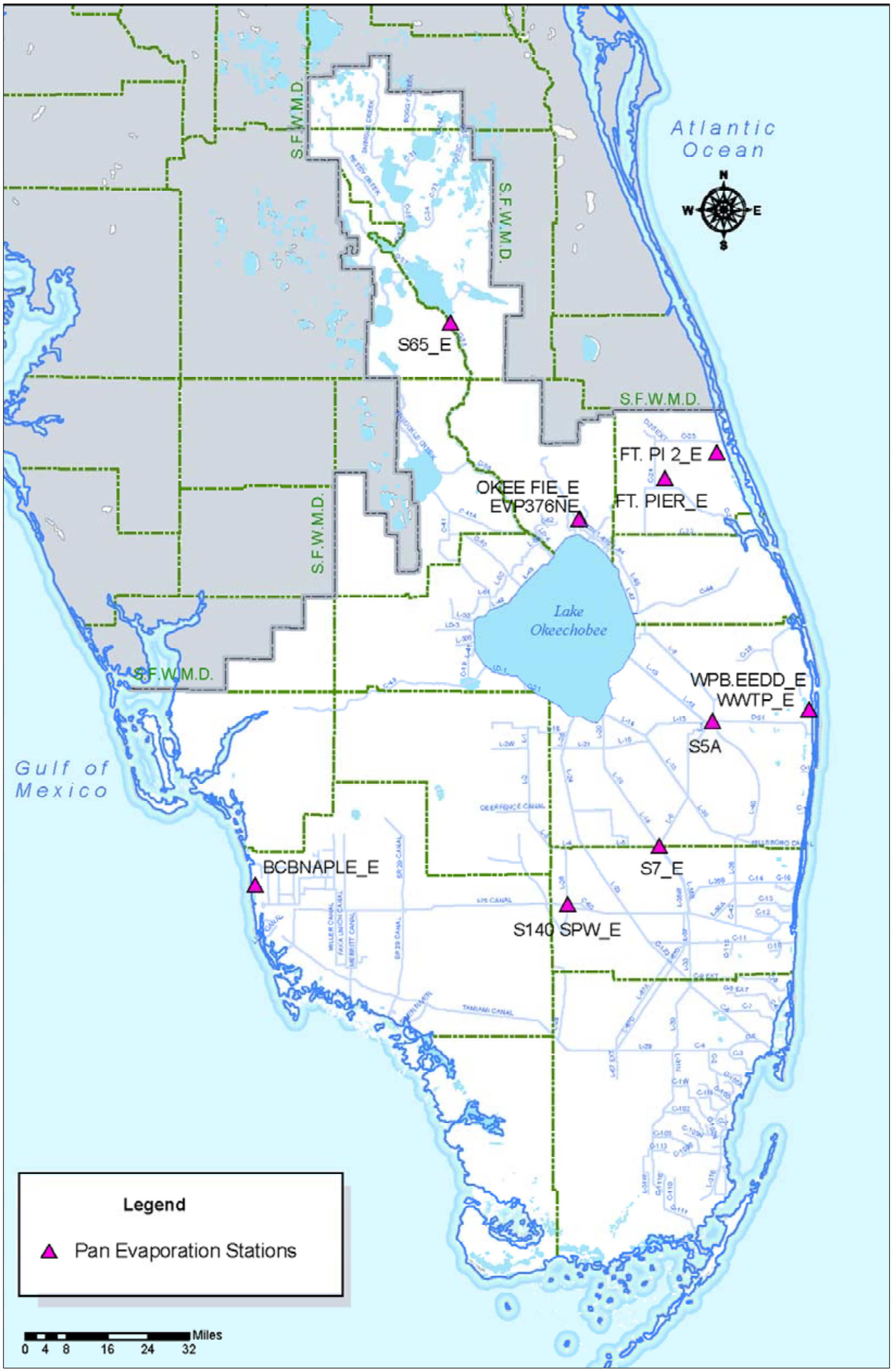

Figure 15. Location of active pan evaporation monitoring stations.

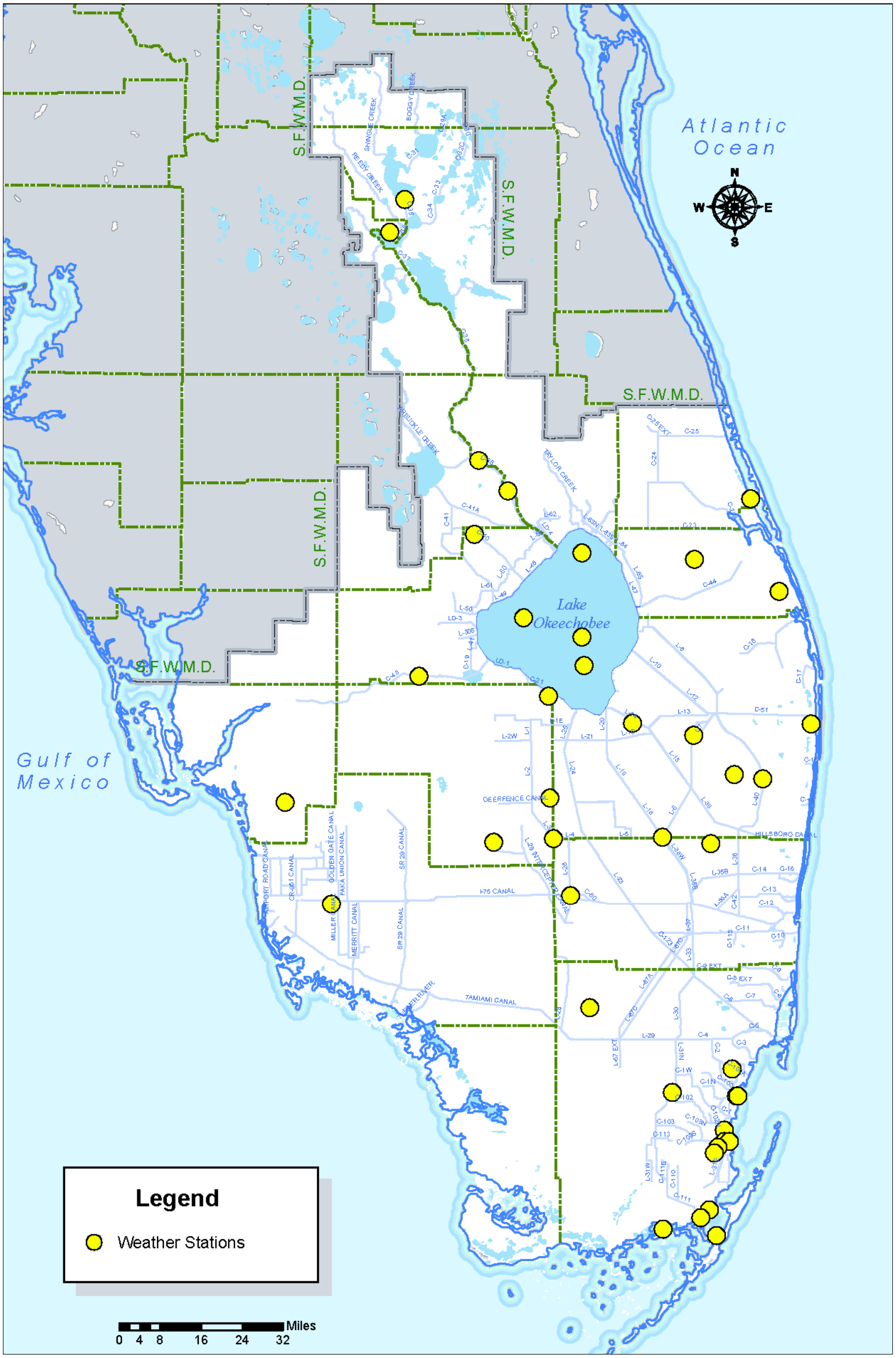

Figure 16. Location of active atmospheric monitoring stations.

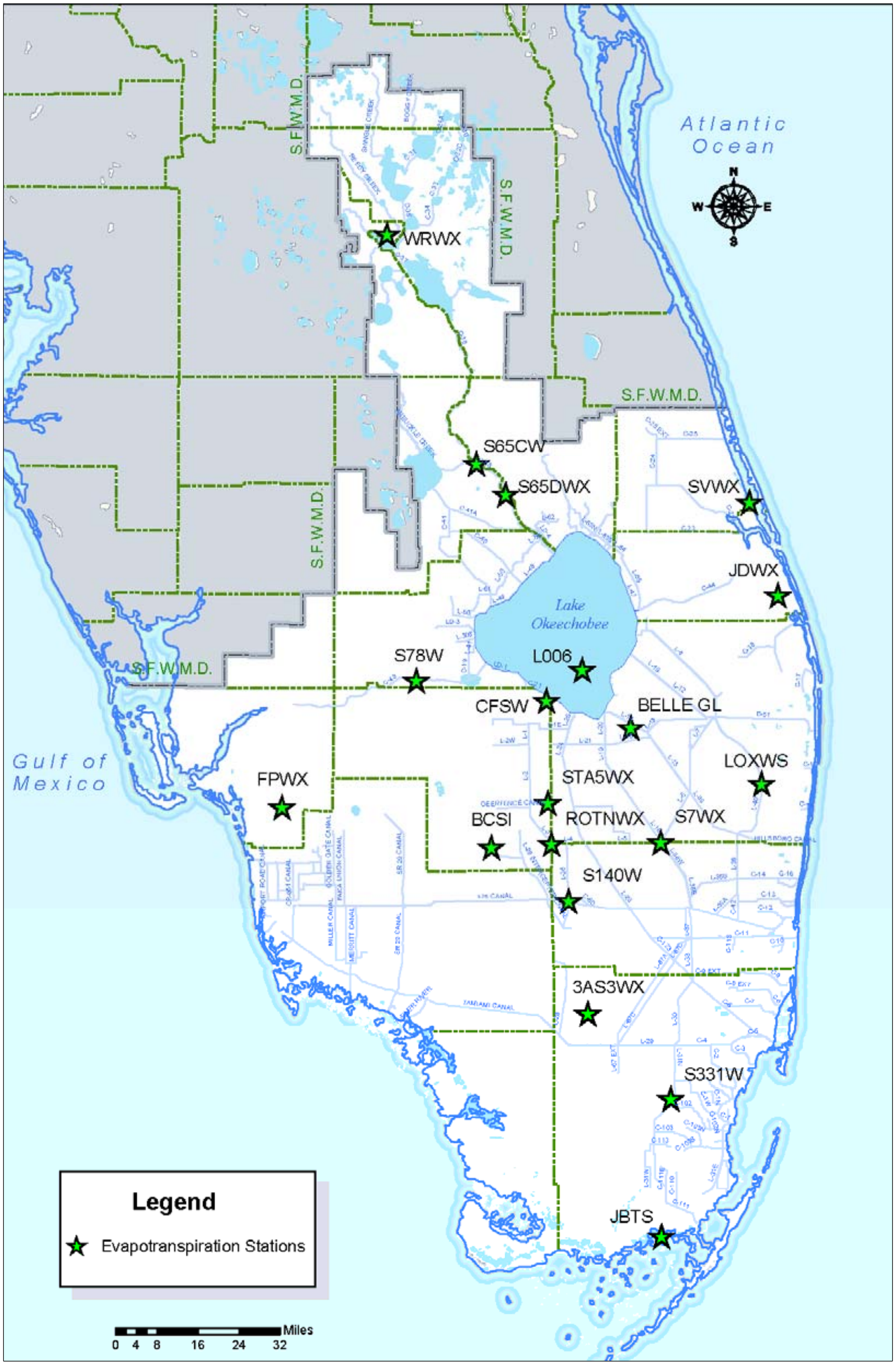

Figure 17. Location of active potential evapotranspiration computation stations.

Figure 18. Weather station L006 in Lake Okeechobee.

C. Meteorological Data

The District operates an extensive network of 45 active weather stations. The meteorological data such as air temperature, barometric pressure, humidity, solar radiation, wind speed, and water temperature are available on breakpoint basis. The breakpoint data can be obtained in 15-minute, hourly, and daily interval formats from the DBHYDRO database. However, pan evaporation data from 11 stations are available as daily data in the DBHYDRO database. In addition, daily PET data are available for 19 weather stations. The PET data were estimated using "the Simple Method" (Abtew et al., 2002). Additionally, historical meteorological time series data from the District are also available in DBHYDRO.

Data codes, or tags, accompany daily data within DBHYDRO in order to provide data users and analysts with an indication of data quality. A "null value" in the data code field corresponds to data that are missing. The "M" tag designates that data are missing, a code indicative of equipment and/or network malfunction. (Reminder: The complete record of DBHYDRO data codes used for rainfall and associated definitions are in **Table 1)**.

The QA/QC post-processing analysis is a second set of operations, which extract preprocessed data from DBHYDRO for select stations to undergo further examination. Presently, data from only 19 PET stations undergo this post processing. Data that has received the additional scrutiny of the QA/QC post-processing analysis is known as "preferred data" (PREF) and represents "best available data" at the District (Sangoyomi et al., 2006).

Since 2004, the District has worked jointly with USGS and the other four water management districts on a satellite-based ET estimation project (SFWMD, 2004). The project uses the Geostationary Operational Environmental Satellite (GOES) satellite data for hourly estimates of solar radiation with a spatial resolution that is significantly better than that available from the ground-based network of radiation sensors. This project will develop estimates of solar radiation, net radiation, PET, and reference evapotranspiration (RET) at a cell scale of 2 km x 2 km (same as the NEXRAD rainfall data grid), and a daily time scale from 1995 to 2004 for the entire state of Florida. The satellite-based PET and RET data are expected to be available in early 2008.

D. Measured Data Accuracy and Precision

The accuracy of the measured meteorological parameters depends on type of sensors that are used for measurement. The accuracies of the meteorological data are shown in Table x below. For radiation data, the precision would be up to three significant digits after the decimal, whereas for the remaining parameters the precision would be up to two significant digits after the decimal.

Table 5a. Accuracy of the measured meteorological parameters.

No.	Parameter	Typical Sensor	Accuracy
1	Pan Evaporation	NWS Class A Evaporation Pan	± 0.4 mm
2	Air Temperature	HMP45C Vaisala Temperature & Relative Humidity Probe	± 0.4 ˚C
3	Barometric Pressure	Vaisala PTA-427 Barometric Pressure Transducer	± 0.375 mm Hg
4	Relative Humidity	HMP45C Vaisala Temperature & Relative Humidity Probe	± 2% (0-90%RH) ± 3% (90-100%RH)
5	Solar Radiation (Net)	REBS Net Radiometer	± 5%
6	Solar Radiation (Photoactive)	LI-COR LI190SB Quantum Sensor	± 5%
7	Solar Radiation (Total)	LI-COR LI200S Pyranometer	± 5%
8	Wind Speed	Vaisala WS425 Ultrasonic Wind Sensor	greater of ±0.3 mph and 3% of reading
9	Wind Direction	Vaisala WS425 Ultrasonic Wind Sensor	± 2 ˚
10	Water Temperature	CS 107 / 108 Thermistor Temperature Probes	± 0.2 ˚C

E. Meteorological Network Design

The existing meteorological network has evolved for just more than two decades whereas the current pan evaporation network has evolved over many decades. An assessment of the evaporation pan network of the District was conducted in 1995 (Chin, 1995). In that study, Ordinary Kriging (OK) and Universal Kriging (UK) methods were used in network evaluation and assessment.

Initially, the main purpose of weather stations was to obtain weather conditions for operations of water-control facilities. Later, these weather parameters were used for evapotranspiration estimation purposes. However, the actual designs of the meteorological network for ET estimation were not performed. An evapotranspiration network design is now planned and is expected to be performed in the next few years depending upon availability of funds at the District.

IV. RAINFALL MONITORING NETWORK

By Chandra Pathak and Madhav Pandey

One of the most important processes in the hydrologic cycle is precipitation. The main source of precipitation, even over land masses, is water vapor derived by evaporation at the ocean's surface. The air is cooled by being lifted up the slope of a mountain range, or up and over colder (and heavier) polar air, or straight up by heated air rising in the process of thermal convection. In all cases, the end result is the same: the air cools below the dew point, moisture condenses on the ever-present condensation nuclei, and a cloud forms.

Rainfall is by far the most important source of precipitation in most areas and the main contributor to runoff, stream flow, and aquifer recharge. In the United States, rainfall is measured by a combination of radar and rainfall readings taken at more than 13,000 standard and automatically recording gauges. These data are input to much-used regional maps and information printouts.

Despite advances in remote-sensing technologies, such as radar and satellite, rain gauges remain the most common method for the measure of rainfall. Rain gauges are fixed instruments that sample precipitation in a cylindrical collector, which is typically 8 inches in diameter.

Although rainfall is a meteorologic parameter, it has a significant role in water resources management and hydrology. Therefore, a separate section on the rainfall monitoring network used by the District is included herein.

A. Development of the Rainfall Monitoring Network

A set of rain gauges was installed in various locations in Florida in the early 1900s by the National Oceanic and Atmospheric Administration (NOAA). The District began operating its own set of rain gauges after its formation in 1949. Since that time, the locations of rain gauges were determined based on District projects that needed the rainfall data. The number of District rain gauges increased significantly after 1965. A total of 780 unique stations have collected rainfall data between 1950 and 2005. **Table 6** shows the total number of stations where daily rainfall time-series data are available on a decade basis.

Table 6. Total number of rain gauge stations in the District from 1950 to 2005.

Years	Total Number of Rain Gauge Stations
1950-1959	61
1960-1969	132
1970-1979	213
1980-1989	311
1990-1999	539
2000-2005	491

The number of existing rain gauges has increased over several decades based on the project needs of the District. The rain gauge network is geographically and spatially uneven; it is relatively dense in some areas and sparse in other areas. For example, the network contains several clusters of rain gauges that are located within 2 to 6 miles of each other. However, there are several tens of square miles within the District without rain gauges. In order to address this deficiency, the District has completed a rain gauge network optimization study (SFWMD, 2006). A summary of that study is given later in this report.

B. Existing Active Rain Gauge Network

The District operates a network of rain gauging stations to provide precipitation data for use in water management operations, modeling, and planning (Huebner et al. 2003). Several limitations have been shown to exist, however, in the sole reliance of point rain gauge measurements, including the introduction of error through the spatial extrapolation of such data. Accounting for spatial rainfall distributions is of particular concern in South Florida, where intense, highly variable convective rain events predominate in the wet season that starts in June and ends in October. Because of the tropical nature of summer rainfall in South Florida, the gauges only give representative rainfall measurements for long averaging periods, and can often miss, or erroneously assess, the magnitude of significant rainfall events.

1. Field Instrumentation at the District

Rain gauges are classified as recording or non-recording. Recording rain gauges supply breakpoint data, or precipitation measurements, collected at “fine time resolution.” Consequently, recording-type gauges offer information regarding temporal rainfall distribution and intensity. The District currently maintains 241 recording gauges, which produce breakpoint rainfall data in 1-, 3-, or 5-minute intervals.

Non-recording rain gauges, also referred to as accumulation gauges, lack the mechanical capabilities of recording-type devices and, as a result, cannot produce breakpoint rainfall data. These instruments collect and store rainfall over a specified time period (usually 24 hours) until a manual reading is taken. The District uses a total of 46 standard-type, non-recording rain gauges to provide daily rainfall accumulation data. The specific types of recording and non-recording rain gauges used by the District are described in **Table 7**.

Table 7. Types of rain gauge instruments used by the District.

TYPE	*Instrument*	Description
RECORDING	***Tipping Bucket*** 	The tipping bucket precipitation gauge operates by measuring water volume in a lightweight, dual-compartment tipping device. The apparatus has two equally sized buckets on either end that balance on a horizontal axis. As one bucket is in the upright fill position, the other one is draining rainwater. Precipitation collected in the first bucket fills the compartment until the weight of the water causes the container to tip due to instability. This causes the second bucket to move into the upright fill position, while the first bucket empties below. Each tip of the container is recorded as an electronic signal over time, and corresponds to a volume of 1/100th (0.01) of an inch of rainfall. This allows for the capture of a discrete series of precipitation measurements over time.
RECORDING	***Weighing Bucket*** 	The weighing bucket rain gauge consists of a rainfall collection reservoir that rests on a scale. Rainfall collected inside the reservoir exerts a weight proportional to the volume of rainfall, which is then recorded on a clock-driven chart. Thus, a continuous account of precipitation over time is achieved, usually in the form of a 7-day graph. The weighing bucket rain gauge allows the analyst to discern rainfall depth to the nearest 1/100th (0.01) of an inch.
RECORDING	***Float-Type Stilling Well*** 	The float-type stilling well rain gauge provides continuous precipitation data by using a float mechanism inside the rainfall collection reservoir. Rainfall enters the collection chamber through a funnel to minimize disturbance of the water surface. A stilling device is located inside the reservoir to lessen erroneous oscillations caused by incoming water. The position of the float is recorded by a pen-trace system on a clock-driven chart to generate a plot of rainfall over time, usually in the form of a 30-day graph.
NON-RECORDING	***Standard Rain Gauge*** 	The standard rain gauge is a simple device that contains no mechanical components and is non-recording. The gauge itself consists of a collection area, funnel, and collection reservoir. Manual readings are typically made on a daily basis with a measuring stick calibrated to express rainfall volume in inches. Measurements are recorded in a field log to the nearest 1/100th (0.01) of an inch.

Rainfall is traditionally measured at a "point" using various types of rain gauges such as the non-recording cylindrical container or the recording weighing, float and tipping bucket. Three types of recording rain gauges are used by the District, and include tipping bucket, weighing, and float-type gauges.

The tipping bucket rain gauge is the preferred instrument for measuring rainfall due to its relative ability to minimize systematic sampling errors and transmit data via telemetry (SFWMD, 2004b). Each time the bucket tips, one event is recorded. Each event represents $1/100^{th}$ (0.01) of an inch of rainfall. A magnetic sensor in the gauge sends a signal to the event recorders, data loggers, or other data-acquisition devices (**Figure 19**). Utilizing real-time radio-frequency telemetry through a series of repeater networks, the data collected can be sent to the District.

Figure 19. View inside of a tipping bucket.

a. Rain Gauge Limitations

Point Measurements

Precipitation gauges are capable of providing accurate point measurements of rainfall. However, rain gauges alone cannot feasibly provide the spatial rainfall distributions necessary for use in hydrologic modeling applications (Huebner et. al., 2003). As a result, several approximation techniques have been developed for the aerial extrapolation of point-gauge measurements to estimate mean precipitation. These techniques include the arithmetic mean method, the Thiessen polygon method, the isohyetal method, and the inverse-distance-squared method. The isohyetal method is not commonly used at the District due to the minimal variability in elevation of the South Florida region.

These rainfall-averaging techniques assume mathematical representations of rainfall distributions, which may not be indicative of actual precipitation characteristics. In addition, approximation techniques may not account for rainfall values which may be higher or lower than those observed at gauge locations, specifically during convective and tropical events (Sangoyomi and Dawkins, 2005). As a result, adopting approximation techniques may introduce a significant amount of error.

Rain gauges may not accurately capture rainfall events that demonstrate high spatial variability. Such events include convective and tropical disturbances that predominate in South Florida during the wet season. Huff (1970) demonstrated the pronounced spatial variability of rainfall rates in Illinois "within and between convective storms" by using a dense network of recording rain gauges, concluding that accurate sampling of convective precipitation may not be feasible for areas greater than 100 square miles. The District realizes that highly variable storm events "may not be captured by the current District rain gauge network" and that this represents a major limitation in the continued use of rain gauge technology.

Equipment Maintenance

Precipitation gauges require a considerable amount of general maintenance in the form of periodic calibration and cleaning, which are time consuming and expensive. Individual gauges must also be attended to when they are not working properly or are in need of relocation or upgrade. Equipment malfunction can also result in the loss of data. Data gaps resulting from mechanical or electrical failure hinder subsequent hydrologic analysis and decision making.

Random and Systematic Errors

Errors produced in rain gauge sampling are generally classified as random or systematic. Random errors are caused by irregular fluctuations in the measurement of rainfall but tend to naturally decrease in magnitude as more samples are taken. Such errors are deemed unavoidable. Conversely, systematic errors produce consistent measurement inaccuracies and, thus, introduce bias. Some common systematic errors in precipitation sampling include errors due to wind, obstructions, evaporation loss, wetting loss, and instrument errors. Systematic errors must be reduced as much as possible to obtain the most accurate rainfall data available from a given rain gauge network (World Meteorological Organization, 1996).

One of the greatest sources of error to consider is undercatch of precipitation due to wind effects (World Meteorological Organization, 1996). Linsley et al. (1975) described gauge catch deficiency as a function of wind speed at the height of the gauge orifice, and further concluded that wind speeds exceeding 20 miles per hour may result in an overall error of 20 percent or more. Similarly, Pathak (2001) reported that "rainfall amounts are under estimated due to wind, and are under estimated as much as 1 percent (of rainfall) per mile per hour (mph) of wind speed." Guo et al. (2001) developed a model to estimate undercatch as a function of wind speed and gauge height. Findings from this study conclude that "rain undercatch ranges from 10 percent to 15 percent under 15 mph wind and can increase to 56 percent under 50 mph wind." Therefore, error produced by wind may be considerable in South Florida, as thunderstorms can produce winds of up to 50 mph and tropical events demonstrate wind speeds from 38 mph to over 156 mph (National Hurricane Center, 2006).

Other systematic errors in rain-gauge measurements are caused by evaporation and wetting loss. Evaporation is primarily a problem in non-recording gauges when the collection reservoir is not protected. Error associated with wetting loss, or the loss of rainfall that adheres to the collection system itself without being collected, is also more prevalent in non-recording gauges (World Meteorological Organization, 1996). The presence of insects, leaves, and other debris can clog gauges or otherwise offset actual readings and lead to error. In addition, the placement of sampling instruments in the proximity of obstructions such as buildings and trees can affect rain gauge accuracy.

Instrument errors result from inaccuracies caused by sampling equipment, and vary according to rain gauge type. Sampling errors specific to the tipping bucket (TB) rain gauge have been studied extensively as the TB gauge is the choice gauge for many hydrologic applications. Nystuen (1999) conducted a study in Miami over a 17-month period to analyze the relative performance of several rain gauge types in different rainfall conditions, including convective, frontal, and tropical event (one occurrence). The investigation concluded that the TB rain gauge consistently underestimated measurements during extremely high rainfall rates. Nystuen (1999) attributed this occurrence to "water loss between tips," meaning that a fraction of rainfall may bypass sampling in heavy rainfall events when rainfall accumulates faster than the bucket mechanism can tip. TB gauges are also known to exhibit error due to splashing of rainfall from the collector during intense rainfall events. These findings suggest that the TB gauge may not be best suited for determining rainfall amounts during periods of heavy rainfall. To adjust for these inaccuracies, the District performs regular monthly calibration of TB gauges. The gauges are also calibrated between servicing when QA/QC pre- or post-processing reveals that measurements are consistently low.

2. *Breakpoint Rain Gauge Stations*

The District uses various methods for the acquisition of precipitation data collected at its rain gauge sites. Data transfer occurs through two different processes: the District's supervisory control and data acquisition (SCADA) system and the manual transport of data. The SCADA system provides direct acquisition of real-time rainfall data wirelessly by means of microwave, radio-frequency telemetry, or telephone lines. The system is also known as Automated Acquisition and Monitoring System (ARDAMS). A major advantage in the use of telemetry, within SCADA, is the transmittal of real-time data, which is pertinent in situations requiring rapid data acquisition and response.

a. Real-Time Rain Gauge Stations

Tipping bucket rain gauges connected to the SCADA system rely on three types of remote terminal units (RTUs) to provide near real-time data: Campbell Scientific CR10X-TDs (LoggerNet), Motorola SCADA (MOSCAD), and Legacy Master Concentrator Unit/Remote Access and Control Units (RACU). Detailed information regarding these RTUs and associated reporter types is presented in **Table 8**. **Figure 20** shows the location of the real-time rain gauge stations.

Table 8. Rain gauge reporter types – real-time SCADA system.

Remote Terminal Unit (RTU)	Reporter Type	Method of Data Transfer	Data Collection Frequency
Campbell Scientific CR10	LoggerNet System	Telemetry	Real Time
Motorola SCADA	MOSCAD	Telemetry	Real Time
Legacy MCU/RACU	RACU	Telemetry	Real Time

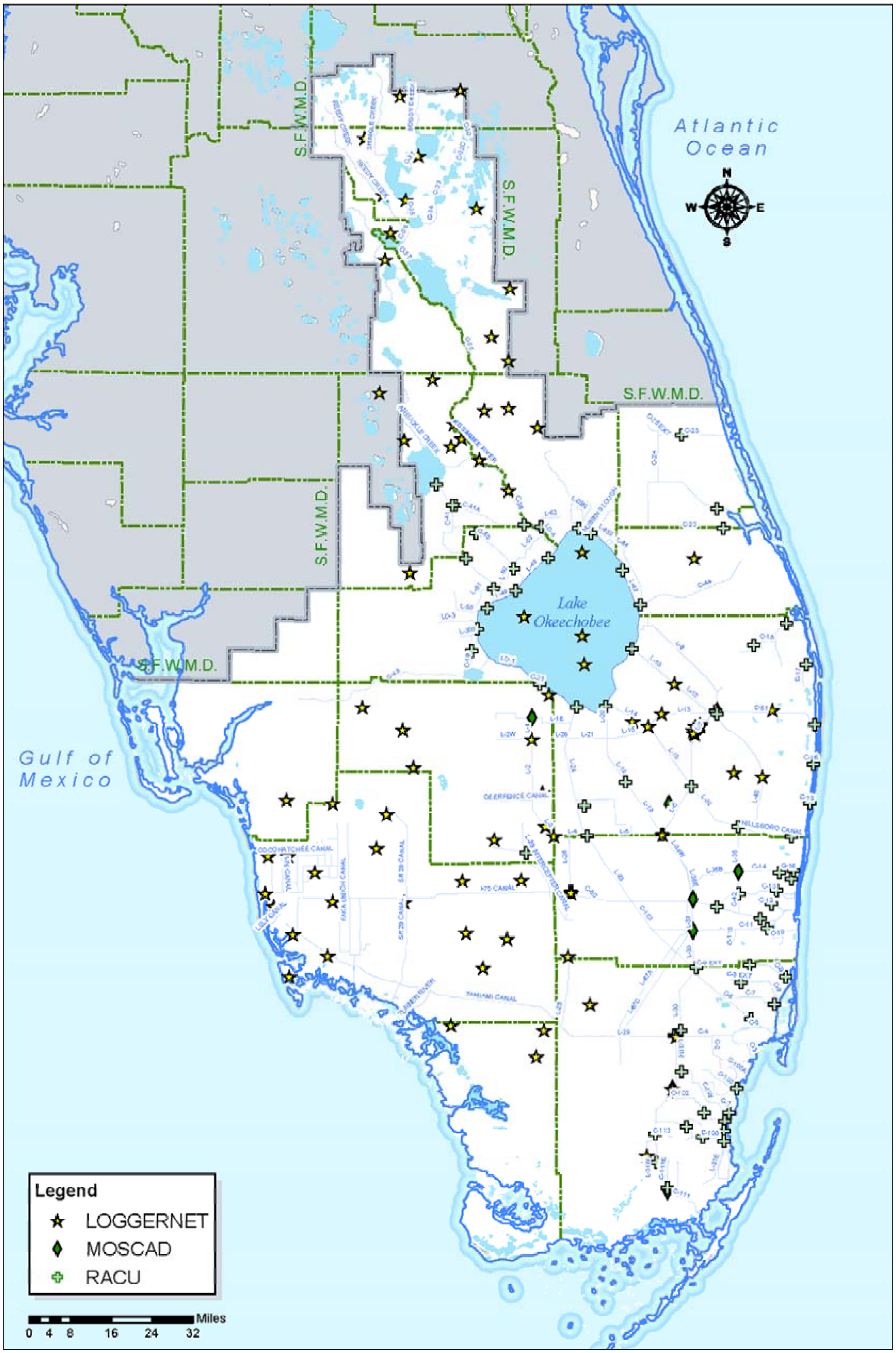

Figure 20. Location of real-time rain gauges in the District.

b. ARDAMS (Daily Rain Gauge Data Retrieval Stations)

SCADA also delivers daily accumulation data through ARDAMS, which transmits data electronically over phone lines and/or radio-frequency telemetry. From several locations with Campbell Scientific CR10 data loggers, the electronic data are transferred after midnight every day via phone lines. These stations are grouped under the ARDAMS system. **Figure 21** shows the location of the CR10 rain gauge stations that provide the data via the ARDAMS system.

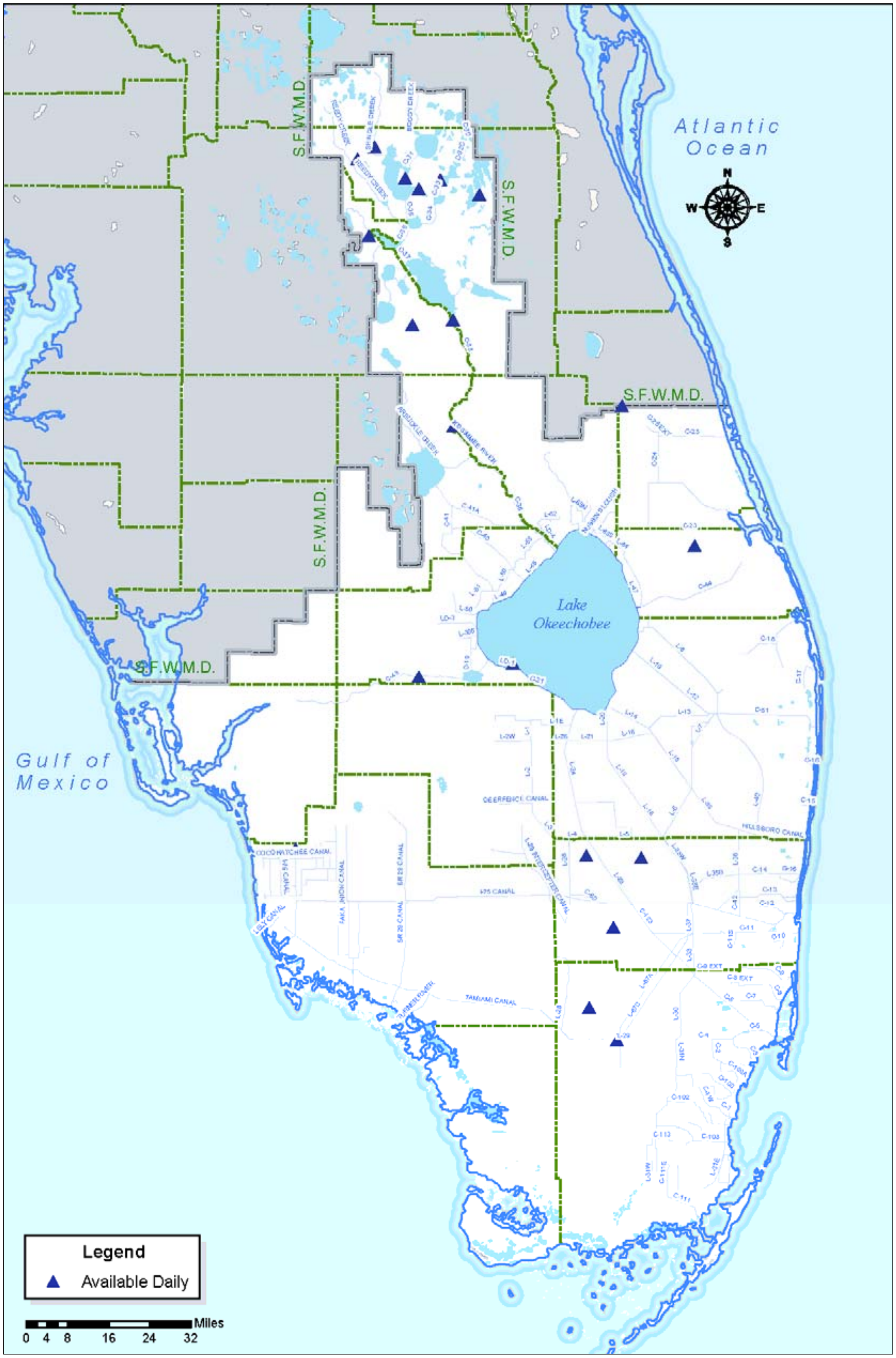

Figure 21. Location of the daily CR10 rain gauge stations.

c. CR10 (Monthly Rain Gauge Data Retrieval) Stations

In addition to the RTUs required for data acquisition via SCADA, two other reporter types are used to manually transfer rainfall data. They include stand-alone Campbell Scientific CR10 data loggers (which, when not connected to the LoggerNet or ARDAMS systems, provide precipitation data that can be downloaded from the RTU each month and manually transported to the District); and graphic charts (a product of weighing and float-type rain gauges, and daily readings from standard-type rain gauges, which are recorded in field logs). **Table 9** summarizes the type of manually downloaded electronic data from this rain gauge reporter type in use. **Figure 22** shows the location of the CR10 rain gauge stations that have data downloaded on a monthly basis.

Table 9. Rain gauge reporter type — manual acquisition of electronic data.

Data Logger	Reporter Type	Method of Data Transfer	Data Collection
Campbell Scientific CR10	CR10	Manual acquisition of electronic data	Once per month

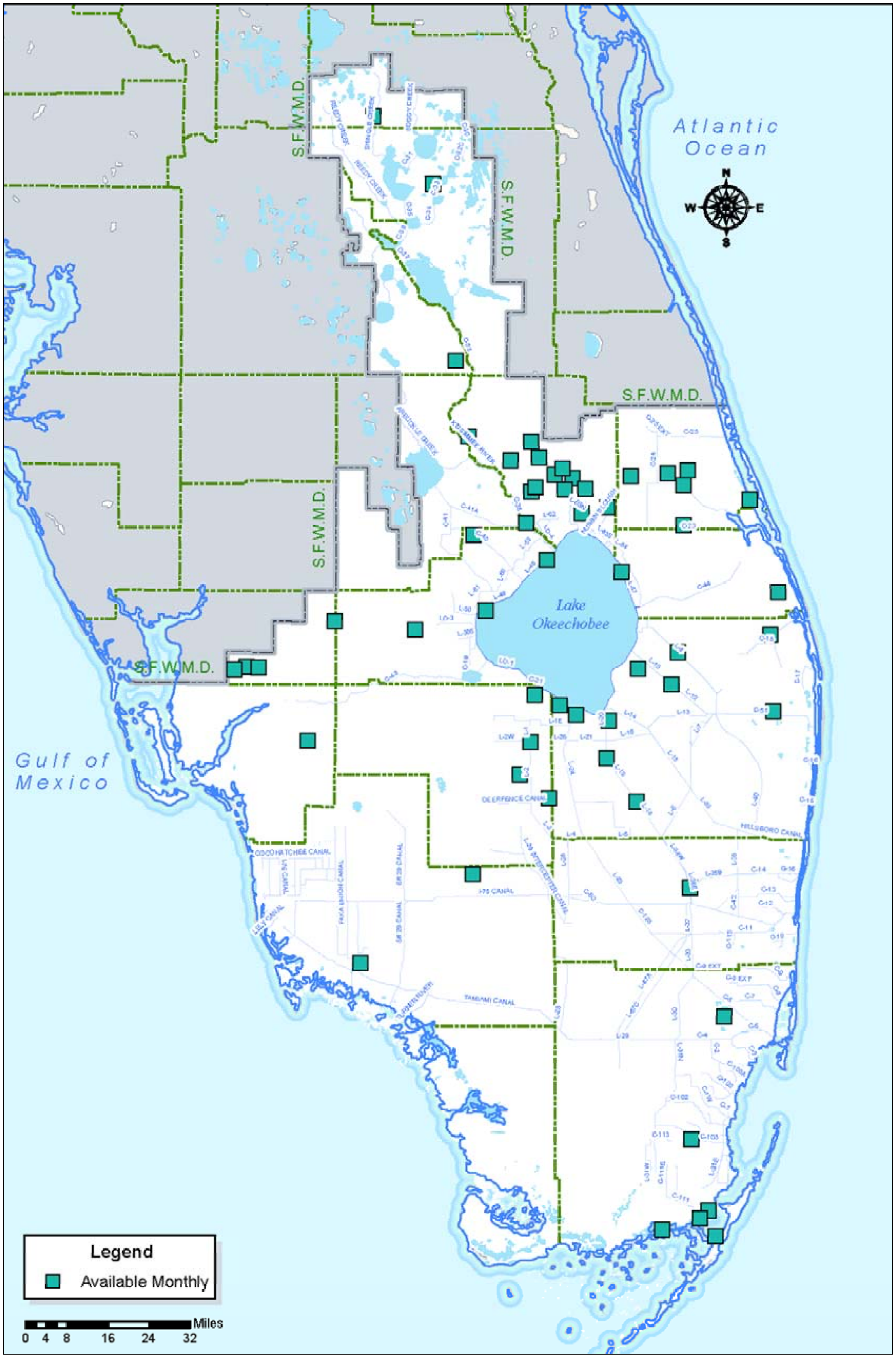

Figure 22. Location of monthly CR10 rain gauges in the District.

3. *Daily Rain Gauge Data Stations*

Daily rainfall measurements are manually taken from standard rain gauge (non-recording type) installations at approximately 7:00 AM Eastern Standard Time (EST). Several limitations exist in the manual transfer of data from rain gauge sites to the District. This procedure requires that dedicated District personnel physically obtain the necessary daily, weekly, or monthly precipitation data at each rain gauge site. Obtaining the daily rainfall data can be problematic during holiday and weekend periods as District personnel are not always available to manually record the data for these days. In addition, data collected manually may incorporate more error by the analyst or from visual interpretation of the data in the field. **Table 10** summarizes the active types of manually collected data from these rain gauges. **Figure 23** shows the location of the non-recording type rain gauge stations that provide daily rainfall data.

Table 10. Rain gauge reporter types — manual data acquisition.

Manual Data	Reporter Type	Method of Data Transfer	Data Collection
Graphic Chart	Graphic Chart	Manual data transport	Once per month
Daily Data	CO-OP Log	Manual data transport	Daily

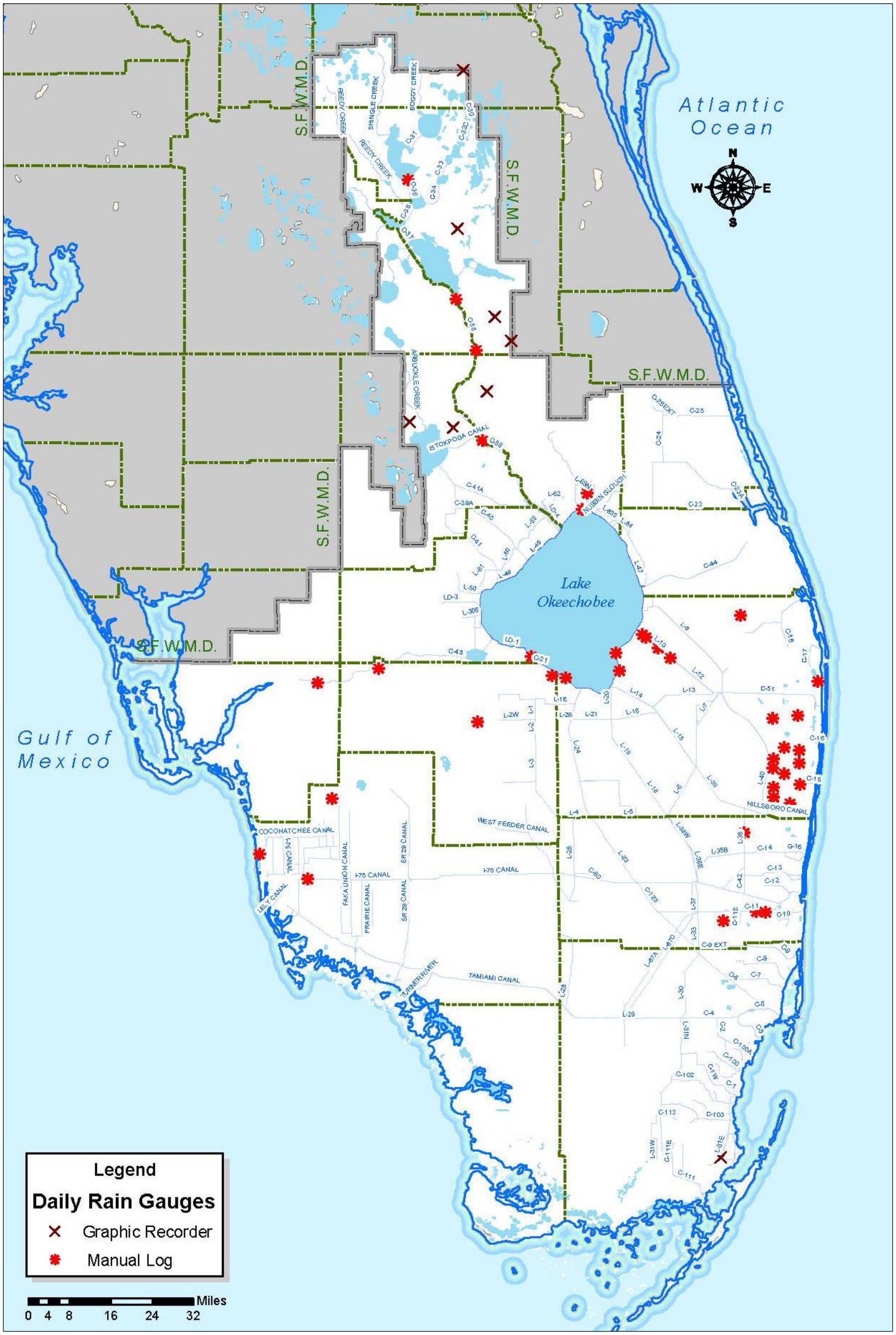

Figure 23. Location of non-recording daily rain gauges.

C. NEXRAD Rainfall Data

Radar images from the U.S. National Weather Service network cover much of the United States and provide a way of measuring the intensity of rain or snowfall. Radar can locate and follow clouds within a range of 200 to 400 kilometers. Weather radar emits microwave energy in short bursts or pulses, which are focused in a narrow conical beam that scans the atmosphere from a slowly rotating antenna. A beam passes through fog and clouds, but when it encounters rain, snow or ice particles (hail), some of the energy is scattered back to the radar's antenna as an echo. The amount of energy the antenna receives is proportional to the intensity of the precipitation; the heavier the rain or snow, the more energy is scattered back to the antenna.

There is a statistical tradeoff between rainfall measurement data collected by rain gauges and weather radar. Rain gauges can provide precise point values of rainfall depth and intensity but cannot economically provide the spatial distribution of rainfall. While rain gauges suffice for frontal-related rainfall events, the timing and orientation of the front is often not well represented and can miss convective rainfall events altogether. South and Central Florida receive most rainfall during the wet season, which is dominated by tropical and convective processes.

Next Generation Radar (NEXRAD) or Weather Surveillance Radar 88 Doppler (WSR-88D) data provides complete spatial coverage of rainfall amounts unobtrusively using a predetermined grid resolution (usually 2 km x 2 km or 4 km x 4 km) (**Figure 24**). The NEXRAD rainfall data is limited by relying on the measurement of raindrop reflectivity, which can be affected by factors such as raindrop size and signal reflection by other objects. Because the reflected signal measured by the radar is proportional to the sum of the sixth power of the diameter of the raindrops in a given volume of atmosphere, small changes in the size of raindrops can have a dramatic effect on the radar's estimate of the rainfall. For this reason, the radar is generally scaled to match the volume measured at the rain gauges (Hoblit and Curtis, 2000). The best of both measurement techniques is realized by using rain-gauge data to adjust NEXRAD values. The readers can obtain additional information on this subject from two references (Huebner et al. 2003 and Skinner, 2006) that are shown in this report.

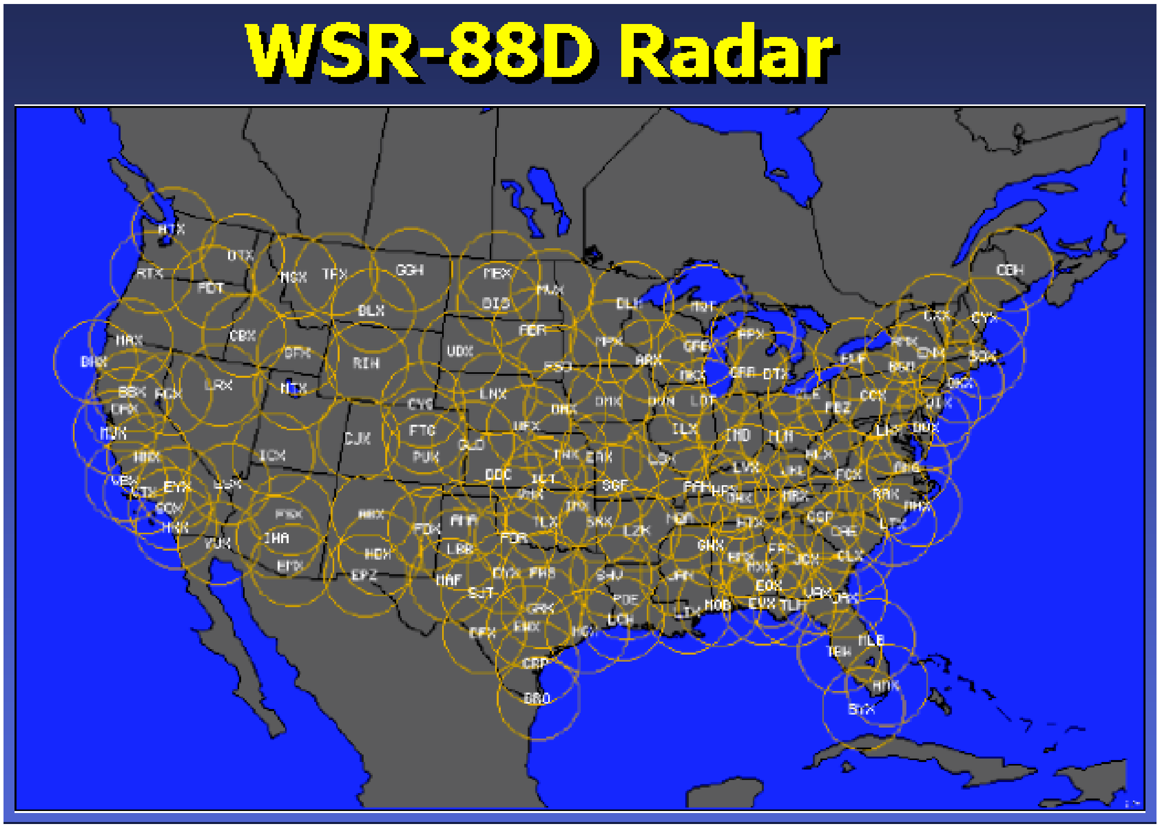

Figure 24. NEXRAD ground-based radar network – Doppler WSR-88D radar covering the U.S.

Four NEXRAD sites operated by the National Weather Service (NWS) cover the District: KBYX in Key West, KAMX in Miami, KMLB in Melbourne, and KBTW in Tampa. Although data is also available from several private radar installations, the District exclusively uses NWS sites for its NEXRAD rainfall database because of longevity and reliability issues. NEXRAD technology offers the distinct advantage of providing water management officials with a spatial and temporal account of rainfall variability. In July of 2002, the District started acquiring NEXRAD rainfall data. Skinner (2006) provides additional details on the NEXRAD rainfall data and gauge-adjustment methodology used in derivation of the data.

1. NEXRAD rainfall data acquisition

Weather data acquired from NEXRAD is used by the District in making decisions for operational purposes. However, the use has been largely limited to visual interpretation of data as opposed to quantitative analysis. From July 2002 to September 2007, the District acquired NEXRAD data coverage from OneRain, Inc. (Huebner et al. 2003). In July 2002, the District, in conjunction with three of the other four Florida water management districts, began to acquire NEXRAD data coverage through a competitive contract awarded by the St. Johns River Water Management District (SJRWMD) to develop a corporate database and methods for data access. From October 2007, four Florida water management districts will acquire similar NEXRAD rainfall datasets from Vieux and Associates, Inc., under a similar contract with the SJRWMD for next five years. The use of a single vendor for processing NEXRAD data for four water management districts provides an opportunity to eliminate data discontinuities at district boundaries. The use of 15-minute data (i.e., taken at 15-minute intervals) and rain-gauge-adjusted NEXRAD data by the District's Operations Control Center (OCC) are major objectives of the acquisition.

a. Near Real-Time Data

OneRain, Inc., provides near real-time, 15-minute rainfall amounts by using the following process:

1. Acquires 15-minute radar rainfall accumulations from the NWS via WSI Corporation, which uses an empirical look-up table to convert reflectivity values to rainfall intensities. Concurrently, 15-minute rainfall accumulation data from approximately 152 telemetry rain gauge sites are sent to OneRain, Inc. via File Transfer Protocol (FTP).
2. Adjusts radar rainfall amounts using gauge data algorithms
3. Places adjusted radar rainfall depths in a flat file and sends via FTP to the District.
4. Checks the flat file for completeness and loads them into the Oracle® database.

The process outlined above takes between 10 to 20 minutes; thus, the data is referred to as "near real-time." Each file contains 33,773 values, one value for each of the 2 km x 2 km cells in the grid covering the District. Each 15-minute interval file is 366 kilobytes (kb) in size and is loaded into the Oracle® database in less than 1 minute. The coverage includes a 35-mile area beyond the boundaries of the District. This provides rainfall information for such areas as the Biscayne and Florida bays. Data for other water management districts is processed concurrently to insure that there are no discontinuities at district boundaries.

b. End-of-Month Data

Near real-time data are verified each month and an end-of-month (EOM) verified set of 15-minute files is produced. The EOM files use additional 81 rain gauge data that are not available in real-time and a proprietary algorithm based on the Brandes method (Brandes, 1975) to adjust radar rainfall values. An expert from OneRain reviews the results to identify and correct any anomalies or apparent errors. When the EOM files are received by the District, the near real-time data are archived, primarily to preserve the information upon which operational decisions may have been made, and are replaced with the EOM verified data set.

2. NEXRAD Rainfall Data Availability

The NEXRAD coverage for the District (Huebner et al. 2003) includes rainfall amounts for 33,773, 2 km x 2 km cells, provided at 15-minute intervals. The current online database contains values from January 1, 2002, to the present. Each cell has a specific time series of rainfall data.

The table structure in the Oracle database complies with the Arc Hydro (Maidment, 2002) architecture. The current online database contains values starting on January 1, 2002, through present. Tables using an ArcHydro schema were produced in Oracle 8i to facilitate corporate implementation of ArcHydro and provide a common framework for accessing NEXRAD data. Several techniques were used to optimize the database and provide timely access to the database. These include storing only non-zero data values in the database and database partitioning based on the calendar year. The Arc Hydro structure was used to facilitate GIS access to the data and to support a uniform corporate database model that was consistent with a published standard, for hydrologic data.

Near real-time data is loaded directly to the Oracle database and can be accessed directly using SQL or ODBC drivers. An ArcIMS-based application (Pathak et al. 2005) is used for gauge-adjusted NEXRAD rainfall data retrieval. This web-based user interface (**Figure 25**) allows for users to access and aggregate 15-minute data for a specified period and produces a data file in ASCII format. The application provides spatially (such as rain areas, drainage basins, watersheds) and temporally (such as hourly, daily, event, monthly, and annual) varied, aggregated datasets in tabular and image formats.

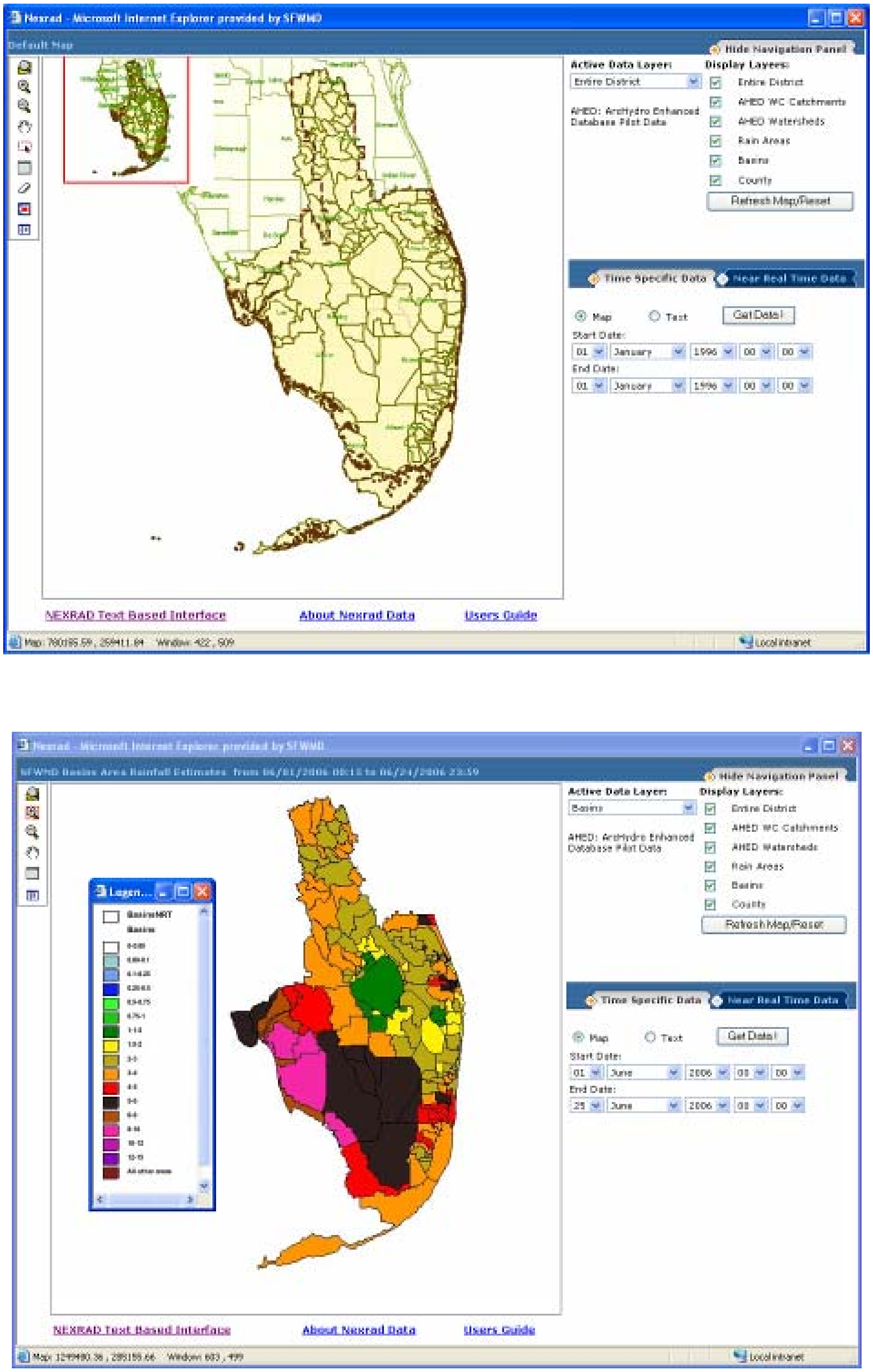

Figure 25. ArcMap-based NEXRAD data retrieval application: (A) input screen and (B) output.

D. Rain Gauge Data

The District operates an extensive network of 287 active rain gauges in order to obtain rainfall data necessary for use in operations, planning, and regulatory aspects of water management. The District's rain gauge network is shown in **Figure 26**. The rainfall data from 241 rain gauge stations are available on breakpoint basis. The breakpoint data can be obtained in a format of 15-minute, hourly, and daily intervals from the DBHYDRO database. The rainfall data from the remaining 46 stations are available as daily rainfall (from non-recording rain gauges) in DBHYDRO database. Additionally, historical rainfall time series data from the District and other external government agencies are also available in DBHYDRO to both internal and external users.

Designation codes account for the different rain gauge reporter types used by the District (**Table 11**). **Table 12** provides the corresponding breakdown of the District's 287 current active rain gauge sites with respect to reporter type.

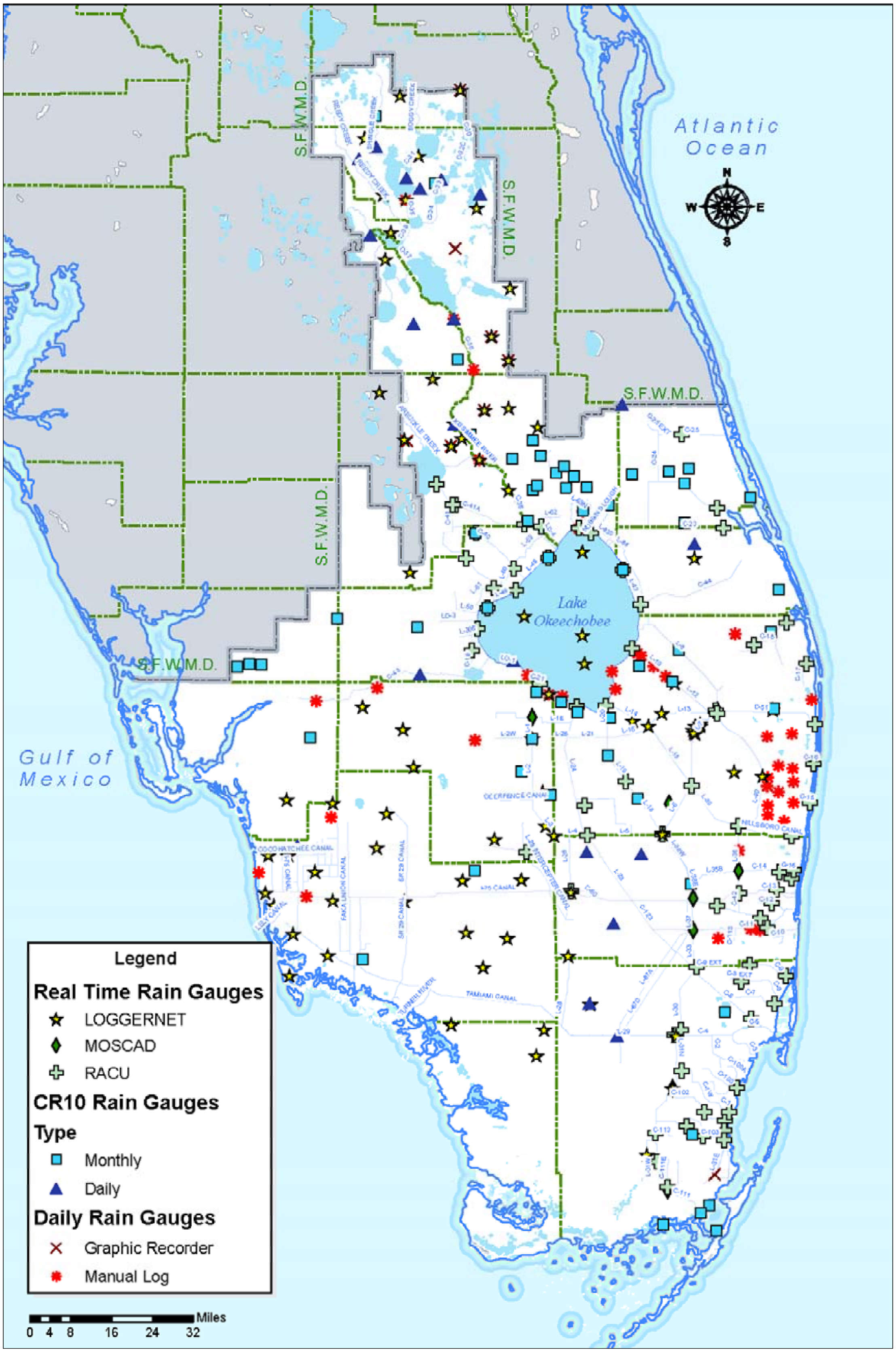

Figure 26. District rain gauge network.

Table 11. Rain gauge reporter codes and associated attributes.

Code	Reporter Type	Tipping Bucket Rain Gauge	Breakpoint Data	Reporting Time (EST)
SS ARDAMS	ARDAMS	Yes	Yes	Midnight-midnight
SS DMS	LoggerNet System	Yes	Yes	Midnight-midnight
SS CR10	CR10	Yes	Yes	Midnight-midnight
RACU	RACU	Yes	Yes	Midnight-midnight
MOSCAD	MOSCAD	Yes	Yes	Midnight-midnight
2A35 Graph and Weekly Graph	Graphic Chart	No	Yes	Midnight-midnight
CO-OP LOG	CO-OP LOG	No	No	7 AM – 7 AM

Table 12. Active rain gauge station IDs and associated attributes.

Break Point Data (241)						Daily Data (46)
Real-Time (152)			Received Daily (21)	Received Monthly (68)		
LoggerNet (74)	RACU (71)	MOSCAD (7)	ARDAMS (21)	CR10 (60)	Graphic Chart (8)	CO-OP LOG (46)
L005+R	CV5-R	S38-R	S78W+R	EAA2+R	MRF185	MRF101
L006+R	G56-R	G136-R	ENR308+R	FLYG+R	MRF187	MRF102
S5AY-R	S123-R	S34-R	951EXT+R	JBTS+R	MRF3	MRF114
LZ40+R	S124-R	S9-R	KREF+R	PALM+R	MRF190	MRF135
S65CW+R	S13-R	S331M-R	EXOT+R	RUCWF+R	MRF158	MRF137
BCSI+R	S131-R	G331D-R	ALL2+R	SCRG+R	MRF155	MRF138
CFSW+R	S153-R	S5AE-R	3AS+R	TPTS+R	MRF23	MRF213
S61W+R	S155-R		LOKEEM+R	MDTS+R	MRF123	MRF250
LXWS+R	S177-R		TOHO10+R	DAV2+R		MRF27
ENR203+R	S18C-R		TOHO2+R	LEHI+R		MRF285
ENR101+R	S2-R		3AS3W3+R	WHID+R		MRF299
ENR301+R	S20F-R		3ANW+R	OPAL+R		MRF300
S331W+R	S20G-R		S12D+R	WLNB+R		MRF301
L001+R	S21-R		3ANE+R	SIRG+R		MRF419
ENR106R	S26-R		KISSFS+R	SBAY+R		MRF5002
S59+R	S28Z-R		CREEKR+R	HOMEFS+R		MRF5004
S336+R	S29-R		INDLK+R	MIALCK+R		MRF5006
BELLW+R	S29Z-R		S65GW+R	PEL23+R		MRF5034
COCO1+R	S33-R		INRCTY+R	S5A+R		MRF5053
CORK+R	S352-R		ROCK+R	3A-36+R		MRF54
WCA1ME+R	S36-R		ACRA2+R	RITTA+R		MRF57
IMMOLF+R	S37A-R			TOWNSI+R		MRF63
COLSEM+R	S37B-R			ALICO+R		MRF78
COLGOV+R	S39-R			SIXL3+R		MRF81
WRWX+R	S40-R			S70+R		MRF90
FPWX+R	S41-R			S65E+R		MRF92
KRBN+R	S44-R			S135+R		MRF133
G600+R	S46-R			S127+R		MRF317
S7WX+R	S5A-R			S131+R		MRF85
S140W+R	S6-R			TCS2+R		MRF151
3ASW+R	G54-R			MOBL+R		MRF243
S6Z+R	S174-R			DUP3+R		MRF32
S65DW+R	S21A-R			MIAMI+R		MRF38
PC61+R	S8-R			DANHP+R		MRF93
BCA15+R	C18W-R			SVWX+R		MRF18
BCA16+R	S332-R			JDWX+R		MRF198
BCA17+R	S169-R			WPBFS+R		MRF212
BCA18+R	S70-R			FTPIER+R		MRF286
BCA19+R	S72-R			SCOTTO+R		MRF144
BCA20+R	S49-R			BLUEG+R		MRF5029
NAPCON+R	S97-R			BSET+R		MRF84
ENR401+R	S99-R			C24SE+R		MRF88

***Table 12** continues next page.*

Table 12. Continued.

Break Point Data (241)						Daily Data (46)
Real-Time (152)			Received Daily (21)	Received Monthly (68)		
LoggerNet (74)	**RACU (71)**	**MOSCAD (7)**	**ARDAMS (21)**	**CR10 (60)**	**Graphic Chart (8)**	**CO-OP LOG (46)**
GOLDF2+R	S71-R			TOHO15+R		MRF303
S5AX+R	S68-R			BRD05R		MRF423C
KIRCOF+R	S83-R			RUCKGW+R		NSID1@R
SGGEW+R	S84-R			MICCO+R		RF376
BRYGR+R	S135-R			EAA4+R		
COCO3+R	S191-R			EAA5+R		
MARCO+R	S127-R			TICK+R		
ROOK+R	S129-R			OKEEFS+R		
OKALN+R	S133-R			COWCRK+R		
OKALS+R	S154-R			FLYGW+R		
FKSTRN+R	G57-R			STA5W+R		
L2GW+R	S47B-R			S75WX+R		
GRFFTH+R	S190-R			PAIGE+R		
AVONPK+R	S167-R			POPASH+R		
PEAVIN+R	S179-R			DCRK+R		
PINEIS+R	S165-R			GTRSLU+R		
SNIVLY+R	S30-R			BASING+R		
KENAN1+R	S334-R			WPBWCA+R		
TAFT+R	S335-R					
POINCI+R	S338-R					
LOTELA+R	S82-R					
SEBRNG+R	S75-R					
BCA4+R	S125-R					
VENUS+R	S7Z-R					
BEELINE_R	S7-R					
ARCAWX+R	S27-R					
MCARTH_R	S140-R					
MAXCEYN_R	S3-R					
WSTWPB-R	G300-R					
MAXCEY_R						
ELMAX_R						
3AS3W+R						

1. Rainfall Data Storage

Rainfall data have been stored within DBHYDRO. They include breakpoint and non-breakpoint data. Breakpoint data are stored in DCVP database. Breakpoint data are accessible in 15-minute, 30-minute, hourly, and daily time intervals, while non-breakpoint data are available only as daily accumulation totals. Daily rainfall data are used most often at the District and represent the preferred time interval for many purposes, such as continuous simulation hydrologic modeling. This is because the daily rainfall time interval makes use of the full extent of rainfall data available through the rain gauge network, and also because daily rainfall data take up less storage volume in computer applications than data of smaller time increments.

Rainfall data codes, or tags, accompany daily rainfall data within DBHYDRO to provide users with an indication of rainfall data quality. A “null value” in the data code field corresponds to data that are missing. The “M” tag designates that rainfall data are missing, a code indicative of rain gauge equipment malfunction. The “X” data code designates that rainfall data are unknown. Rainfall data demonstrating the “X” tag are eventually followed with an “A” code, meaning that an accumulative amount of rainfall was measured over the time period indicated by the “X” tag. The complete record of DBHYDRO data codes used for rainfall and associated meanings are presented in **Table 1**.

2. Data Quality Assurance/Quality Control

The QA/QC post-processing analysis is a second set of operations that extract pre-processed data from DBHYDRO for select stations to undergo further examination. Presently, data from approximately 21 District rain gauge stations receive additional processing due to legal mandates under the Florida Forever Act. Data that have undergone the additional scrutiny of the QA/QC post-processing analysis are known as “preferred data” and represent the “best available data” at the District (Sangoyomi and Dawkins, 2005).

E. Measured Data Accuracy and Precision

At most of the stations, the rainfall data are measured by the tipping bucket rain gauges that have a least count of 0.01 inch. Hence, the rainfall data have accuracy of 0.01 inch and precision over an event rainfall would be up to two significant digits after the decimal.

F. Rain Gauge Network Optimization Study

The District performed a rain gauge network optimization study (SFWMD, 2006) to analyze the existing network and identify areas that have excess or deficiency of coverage. Specific recommendations were made for improving the existing rain gauge network to achieve a consistent level of accuracy across the District.

The optimization study of the existing rain gauge network using NEXRAD radar rainfall data was performed within an optimal estimation framework that accounts for local rainfall patterns defined by spatial autocorrelation at hourly and daily timescales. The rain gauge network operates in combination with radar to produce the archival rainfall product for use in operational decision making. The methodology used the existing DBHYDRO rainfall data derived from the District's rain gauge network and radar rainfall from calendar year 1995 to 2005 at a 2 km x 2 km resolution, which was the longest period available with a consistent method of estimation. The approach to network optimization was tailored to accomplish the District's objective of having an optimal rain gauge network that supports hydrologic monitoring at hourly and daily intervals.

Rainfall measurement accuracy depends on the statistical properties of rainfall and its spatial distribution. A regular array of analysis blocks was used to account for variability in point rainfall processes from the rain gauge data and geo-spatial variability of the radar data. Using the optimal number of gauges per analysis block as a requirement, the study recommended adjusting the existing gauge network with new, relocated, and removed gauges. The study's new network design utilized existing gauges where possible, relocated gauges that were too closely spaced, and placed additional gauges such that the optimal gauge number per analysis block was achieved.

The resulting proposed network of 332 (154 proposed and 178 existing) gauges contained the number of total gauges that would be required to achieve the accuracy of standard error of 0.3 inch, which was determined to be reasonable and acceptable to the District. Of the 154 proposed gauges, 133 are new and 21 are relocated. With the addition of new gauges in areas of insufficient coverage, removal of gauges from areas of excess coverage, and relocation of existing gauges, the net increase will be 53 gauges. The proposed new network can be summarized as follows:

Proposed (new and relocated)	= 154
Existing Network	= 178
Resulting Network (total)	= 332

The proposed network with 332 rain gauges has an average spacing of 12.3 km, or 150.6 km^2 per gauge (**Figure 27**). The result of the study's analysis was a proposed rain gauge network of variable density that takes into account rainfall statistical properties, and the covariant structure of the rainfall field. Implementing these recommendations will provide a network that has a more varied density and achieves a consistent level of accuracy across the District.

Follow-up work of this study was completed earlier in 2007. In this second phase of the work effort, implementation strategies of the recommendations were developed.

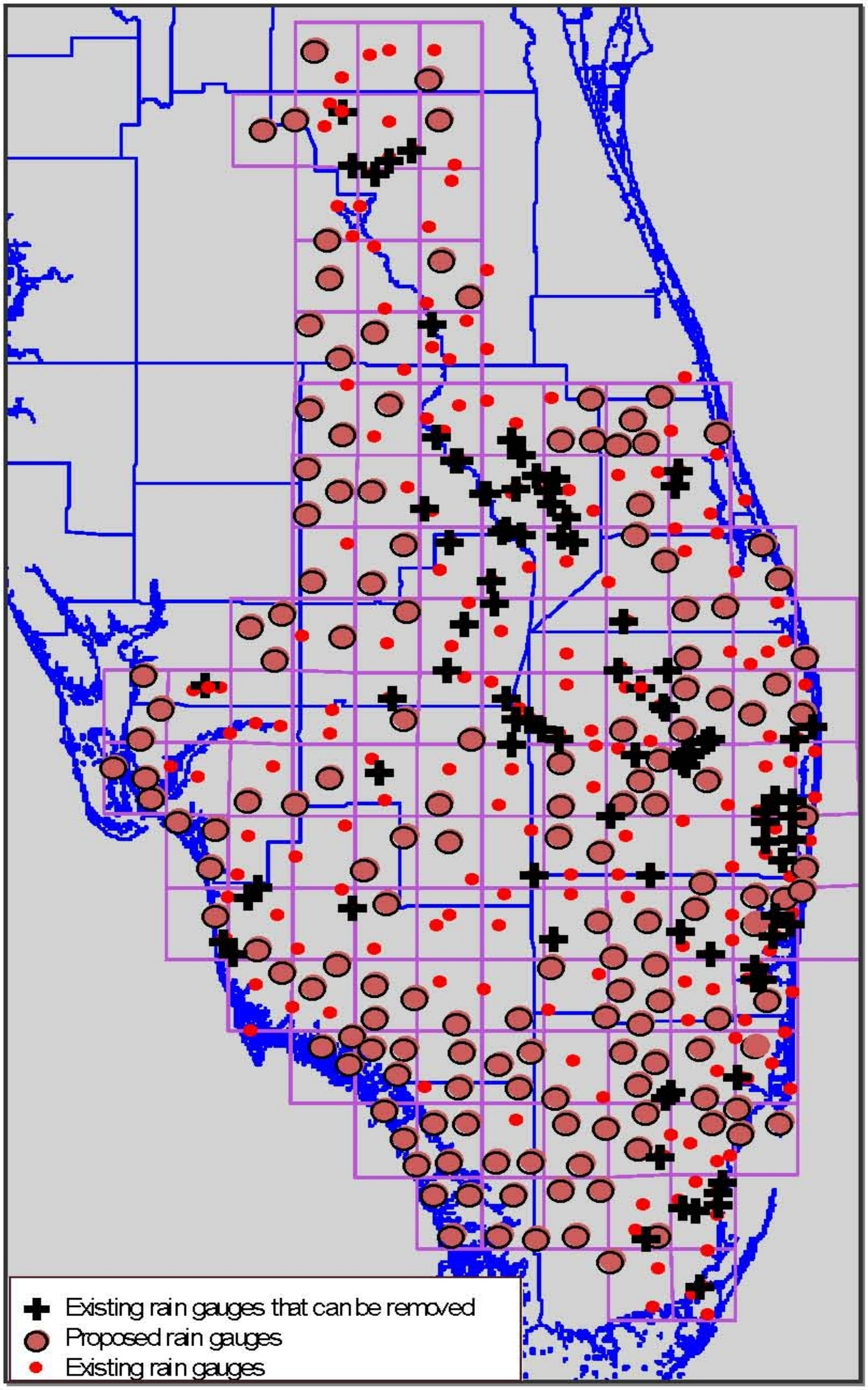

Figure 27. Proposed rain gauge network.

V. SURFACE WATER STAGE MONITORING NETWORK

By Chandra Pathak and Madhav Pandey

"Stage" is defined as the height (elevation) of the water surface above an established datum. Stage is usually expressed in units of feet or in meters above a datum (or point of reference). There are two vertical datums currently used in South Florida: the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88). The District monitors both surface water and groundwater levels; however, this section only addresses surface water levels. Accurate water level/stage data are used by engineers, scientists, and water managers to make operational decisions (i.e., gate openings and pump activity). These data are also indispensable for estimating flows at hydraulic (water control) structures and other District flow-monitoring sites (SFWMD, 2004a).

Surface water levels (or stage) measurements are typically made in canals, lakes, rivers, springs, wetlands, reservoirs, estuaries, and water control structures. The term "stage" is synonymous with water level. The term "stage" is also used to reference the parameters of headwater (upstream) and tailwater (downstream) water levels at water control structures in the District's canal systems. Surface water data is recorded based on the elevation relative to a standard reference and expressed in units of feet. Surface water levels in a water body are influenced by the size of the contributing drainage basin, amount of rainfall in the basin, and inflow from groundwater withdrawals and groundwater recharge. Rainfall can increase water levels in District canals significantly and trigger changes in water control structure operations (SFWMD, 2004a).

The actual accuracy and precision of stage measurements depends upon the instrumentation used. The stage of a water body can either be determined continuously (as a time series) from a variety of instruments that measure water-surface elevation, or intermittently by "systematic" manual observations of a non-recording staff gauge (SFWMD, 2004a).

Continuous water-level measurement devices include stage recorders that measure and record the surface elevation of the water. Water-level measurements require the use of "stilling wells" to accommodate the stage recorder, and to damp out natural oscillations of the water surface. Some stage recorders utilize a float on the surface of the water that is attached to a moveable gear in the recorder. A rise or fall of the water surface causes the float to rise or fall. This rotates the gear and the movement is recorded. Other stage recorders (or sensors) monitor either relative or absolute pressure at a point under the water surface. This pressure measurement can then be converted to the height of the water surface (SFWMD, 2004a).

A data collection platform (DCP) will store these data in a remote terminal unit and transmit the data through satellite transmission or phone modem to the District database. Non-recording gauges, such as a vertical staff gauge (**Figure 28**) are mostly installed adjacent to continuous recording gauges for use as an auxiliary reference (SFWMD, 2004a).

Figure 28. Stilling well and stage recorder (left) and vertical staff gauge (right).

A. Development of the Surface Water Stage Monitoring Network

Several manual surface water stage gauges were installed in various locations of South Florida in the early 1900s by the USGS. The District began operating its own surface water stage gauges after 1979, with the number of gauges growing since then. During that time, the stage gauges were added based on the project needs of the District. Additionally, during this time, many of the manual stage gauges were replaced by various recording devices that included varied levels of automation of stage data collection. **Table 13** shows the total number of stage gauges that were used in data collection on a decade basis with a significant increase after 1990.

Table 13. Total number of surface water stage gauges at the District between 1950-2005.

Years	Total Number of Stage Gauges
1950-1959	1
1960-1969	76
1970-1979	158
1980-1989	305
1990-1999	747
2000-2005	931

The existing stage gauge network was not designed, but evolved based on the project needs of the District. The network contains several surface water stage gauges that are located in lakes, wetland areas; additional gauges reside upstream and downstream of water control structures. The stage gauges are used to operate water control structures that regulate flows from lakes and canals, which in turn, changes surface water stages in the hydraulically connected water bodies (SFWMD, 2004a).

B. Existing Surface Water Stage Network

1. Field Instrumentation at the Station

The accuracy and precision of stage measurements depends upon the instrumentation used. There are several types of water level/stage devices available, but the two basic types are recording and non-recording. Recording type instruments keep track of stage levels at preset intervals and non-recording gauges require a field observer to read stage height from a gauge.

Recording devices measure stage continuously (as time-series data) with automatic sensors (float/counterweight, shaft encoders, pressure transducers, ultrasonic, acoustic, etc.) interfaced with RTUs. Stage measurements require the use of a stilling well to reduce errors induced by surges and wind wave action. A stilling well is a chamber that is hydraulically connected to the river through intake pipes. The stilling well eliminates turbulence that may occur in the river and the elimination of waves and surges results in more accurate readings. Measuring sensors are placed inside stilling wells to measure the water levels relative to a standard reference (**Figure 28**).

Recording devices can be grouped into one of the following categories: (1) mechanical, (2) electronic, or (3) combination. Mechanical types include digital punched paper tape and analog graphical strip chart recorders. Analog strip chart recorders convert rotational shaft positions into the position of an ink pen on a graphic chart. As the chart moves by the pen, an analog graph representing the action of the water level over time is generated. Punched paper tape recorders convert rotational shaft position into coded digital information and periodically record this information as punched holes in paper tape. Combination recording devices use both mechanical and electronic technology. The shaft is positioned mechanically, but the position of the shaft is sensed and recorded electronically. Totally electronic devices such as acoustic transducers use the liquid/air interface as the measuring point and therefore require no mechanics. Both combination and electronic recording devices record water-level measurements digitally and store the values in the RTU (e.g., solid-state data logger) memory.

A simple non-recording gauge is the vertical staff gauge. Vertical staff gauges are commonly used as reference gauges in stilling wells; or could be attached to a bridge piling or other permanent, fixed structure, or in the river channel itself. Staff gauges require a field observer to take regular measurements. Staff gauges are usually used as reference gauges for setting a water level (stage) recorder. However, in some instances staff gauges are installed without a recording device, when the gauges are usually observed at a predetermined frequency (most often on daily time interval).

The District acquires stage data at various time intervals depending on the “type” of instrumentation actually installed at a specific location within the District’s stage monitoring network. District’s SCADA system acquires real-time data from Motorola SCADA (MOSCAD) RTUs, Legacy Master Concentrator Unit/Remote Access and Control Units (RACU) RTUs and Campbell Scientific CR10X-TD (LoggerNet) RTUs.

The District also receives breakpoint data from CR10X (ARDAMS) RTUs on a daily basis (midnight to midnight) via phone lines and radio-frequency telemetry. Some stage data are acquired from the U.S. Geological Survey (USGS). The reasons for stage data problems and data changes are varied; among them are datum adjustments (reference elevation changes) and instrumentation and/or communication network problems.

2. *Active Surface Water Stage Gauge Stations*

Information on all the active surface water stage gauges was obtained from the DBHYDRO database. The stage gauge network has been expanding rapidly due to Acceler8 and CERP projects. If the stage gauge was collecting the data as of April 30, 2007, it was considered as an active stage gauge at the time of this report. The surface water stage network was grouped into four location groups – water control structures, wetland areas, lake areas and others (such as canals, small ponds, and other water bodies).

a. Surface Water Stage Gauges at Water Control Structures and Flow-Monitoring Sites

A pair of stage gauges, both upstream and downstream of a water control structure, are used for estimating flow volumes that pass through the structure. The data from these gauges are used for water management purposes that vary with wet and dry seasons. Presently, there are 422 pairs of stage gauge stations located near 422 structures. These locations account for a combined 844 stage gauges. In addition to this total, there are 18 single stage gauges (located near two spillways, two weirs, two pumps, and 12 index-velocity meter stations) for a total of 862 stage gauges that are used in estimating flows at the flow-monitoring sites. **Figure 29** shows the location of the stage-monitoring stations at the flow-monitoring sites.

b. Surface Water Stage Gauges in Wetland Areas

There are 77 stage gauges located in the wetland areas of the District. **Figure 30** shows the location of the stage monitoring stations within the wetland areas. The stage data collected from these stations are used for various purposes including hydrological, ecological, and biological conditions of the wetland areas.

c. Surface Water Stage Gauges in Lake Areas

In the lake areas of the District, there are 26 stage gauges. **Figure 31** shows the location of these stage monitoring stations within the lake areas. The stage data collected from these gauge stations are used for various purposes including assessing the hydrological, ecological, and biological conditions of the lake areas.

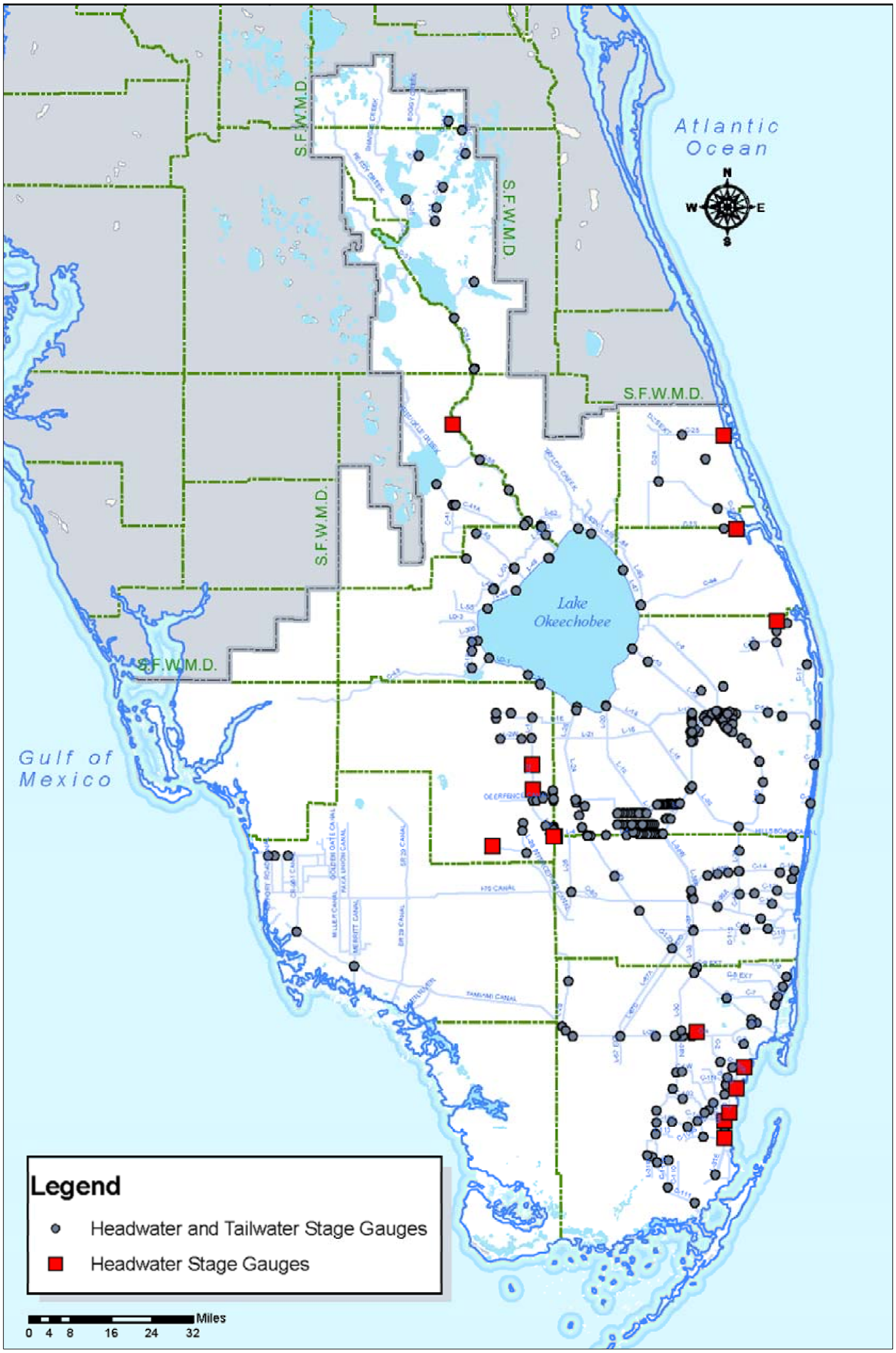

Figure 29. Location of stage monitoring gauges at the flow monitoring sites.

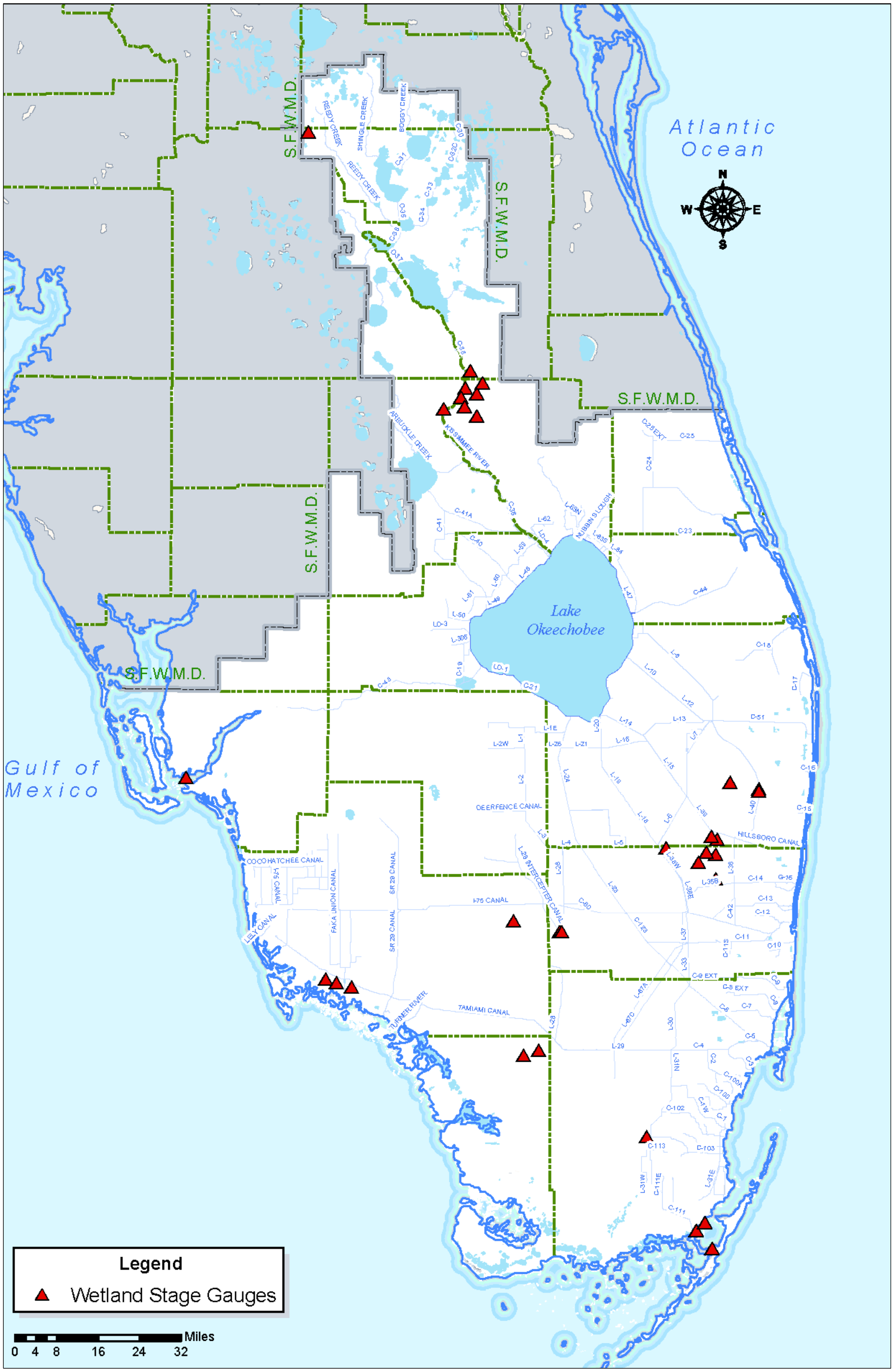

Figure 30. Location of stage monitoring gauges within wetland areas.

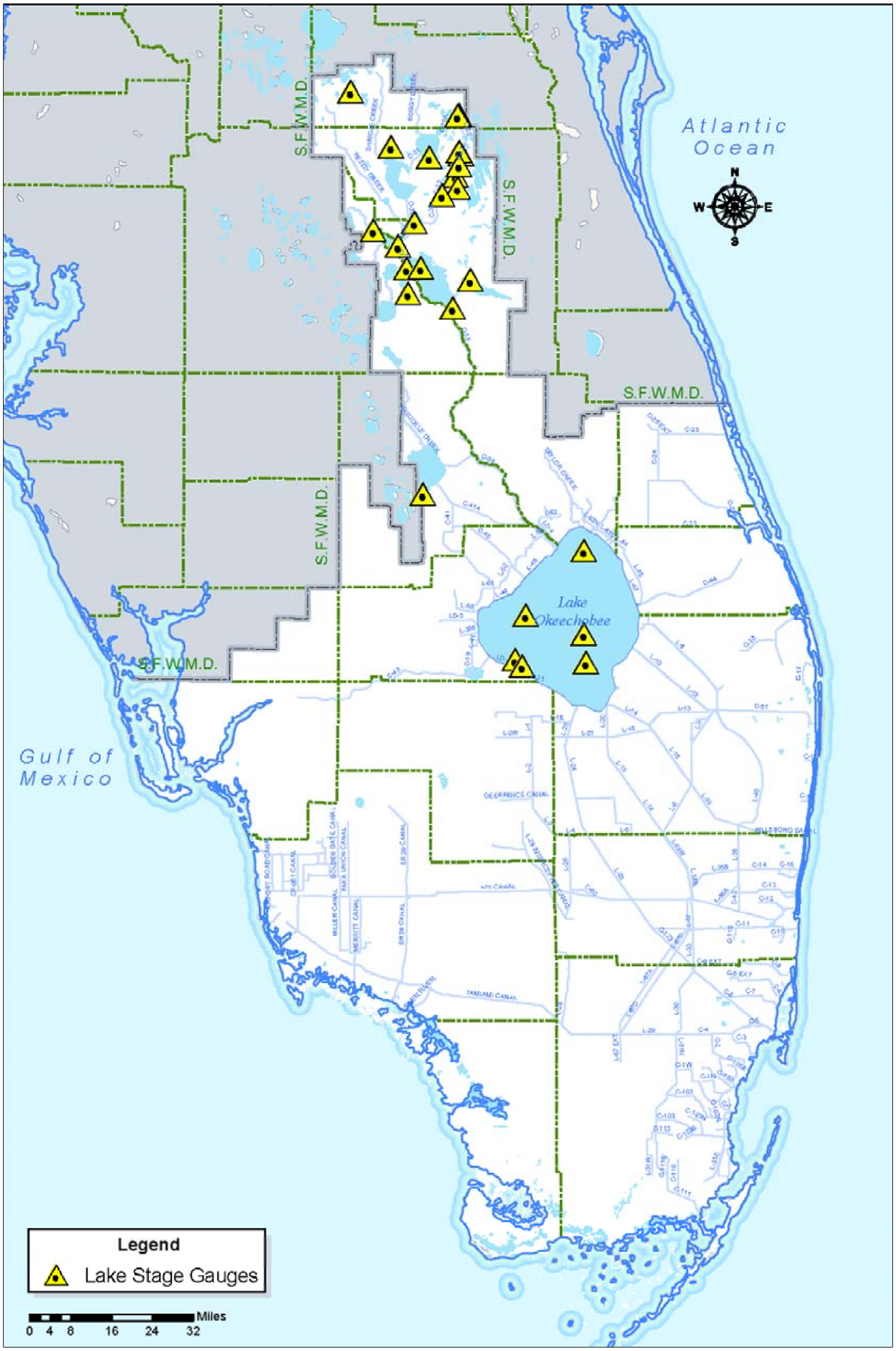

Figure 31. Location of stage monitoring gauges within lake areas.

d. Surface Water Stage Gauges in Other Water Areas

In addition to the stage gauges located in wetland and lake areas, there are 300 stage gauges in other water bodies of the District that include canals, detention facilities, and small ponds. The data collected from these gauge stations are also used for various purposes including operations and determining the hydrological condition of the areas. **Figure 32** shows the location of the 300 stage monitoring stations within the other water areas.

C. Surface Water Stage Data

The District operates an extensive network of 1,265 active surface water stage gauges in order to obtain stage data necessary for use in operations, planning, and regulatory aspects of water management (**Figure 33)**. Surface water stage data from 1,223 stations is collected from recording gauges. Therefore, the stage data are available on a breakpoint basis. The breakpoint stage data can be obtained in 15-minute, hourly, and mean daily interval formats from DBHYDRO database. However, surface water stage data from 42 stations are collected as daily manual stage/staff readings and hence, once-daily stage data from these stations is available in DBHYDRO database. Additionally, historical surface water stage time-series data from the District and other external government agencies are available in DBHYDRO.

1. Stage Data Storage

Stage data stored are available within DBHYDRO after 1959, and include breakpoint and non-breakpoint data. Breakpoint data are accessible in 15-minute, 30-minute, hourly, and daily time intervals, while non-breakpoint data are available only as daily values. Daily mean stage data are used most often at the District for hydrologic modeling, whereas breakpoint stage data are the preferred time interval for the support of water control structure operations in the District's OCC.

Stage data codes, or tags, accompany daily stage data within DBHYDRO in order to provide data users and analysts with an indication of data quality. A "null value" in the data code field corresponds to data that are missing. The "M" tag designates that stage data are missing, a code indicative of gauge equipment malfunction. (The list of DBHYDRO data codes used are presented in **Table 1**.)

2. Data Quality Assurance/Quality Control

The QA/QC post-processing analysis is a second set of operations, which extract preprocessed data from DBHYDRO for select stations to undergo further examination. Presently, data from approximately 12 District stage gauge stations receive additional processing due to legal mandates under the Florida Forever Act. Data that have undergone the additional scrutiny of the QA/QC post-processing analysis are known as "preferred data" (PREF) and represent the "best available data" at the District.

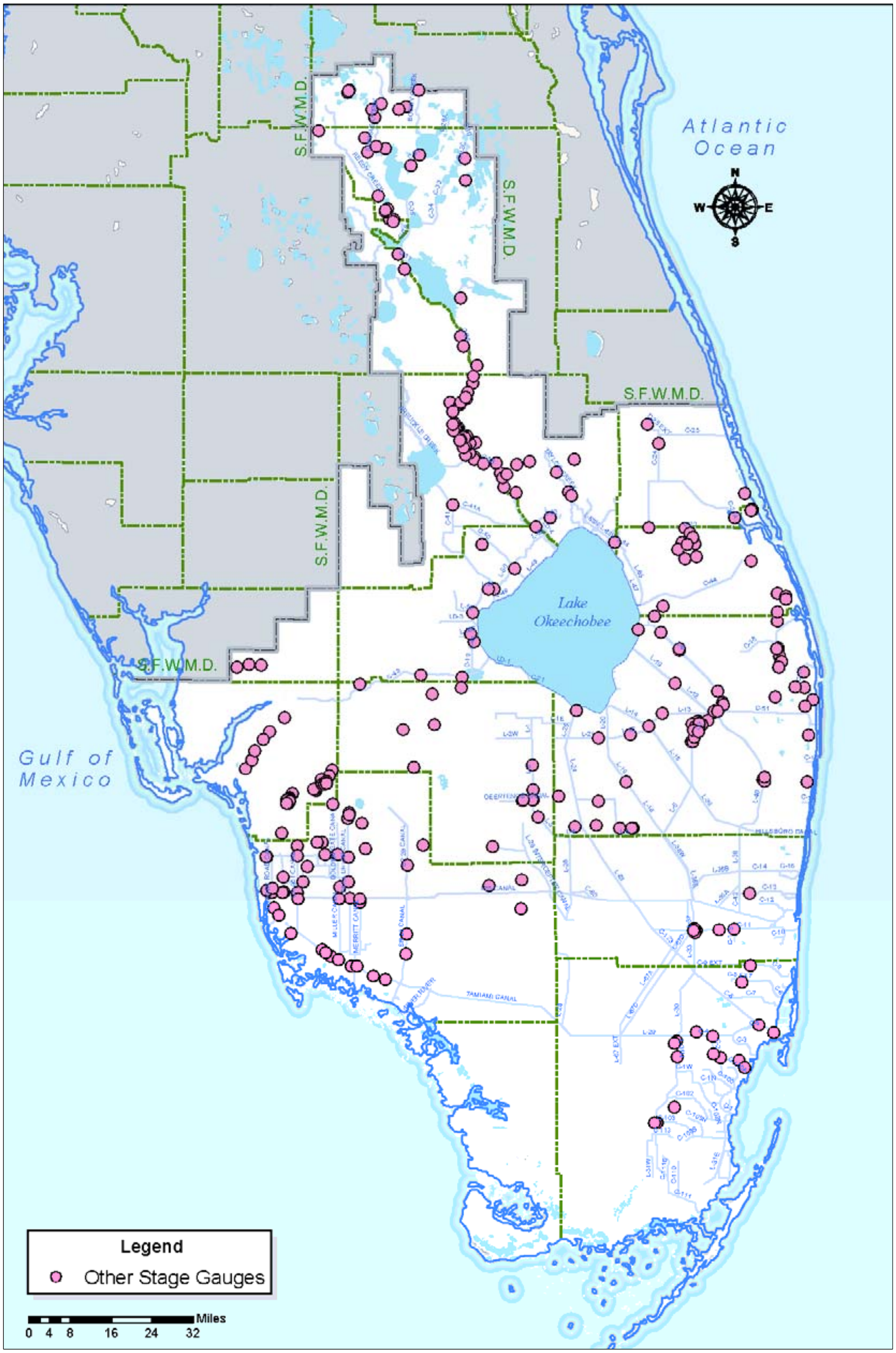

Figure 32. Location of stage monitoring gauges within other water bodies/areas.

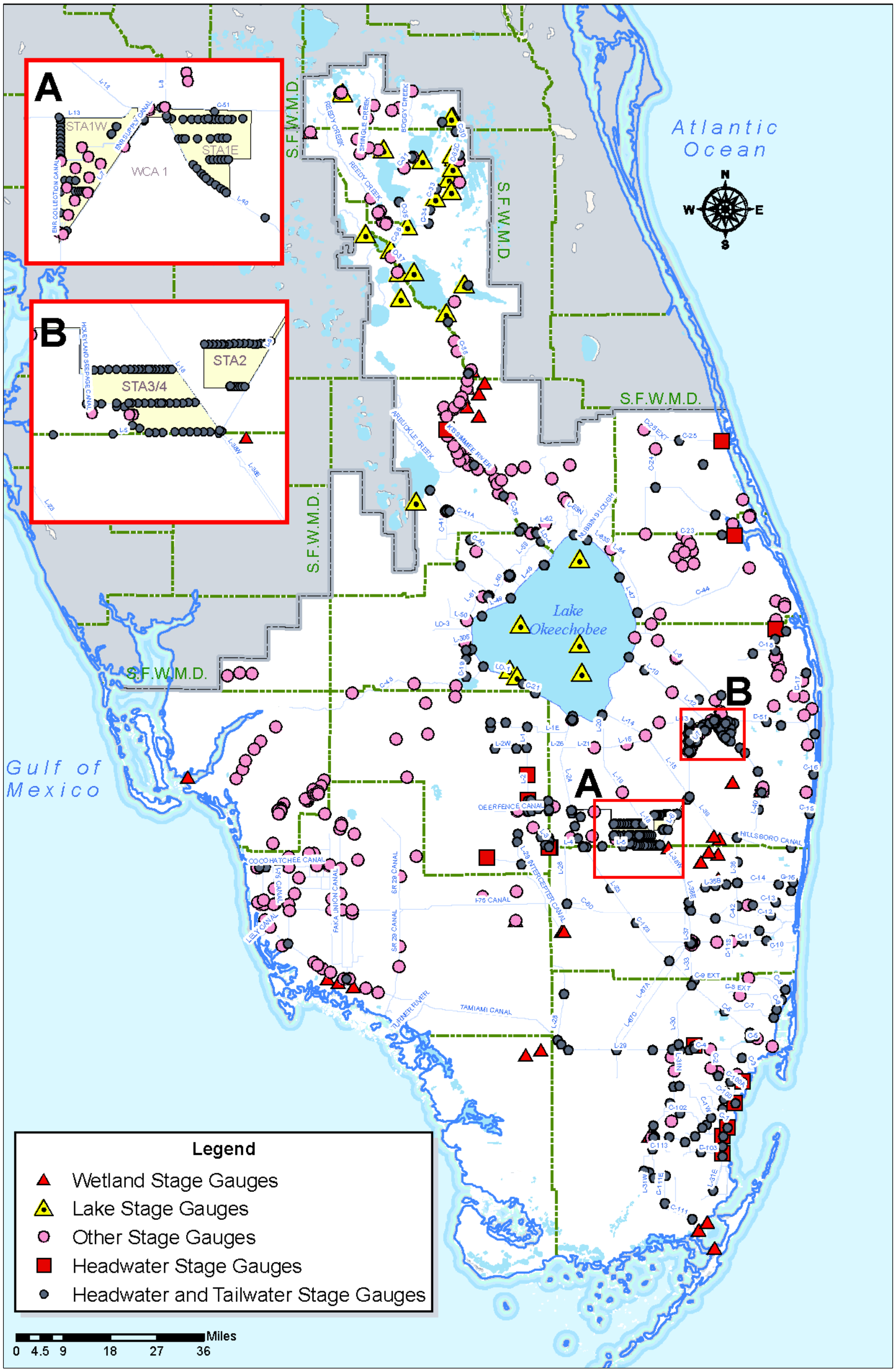

Figure 33. Surface water stage monitoring network in the District.

D. Measured Data Accuracy and Precision

At most of the stations, the surface water stages are measured by stage sensors that have an accuracy of 0.01 ft. However, the accuracy of the stage measurement varies due to many factors such as measurement errors caused by mechanism, elevation errors of the reference elevation of the stilling wells, wind effects and others; and is estimated to be approximately 0.05 ft. The precision of the stage during a sampling would be up to two significant digits after the decimal.

E. Surface Water Stage Network Optimization Study

In past, the District has not performed any network design or optimization studies for the surface water stage network. However, during 2004 and 2005, two pilot studies on stage and flow network optimization were performed (SFWMD, 2004c; Martinez, 2006).

The first pilot study, conducted in 2004, looked at ways to enhance — via statistical and GIS tools — the stage monitoring network for a portion of the Everglades wetlands areas. The study also included tools and methodologies developed to enhance the design of stage monitoring networks. The publication "Enhancement of Stage Monitoring Network for Greater Everglades Wetland Areas" reports the details of this study (SFWMD, 2004c).

The second pilot study, conducted in 2005, addressed network optimization of monitoring stations located in lakes and streams (or canals) in selected drainage sub-basins of the Kissimmee River basin. The study provided a toolset for optimizing stage gauge stations in lakes. Another toolset was provided for optimizing stage gauge stations that are located upstream and downstream of the water control structures in the canal(s) and this pair of stage gauges is used for estimating flow volumes along the canal. The final report, "Pilot Study for Flow and Stage Network Optimization" (SFWMD, 2005; Martinez, 2006) includes user manuals for the two tools.

After completing these two pilot studies, follow up work efforts are expected to be performed in next few years, depending upon availability of funds at the District. These work efforts for surface water stage network optimization are divided into two projects:

***Project 1: Stage Network Optimization for the Everglades Wetlands Areas* –** This project involves the application of the stage network optimization methodology proposed in the publication "Enhancement of Stage Monitoring Network for Greater Everglades Wetland Areas" for the 52 Everglades wetland regions.

***Project 2: Stage Network Optimization for Major Lake Areas* –** This project involves the application of the network optimization methodology and tools developed and presented in the publication "Pilot Study for Flow and Stage Network Optimization" (SFWMD, 2005; Martinez, 2006). Specifically, this task requires application of the methodologies and tools to the active stage network in two major lakes — Upper Chain of Lakes in Kissimmee River basin and Lake Okeechobee — within the District's boundaries.

VI. SURFACE WATER FLOW MONITORING NETWORK

By Zhiming Chen and Chandra Pathak

Surface water flow, or discharge flow rate, is the amount of surface water moved through a particular location per unit of time, usually expressed in cubic feet per second (cfs) or cubic meters per second (cms). In scientific literature, flow and discharge are sometimes used interchangeably. Surface water flow data are either measured or estimated using mathematical equations (SFWMD, 2004a).

The amount of flow in a river, creek, stream, or estuary is directly related to the amount of water moving off the watershed (river basin) into the stream channel. It is affected by weather, increasing during rainstorms and decreasing during dry periods. It also changes during different seasons of the year. In managed canal systems, released flow are affected by various water management policies and, water quality and environmental constraints (SFWMD, 2004a).

Surface water flow data are critical for water management, operations of the water control structures, hydrological modeling, water balance analysis, flood control, hydrological analysis, and many other purposes. In South-Central Florida, flow monitoring is primarily the responsibility of the District. However, USGS continues to monitor some “designated” sites in cooperation with the District and USACE. The District works closely with the USGS, the USACE, and various local agencies in measuring and/or estimating flow through the District’s water control structures.

The District’s water control structures are used to divert, restrict, stop, or otherwise manage the flow of water. Water control structures include pump stations, spillways, weirs, and culverts. District structures are typically designed to operate under a combination of water levels and operating conditions, which in turn results in different flow conditions. Flow that moves through the structure is estimated by using a rating equation appropriate for the flow conditions based on the structure’s static and dynamic data. The “static” data include the geometric characteristics of the structure, whereas the “dynamic” data comprise the prevailing headwater and tailwater stages and operating conditions (gate opening for spillways and culverts and pump speed for pumps) (SFWMD, 2004a).

A. Development of the Surface Water Flow Monitoring Network

Surface water flow data were estimated at various locations within South-Central Florida in the early 1900s by the USGS. The District began operating its own surface water flow monitoring sites after 1950, with the number of sites growing since then. Flow monitoring sites were added at new water control structures constructed in the District over the past several decades.

Table 14 shows the total number of surface water flow monitoring sites. The number of surface flow monitoring sites grew within the District over the years, especially after

1969. This reflects the increasing demand for flow data within the District. As of March 2005, 45 percent of flow monitoring stations were located in the Stormwater Treatment Areas (STAs) with the remaining sprawled throughout the other areas of the District (Pathak and Chen, 2005). These structures are grouped into culverts (58 percent), spillways (25 percent), pump stations (13 percent), and weirs (4 percent). Most surface water flow monitoring sites are located in east coastal areas and Kissimmee Basin, around Lake Okeechobee, and Water Conservation Areas (WCAs). With Kissimmee Basin and Everglades ecosystem restoration efforts under way, it is expected that many more surface flow monitoring sites will be added to the network in the coming years.

Table 14. Total number of surface flow monitoring stations in the District.

Years	Total Number of Stations
1950–1959	1
1960–1969	76
1970–1979	158
1980–1989	287
1990–1999	527
2000–2005	572

Prior to the 1990s, the District's surface water flow monitoring sites have been primarily used for flood control and structure operation purposes that did not require very accurate estimations of flow data. However, since 1990, demand for accurate flow data has increased significantly for estimating pollutant loadings. In turn, there is now an increased need for more stream gauging data to improve flow equations for each water control structure. In 1995, the District began to install flow meters at structures and in canals and rivers. The flow meters generally provide more accurate flow data, especially for complex flow conditions and flows under small head difference between headwater and tailwater.

B. Existing Surface Water Flow Network

1. Field Instrumentation at the Station

At surface water flow monitoring telemetry sites, an electronic supervising control and data acquisition system (SCADA) collects current headwater and tailwater stage and a structure's operation data from the field sensors. The details of the stage recording devices are presented in Section V. The structure's gate opening data and pump's operation speed data are recorded by various automated electronic recording devices. However, at few select sites the data are recorded manually.

The recorded data from the sensors are transmitted using one of the four types of remote terminal units (RTUs): Remote Acquisition Control Unit (RACU), traditional CR10 configuration, LoggerNet CR10, and Motorola SCADA (MOSCAD). The RACU system provides real-time water level data when it is polled from District's Operations

Control Center (OCC) and has no local memory to store data. This system is primarily used at structures where control of gates and/or pump stations is needed. Data from the units of the traditional CR10 configuration are collected either manually once a month or daily by telemetry through the Automatic Remote Data Acquisition and Monitoring System (ARDAMS). Data is routinely collected via telephone lines or telemetry on a daily basis. This system is used primarily where only monitoring, and no gate and/or pump control, is needed. The LoggerNet system uses a terminal server to poll all RTUs within its range, and collects new data recorded in the RTU. All traditional RTUs on the ARDAMS system will eventually be replaced by LoggerNet RTUs. They are also used primarily where only monitoring, and no gate or pump control, is needed. The MOSCAD system uses a scheme called "report by exception" to report water level and operation data. The MOSCAD RTU polls each sensor, continuously in less than a second, and when it detects a change of state of ± 0.01 foot, it automatically bursts the data back to OCC. In next few years, the MOSCAD system will be eventually replace the old RACU system.

Besides telemetry data, the District currently receives manually observed stage, gate, pump, and flashboard data from a small number of non-recording stations throughout the District. The manual data are systematically collected by the District's field personnel and volunteers such as ranchers, lock-tenders, landowners, and other agencies through cooperative (co-op) agreements with the District.

The data collected from the field are examined following a structured QA/QC procedure (see Section V) to ensure that stage data collected are of best possible quality before they are used for flow-computation purposes.

2. Active Flow Monitoring Sites

Information on all of the active surface flow stations was obtained from the DBHYDRO database. A surface flow site is considered to be active if it has been collecting data as of April 30, 2007. The District surface flow monitoring sites are divided into five types: pump, spillway, culvert, weir, and index velocity meter. The location of each type of surface flow monitoring sites is shown on the maps that follow the discussions.

a. Flow Monitoring Sites at Pump Stations

Pumps lift water from a lower to a higher elevation (**Figure 34**). There are 67 flow monitoring sites located at pump stations (**Figure 35)**. Most of the pumps are located around Lake Okeechobee, the WCAs, and in east coastal areas. In order to compute flow at pump stations, headwater and tailwater stages, and pump speed are required.

Figure 34. Pump station.

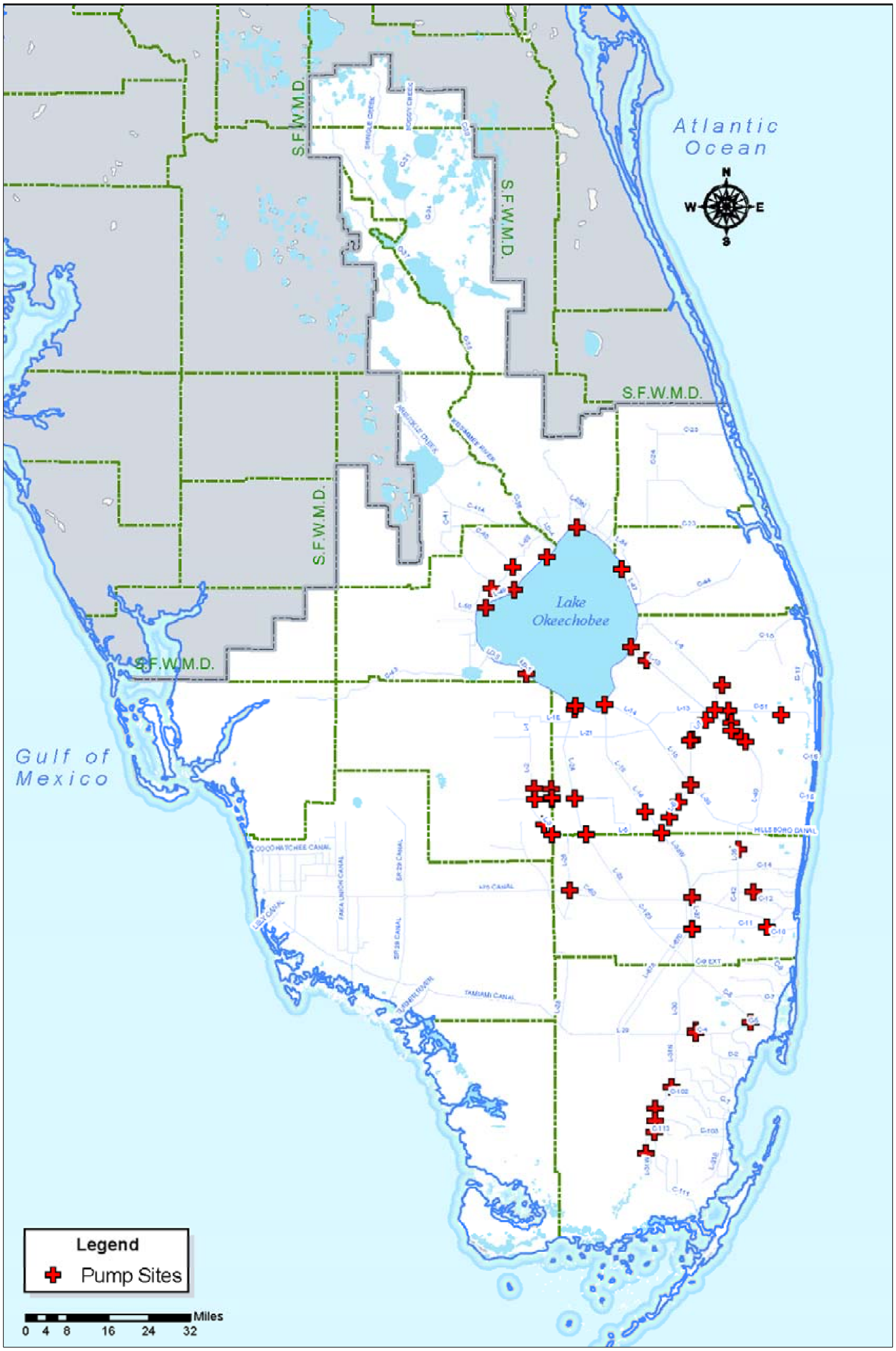

Figure 35. Location of flow monitoring sites at pump stations.

b. Flow Monitoring Sites at Spillways

A spillway is a gated structure over which flow is discharged from a reservoir or a canal (**Figure 36**). The purpose of a spillway is to control the stage and/or flow of water. As of April 30, 2007, the District monitored flow at 100 spillways (**Figure 37)**. The spillways are mostly located around Lake Okeechobee, WCAs, Kissimmee Basin, and coastal areas. Flow computation at spillways requires headwater and tailwater stage measurements and gate opening data.

Figure 36. Spillway.

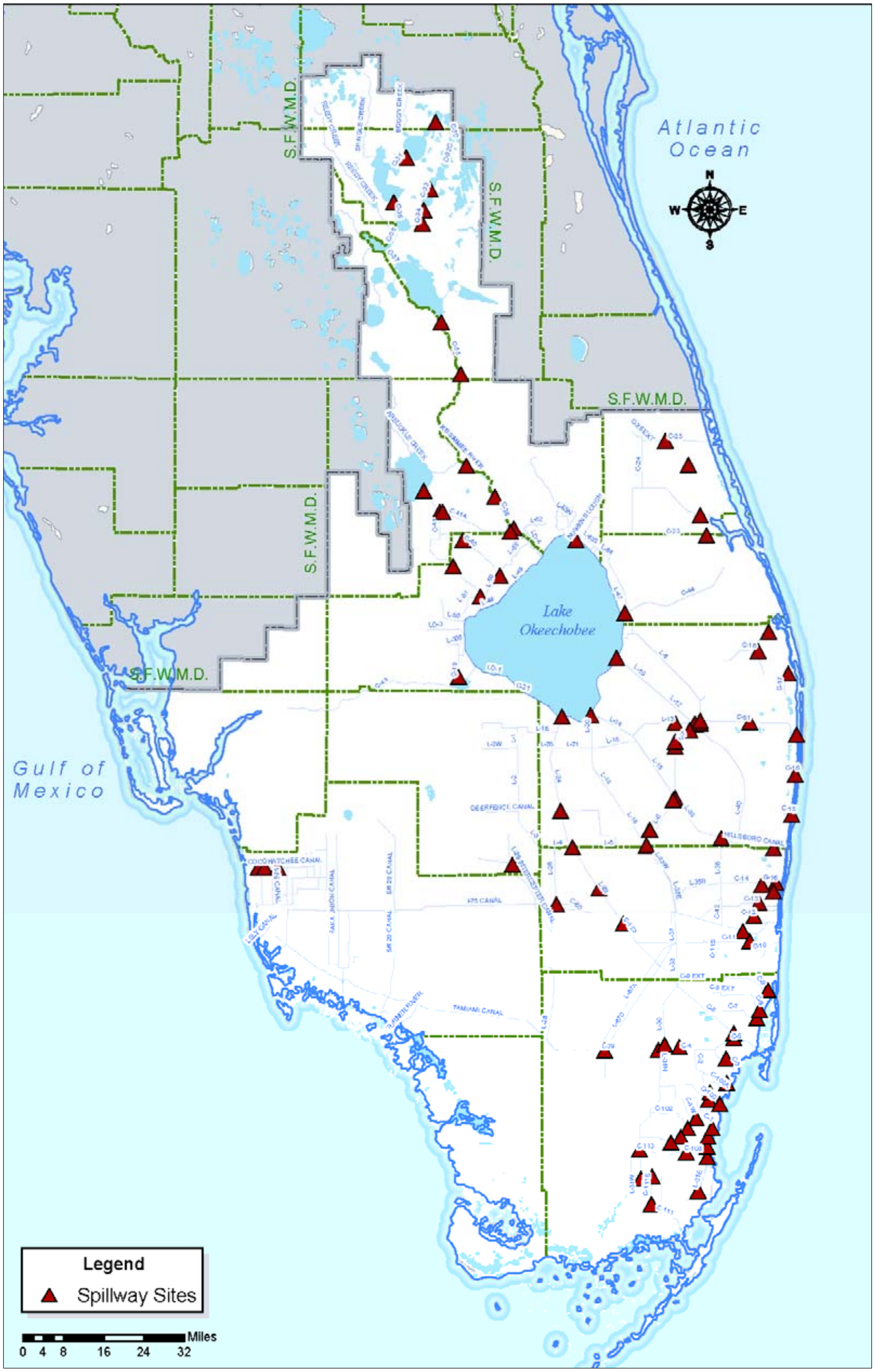

Figure 37. Location of flow monitoring sites at spillways.

c. Flow Monitoring Sites at Weirs

A weir is a structure (without a gate) over which flow is discharged from a reservoir or a canal (**Figure 38**). The District monitors flow at 14 weirs (**Figure 39)**. Flow computation at weirs usually requires headwater and tailwater stage measurements. However, if flow is free, i.e., tailwater does not affect flow, discharge can be estimated from headwater stage measurements and weir static information.

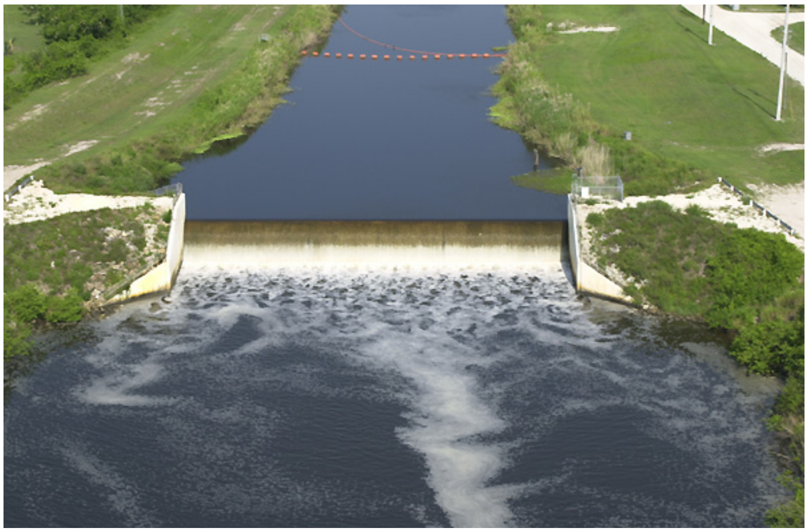

Figure 38. Weir.

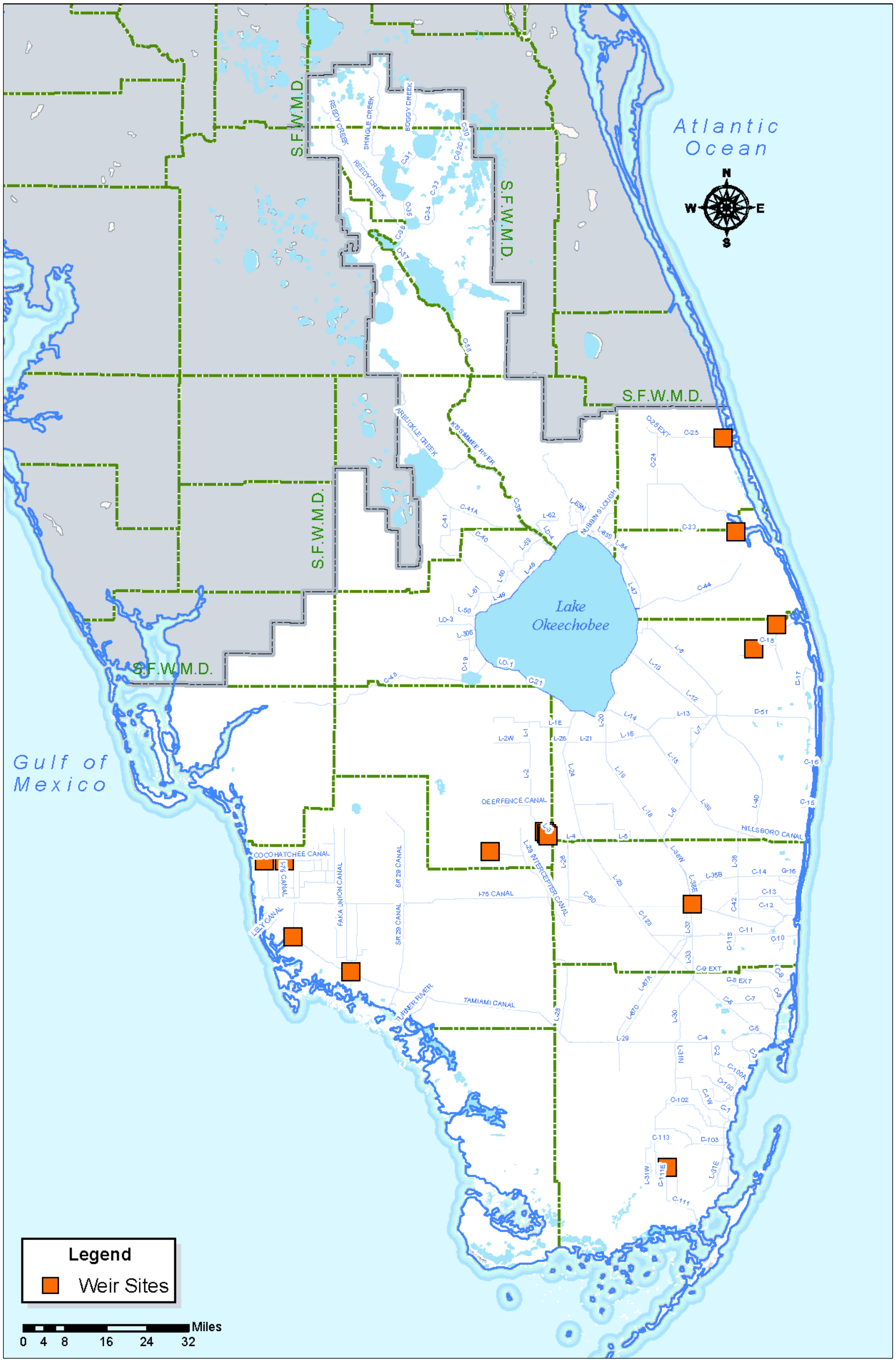

Figure 39. Location of flow monitoring sites at weirs.

d. Flow Monitoring at Culverts

Culverts are a closed conduit for conveyance of water (**Figure 40**). In the District, culverts may be either circular or rectangular in cross section and may have gates. Culverts provide a means for water to pass underground from one location to another.

The District monitors flow at 253 culverts (**Figure 41)**. The figure shows that most culverts are located in STAs, WCAs, and lower east coastal areas. Culverts usually pass smaller flows compared to spillways. Flow computation for culverts requires headwater and tailwater stage measurements, and gate opening, if gates are located in the culverts.

Figure 40. Culvert.

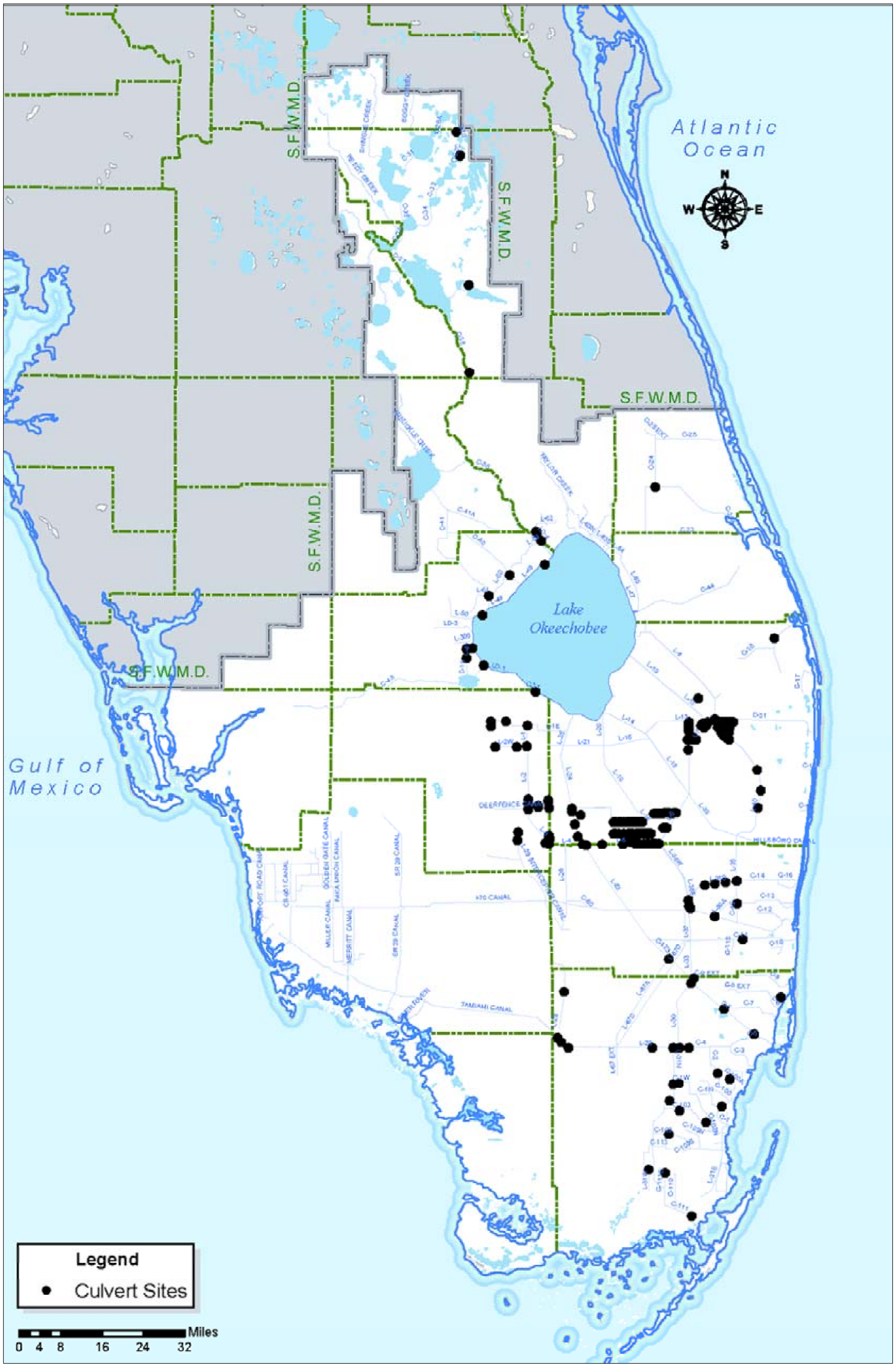

Figure 41. Location of flow monitoring sites at culverts.

e. Flow Monitoring Sites with Index Velocity Meters

Acoustic index velocity meters enable direct, continuous, non-contact measurements of velocity in open channel and closed conduits. The water velocity measured by these instruments is used as an estimator, or "index," of the mean cross-sectional velocity. The mean velocity is then calculated from the index velocity through a rating equation and is used to predict flows at the cross section. District index meters include Ultrasonic Velocity Meter (UVM), Argonaut Side-Looking (Argonaut-SL), and Argonaut Shallow Water (Argonaut-SW).

Figure 42 shows a flow monitoring site with an index meter. Flow data at 12 index velocity meter sites (**Figure 43)** are published in DBHYDRO. The District has installed index flow meters at many other important sites, and flow data at these sites will be available soon from DBHYDRO. Installation of more index meters in critical streams and structures has been planned. For index velocity meter sites, both stage and index velocity measurements are required.

Figure 42. Index velocity meter site.

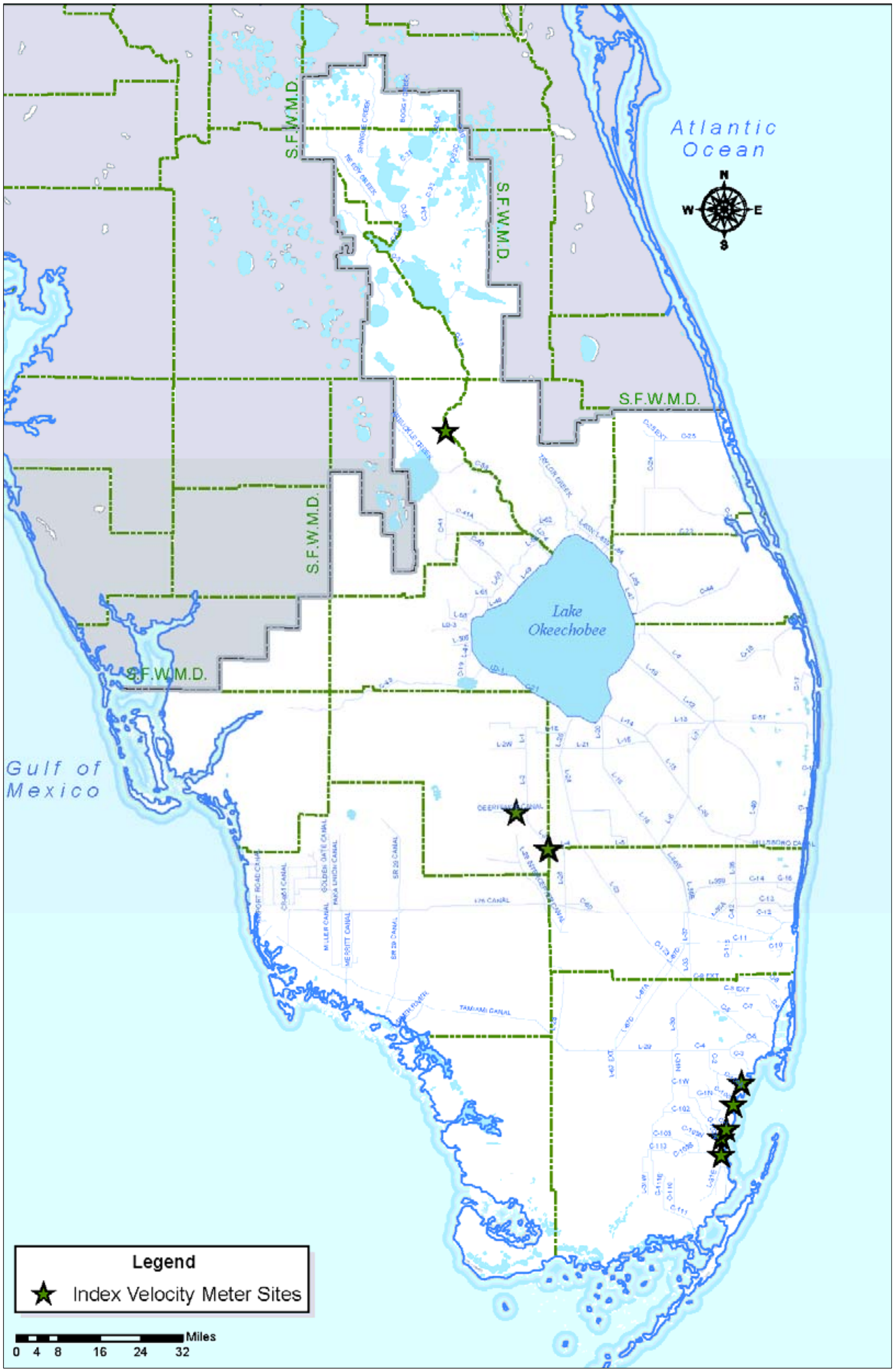

Figure 43. Location of flow monitoring at index velocity meter sites.

C. Surface Water Flow Data

1. Stream Gauging Data

Stream gauging is the process of measuring the flow rate of water at a cross section in a river, canal, creek, stream, estuary, or a culvert. The acquired data in stream gauging is used to verify, calibrate, and validate flow-rating equations. These flow-rating equations are used to compute flow rate at a cross section in a canal, stream, river or culvert. The accuracy of the flow data depend on the accuracy of the flow ratings, which in turn largely depend on the accuracy of stream gauging flow measurements (OHDM, 2004).

Historically, flow measurements were made with a Price AA current meter (**Figure 44**) or other mechanical instruments. The Price meter measures the flow velocity at several locations of a vertical of a cross section. Velocity measurements in several verticals of a cross section are usually required for accurate flow estimation at a cross section. The discharge at the given cross section is then computed from the measured velocities and their representative areas. This area-velocity method is labor-intensive and time-consuming.

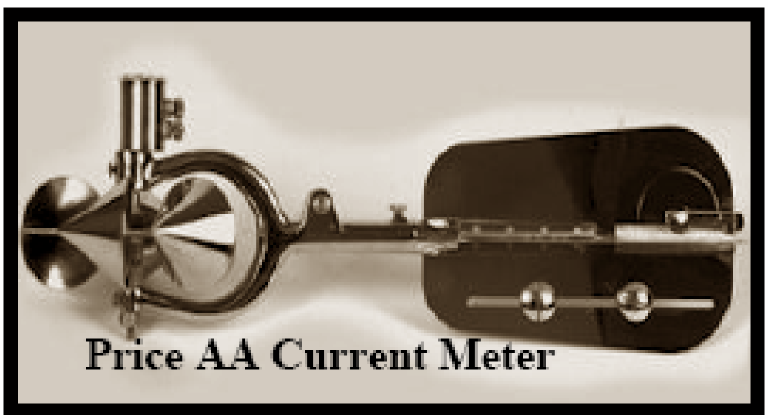

Figure 44. Price AA current meter.

Starting in the 1990s, new field flow measurement instruments were developed. These instruments include Acoustic Doppler Current Profilers (ADCPs) (**Figure 45**), Acoustic Doppler Flow Meters (ADFMs), Acoustic Doppler Veloci-meters (ADVs), and many other instruments. These new instruments are based on the acoustic Doppler principle. These new acoustic instruments provide much more detailed flow data in terms of frequency and/or velocity distribution than a Price meter or other mechanical instruments.

Figure 45. An acoustic Doppler current profiler (ADCP).

Currently, the most commonly used flow measurement (**Figure 45**) instrument in the field is an ADCP. An ADCP provides flow velocity distribution of a cross section when the ADCP moves along a transect (usually perpendicular of the stream flow). ADCP flow measurements are cost effective and provide accurate flow measurement data.

In shallow water, flow measurement can be performed with a StreamPro — a micro ADCP mounted on a small boat (**Figure 46**). StreamPro can measure flow in streams from 15 to 200 cm in depth. Data is collected in real-time and transmitted via a wireless data link to a convenient palm PC loaded with a user-friendly software. In many swamps or small streams, StreamPro may be the only solution for flow data collection.

Figure 46. StreamPro.

In pressurized pipes and culverts, Acoustic Doppler Flow Meters (ADFMs) are often used for flow data collection. The ADFM can be installed in culverts and is capable of collecting a large amount of flow data with the accuracy needed for calibrating culverts operating under free-surface flow and pressured conditions. The ADFM is a quasi-direct velocity meter that relies on theoretical consideration application to fully developed flow. Thus, the applicability of the ADFM for measuring flows in culverts in a great extent depends on the velocity distribution in the culvert.

Figure 47. An ADFM.

Stream gauging data are checked following QA/QC procedures before input into a stream gauging database (known as the QMEAS database) for calibration or verification of flow ratings. The details of the QA/QC procedures for stream gauging data can be found in the document "QA/QC of Flow Data Procedures" (Sangoyomi et al., 2005).

Figure 48. Flow measurement with a StreamPro.

2. Flow Equations (Flow Ratings) Used in Computing Flow Data

At pump stations, spillways, weirs, and culverts, flow is estimated using flow equations. The flow equations use headwater, tailwater, and operation data (gate opening or pump speed) to compute flow. In the flow equations, some parameters are associated with local flow conditions and are usually calibrated or verified using stream-gauging data collected at the structure. If the computed discharges using the calibrated flow rating equation do not agree with the flow measurements, development of a new flow equation may be required. **Figure 49** shows schematically how the stream-gauging data are used in calibration or verification of a rating. At index velocity meter sites, flow is estimated from measured index velocity and stage. The index velocity is used to compute mean cross-sectional velocity through rating, and the stage is used to compute cross-sectional area through relationship between stage and area.

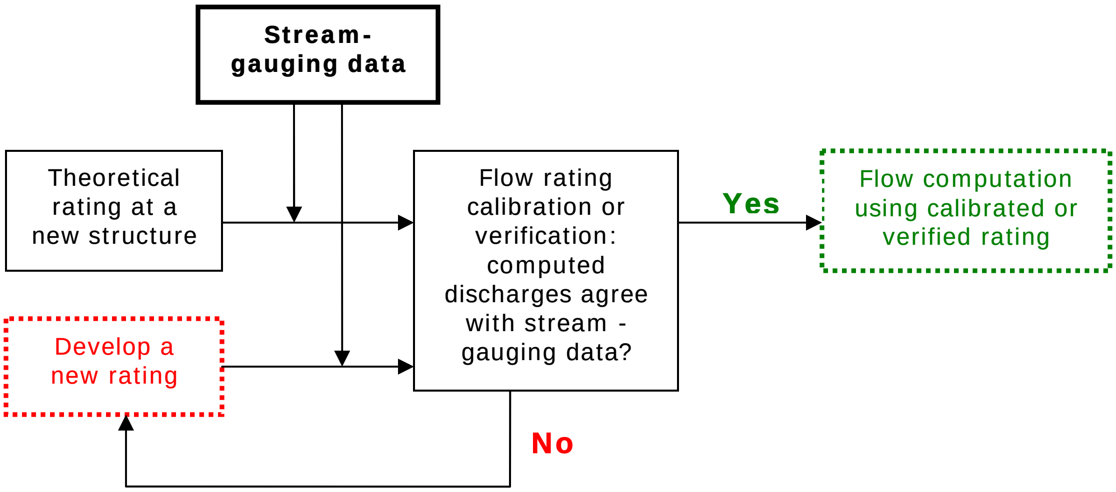

Figure 49. Flow ratings used in flow computation.

Originally, the USACE developed and calibrated the rating equations for most of the pumps in the District (Otero, 1995). The flow equations used for computing flow at culverts were developed by Fan (1985). The flow equations for spillways and weirs were based on experimental work from the 1960s by the USACE (Grace, 1963). These flow equations sometimes provided erroneous flow estimation and were later revised by the District.

The District has been working on improving the flow equations used and has made significant progress. New flow equations for pumps were developed (Damisse, 2000; Imru and Wang, 2003). Significant efforts have been made on improving spillway flow computation by Ansar et al. (2002, 2003a, 2003b, 2005) and Chen et al. (2006a). Nair (2003) and Damisse and William (2006) proposed new flow equations for culverts. Chen et al. (2006b) improved flow computation for several culverts that are located in the STA-3/4. The new flow equations for pump stations, culverts, spillways, and weirs significantly improve flow computation for some flow conditions. Some of these newly developed flow equations have been implemented in the District flow computation program. The remaining equations will be implemented in the District's new FLOW computation program (software application) that is currently being developed. The existing and/or improved flow equations are examined before they are used for flow computation. The District has established guidelines for the QA/QC of flow equations (Sangoyomi et al. 2005).

At index velocity meter sites, the relationship is established between cross-sectional mean velocity obtained from the stream-gauging data and the velocity measured with the index meter. Once the relationship is developed, the flow through the cross section is computed from the measured index velocity and the cross-sectional area derived from the relationship between stages and cross-sectional areas.

3. Surface Water Flow Data

Presently, the flow computation is performed by the FLOW program, a FORTRAN-based application that was developed by the District approximately 25 years ago. A new FLOW computation program (software application) is being developed and is expected to be available by end of 2008. The existing FLOW program uses rating equations for various flow regimes to compute flow. A flow rating equation is the relationship between the flow, the stage level (headwater and tailwater elevations) and the operating status (gate openings, pump speed, weir crest elevations, etc.). Rating equations are defined for each type of structure and each potential flow case. For example, rating equations are defined for each of the five cases of flow through a gated spillway thus: (1) controlled submerged flows, (2) controlled free flows, (3) uncontrolled submerged flows, (4) uncontrolled free flows, and (5) over-the-top flows.

The computed flow data are then scrutinized using the District's QA/QC before they are published in DBHYDRO. The QA/QC procedure uses statistical analysis and hydraulic principles to check the accuracy of the computed discharges and investigate questionable values.

Flow computation for each structure is based on available static and dynamic data. The District determines the static structure information from the "as-built" drawings of structures, and this information is stored in the DBHYDRO database. However, this static structure information is often not of sufficient quality to compute flow accurately in certain hydraulic conditions, and in some cases, the information is erroneous or out of date. To address this issue, the STRucture Information VErification (STRIVE) project was initiated to verify static structure information. As of March 2005, field surveys for 367 water control structures have been completed. The flow data for 168 of these structures have been adjusted and archived in DBHYDRO (Pathak and Chen, 2005).

4. Flow Data Availability

The District operates an extensive network of 446 active flow monitoring sites that are used in operations, planning, and regulatory aspects of water management. The District's flow monitoring network is shown in **Figure 50**. The flow data from 425 sites are available on breakpoint basis. The breakpoint stage data can be obtained in 15-minute, hourly, and mean daily format from the DBHYDRO database. Historical flow time-series data from the District and other external government agencies are also available in DBHYDRO.

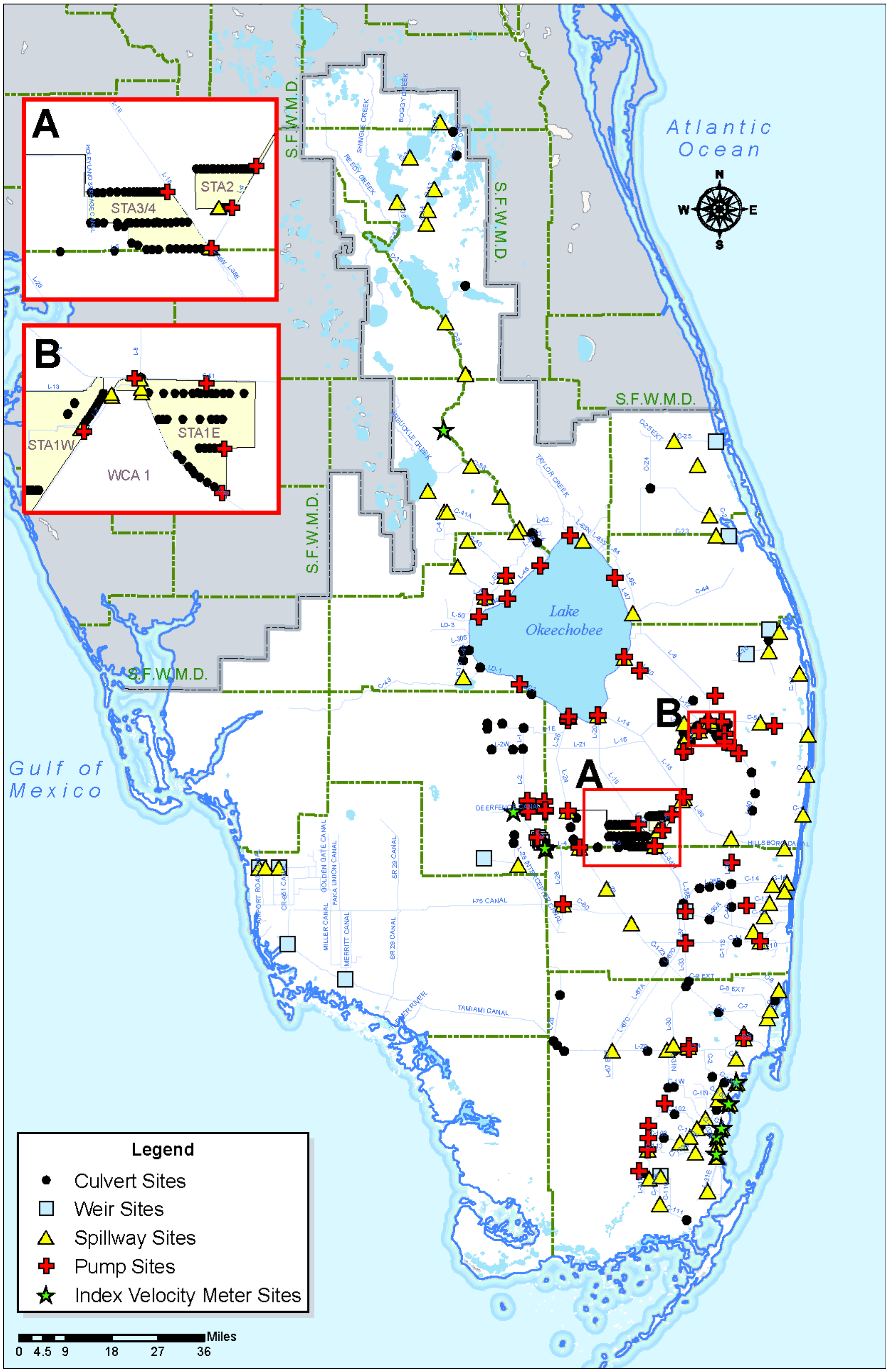

Figure 50. District flow monitoring network.

Hydraulic structure information and flow data can also be obtained using the application called Web Atlas, a web-based GIS interface. From Web Atlas, structure photos, structure static information (including structure geometry and discharge coefficients that are used in the structure's flow equations), historical daily and breakpoint flow data, and real-time flow data are available. **Figure 51** shows a screenshot of the Web Atlas interface.

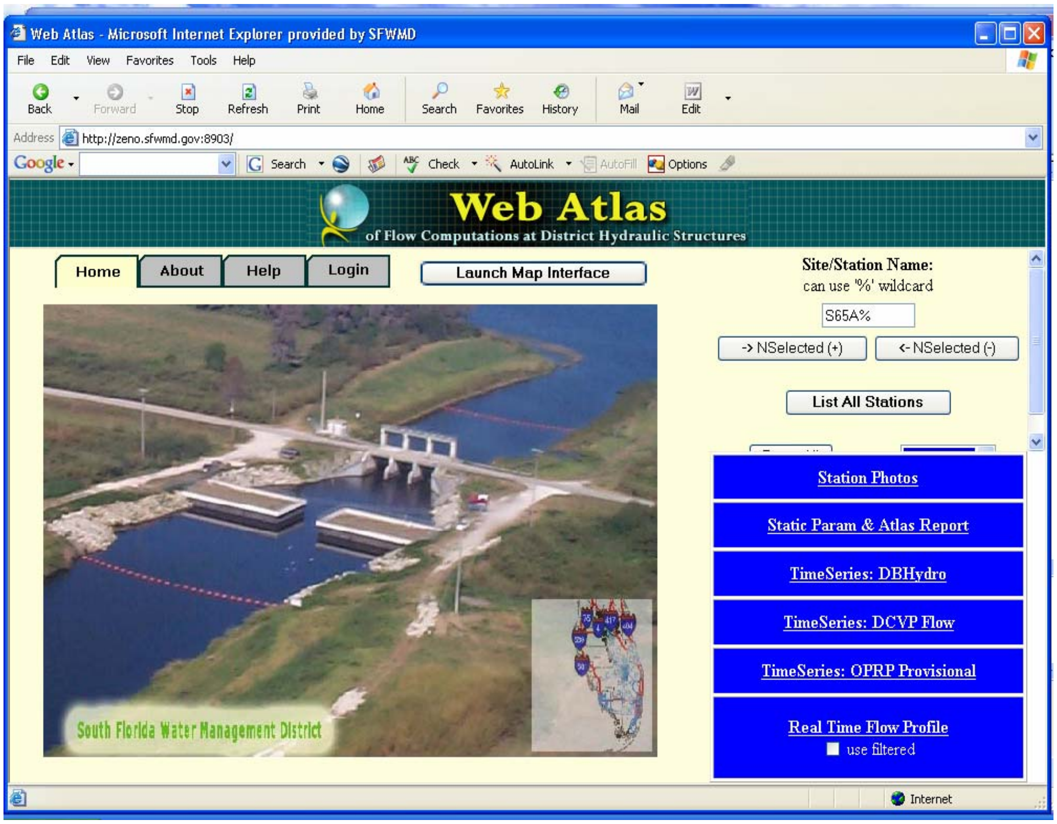

Figure 51. Screenshot of the Web Flow Atlas for Hydraulic Structures and Flow Data.

a. Flow Data Storage

Flow data are stored and are available in DBHYDRO. Data include breakpoint and non-breakpoint data. Breakpoint flow data are accessible in 15-minute, 30-minute, hourly, and daily time intervals, while non-breakpoint data are available only as daily values. Daily mean flow data are used most often at the District for hydrologic and ecological data analyses, whereas breakpoint stage data are the preferred time interval for the support of water control structure operations, hydrologic and hydraulic modeling, and various other purposes.

Flow data are tagged within DBHYDRO in order to provide information on the quality of the data. The complete record of DBHYDRO data codes used for flow and associated meanings are presented in **Table 1**.

b. Flow Data Quality Assurance/ Quality Control

The QA/QC processing further examines the flow data quality, including checking and analyzing data (including headwater, tailwater, and operational data) from different sources, and performing statistical, hydrological, and hydraulic analysis. Presently, data from approximately 162 District flow sites receive this additional processing due to legal mandates under the Florida Forever Act. Data that have undergone this additional scrutiny of the QA/QC Post-Processing Analysis is known as “preferred data” and represent the “best available data” at the District (Sangoyomi et al. 2005).

D. Data Accuracy and Uncertainty

The uncertainty of the computed flow at water control structures is affected by several factors. First, the flow equations may not completely describe the physics of flow at a structure. Second, the computed flow at a structure are based on the measurements of headwater stage, tailwater stage, and structure operation (gate openings for spillways and culverts, and pump speeds for pumps). The uncertainties in these measurements are propagated to the computed flow. Third, the coefficients of the flow equations are derived using the stream flow measurements at the structure. At hydraulically complex structures, accurate flow measurements are a significant challenge. Large uncertainty in the flow measurements results in significantly large uncertainty in the computed flow. In several situations, when the difference between the headwater and tailwater stages is small, consequently, the relative uncertainty in the head difference (less than 0.1 ft) is significant and that translates into relatively large uncertainty in the computed flow. In general, the uncertainty in the computed flow varies at the structures, from less than 5 percent to more than 15 percent.

E. Surface Water Flow Network Optimization

As discussed in detail in Section V, a 2005 pilot study on stage and flow network optimization was performed. The final report, “Pilot Study for Flow and Stage Network Optimization” (SFWMD, 2005 and Martinez, 2006), includes user manuals. Follow-up on the pilot study for surface water flow network optimization is expected in the next few years, depending upon availability of funds at the District. The two projects related to surface water flow are:

Project 1: Flow and Stage Network Optimization for Active Water Control Structures in the Central and Southern Florida (C&SF) System. This project involves the application of the network optimization methodology and tools developed and presented in the publication “Pilot Study for Flow and Stage Network Optimization”. Specifically, this task requires application of the methodologies and tools to the approximately 232 water control structures in the District's C&SF system.

Project 2: Flow and Stage Network Optimization for Water Control Structures in the Storm Water Treatment Areas (STAs). This project involves the same application as for Project 1. However, this task differs by requiring the application of the methodologies and tools to the approximately 191 water control structures in five STAs — STA-1W, STA-2, STA-3/4, STA-5, and STA-6 — within the District's boundaries.

VII. GROUNDWATER MONITORING NETWORK

By Taiye Sangoyomi and Anthony Larenas

Groundwater is water below the earth's surface in underground streams and aquifers. Groundwater level or head for a water table (unconfined) aquifer is simply the elevation of the upper surface that indicates the uppermost extent of groundwater, and is usually expressed in units of feet or meters above an established datum. For a confined aquifer, the groundwater is under pressure and the groundwater level (or head) is the elevation that coincides with the piezometric or hydraulic head in the confined aquifer, which may be above the land surface (**Figure 52**).

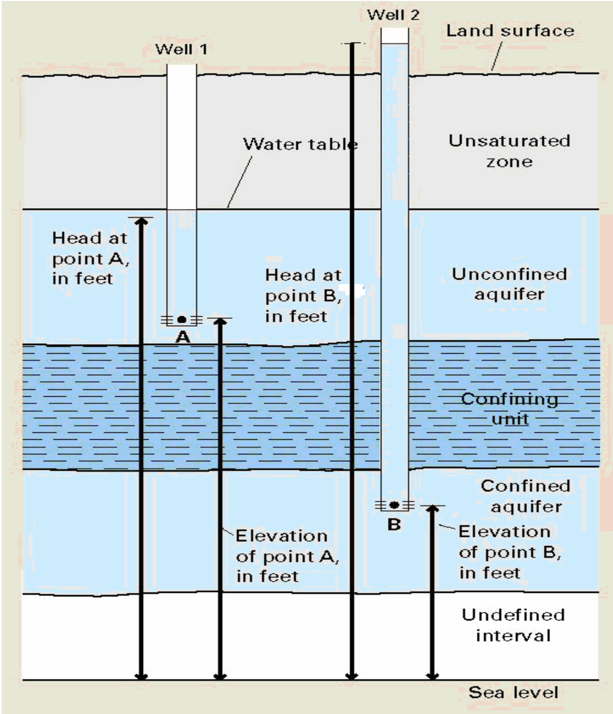

Figure 52. Groundwater level or head in a well in an unconfined aquifer (Well 1) and a confined aquifer (Well 2) (source: modified from Taylor and Alley, 2001).

The aquifers in the District are classified into three general groups — surficial aquifer system, intermediate aquifer system, and Floridan aquifer system. The surficial aquifer system is a water table aquifer system that includes the Biscayne Aquifer, Lower Tamiami Aquifer, and all of the otherwise undefined aquifers that are present at the land surface and are generally under unconfined, or water-table, conditions. The surficial aquifer system is typically less than 50 feet (ft) deep in most areas but can range up to 400 ft deep in Indian River and St. Lucie counties (http://www.dep.state.fl.us/swapp/Aquifer.asp) (2007).

Aquifers between the surficial and Floridan aquifer systems are collectively referred to as the intermediate aquifer system, and consist of one or more water-bearing units separated by confining units. The intermediate aquifer system is present only in southwestern Florida. This system includes the Sandstone and Mid-Hawthorn aquifers.

The Floridan aquifer system underlies the entire District region and includes the Lower Hawthorn aquifer, Suwannee aquifer, and Ocala group. **Table 15** provides a summary of the aquifer system and each system's thicknesses. **Figure 53** provides a three dimensional view of the aquifer system over Florida.

Table 15. Aquifer systems of the District.

Aquifer System	Aquifer Unit	Thickness (feet)
Surficial	Water Table Biscayne Lower Tamiami	40 to 400[a]
Intermediate	Sandstone Mid-Hawthorn	0 to 260[b]
Floridan	Lower Hawthorn Upper Floridan Middle Floridan Lower Floridan	1,800 to 3,600[c]

(a) http://www.dep.state.fl.us/swapp/Aquifer.asp
(b) Tables 3 to 5, SFWMD, 2000
(c) Figure on page 50, Fernald and Purdum, 1998

The remainder of this section is organized into four parts: (1) the development of the groundwater monitoring network and history and evolution of the network; (2) the existing groundwater network, as of April 30, 2007, with maps showing the locations of the wells by aquifer system; (3) the QA/QC procedures for the water level data and data availability; and (4) the future groundwater network design.

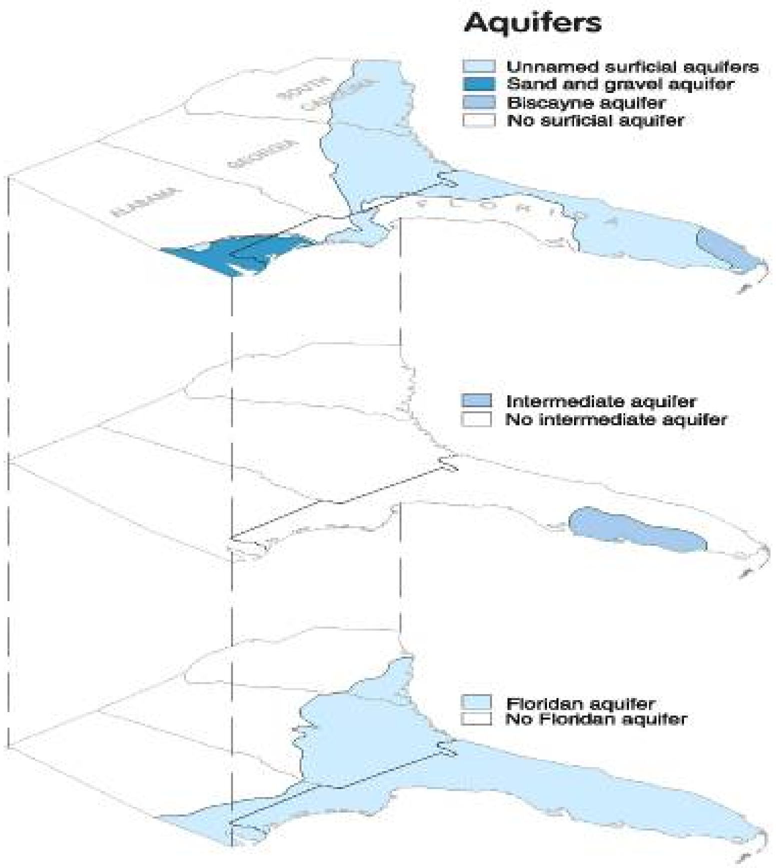

Figure 53. Three-dimensional view of the aquifer system in Florida (Berndt, 1998).

A. Development of the Groundwater Monitoring Network

The District's groundwater network consists of wells that have data publicly available through the District's DBHYDRO database but also in other databases not publicly accessible (these are mostly project-specific). There are ongoing plans to migrate non-publicly accessible data into the DBHYDRO database. The groundwater network also consists of wells monitored by the USGS through a cooperative agreement with the District. Most of the data on these wells are also available in DBHYDRO, but all can be accessed from the USGS's database accessible at http://nwis/waterdata.usgs.gov/fl/nwis.

The District has managed and/or funded the groundwater monitoring network within and near the District boundaries since 1955. **Table 16** below shows the total number of monitoring wells available on a decadal basis since 1950.

Table 16. Total number of groundwater monitoring wells at the District from 1950 to 2005.

Years	Total Wells	USGS Wells	District Wells
1950–1959	311	311	0
1960–1969	286	282	4
1970–1979	1,562	1,540	22
1980–1989	1,724	1,551	173
1990–1999	616	314	302
2000–2005	978	360	618

The benefits from funding this long-term groundwater-monitoring network for the District include the following (Lukasiewicz et al. 2002):

- To provide a means of assessing long-term trends in groundwater availability.
- To develop, verify, and calibrate groundwater flow models from groundwater data collected.
- To provide data to regularly assess temporal groundwater conditions during droughts.
- To provide data for water use permit application evaluations.
- To assist the District in legal proceedings involving regulatory and other groundwater disputes.
- To determine background conditions for use in design and performance evaluation of various District projects.

Groundwater data archived by the District are also accessible to the public, consulting firms, and staff from other governmental agencies. Uses of the data include developing the appropriate scientific and technical understanding required by District rules to support applications for Environmental Resource Permits, Consumptive Use Permits, and other purposes applicable to the District's mission.

The coverage provided by the groundwater monitoring network is constantly being evaluated. The USGS and District cooperative wells are evaluated annually to identify redundant wells that can be removed from the network. New wells are also being added to the network to fill data gaps for improved groundwater modeling. In 1996 the District completed a rigorous statistical analysis of the groundwater network in southwestern Florida (Switanek, 1999). This optimization study was an effort to determine how to optimize the cost effectiveness of the network. It was concluded that 41 wells could be removed from the network without significantly decreasing spatial coverage. With this conclusion, the District and USGS staff met to review non-statistical considerations for these 41 wells to determine how to discontinue monitoring without a significant loss of information. The criteria used for discontinuation included historic record, sensitive water shortage areas, and multi-agency studies of these wells. Another factor in the network's reduction was a change in the District's permit criteria. The new criteria mandated that public water supply utilities provide groundwater-level data to the District on a monthly basis; this eliminated the need for wells located near reporting utilities. As a result, it was concluded that 24 of the 41 wells would be removed from the network within the Lower West Coast Planning Area.

In a separate District analysis, Lukasiewicz et al. (2002) concluded that 15 additional wells could be removed and 54 new wells should be installed in the network. At the time of the study approximately 20 percent of the groundwater network's 669 wells were being continuously recorded with automated equipment. The study recommended that an additional 40 percent of the wells should have automated monitoring equipment installed. Many of the recommendations from this study were implemented and the groundwater network increased in size.

B. Existing Groundwater Network

A total of 907 wells were monitored on a regular basis (15-minute continuous, monthly, or greater than 1-month intervals) as of April 30, 2007. The District is solely responsible for monitoring, maintenance, QA/QC, data archival, and funding for 568 of these wells. The remaining 339 wells are monitored and QA/QC'd by the USGS under cooperative agreements with the District.

1. Location of Wells by Aquifer

The locations of the District wells are shown in maps on **Figures 54** through **56**, corresponding to the three aquifer systems. **Figure 54** shows the location of the wells in the surficial aquifer system, **Figure 55** shows the wells in the intermediate aquifer system, and **Figure 56** shows the wells in the Floridan aquifer system.

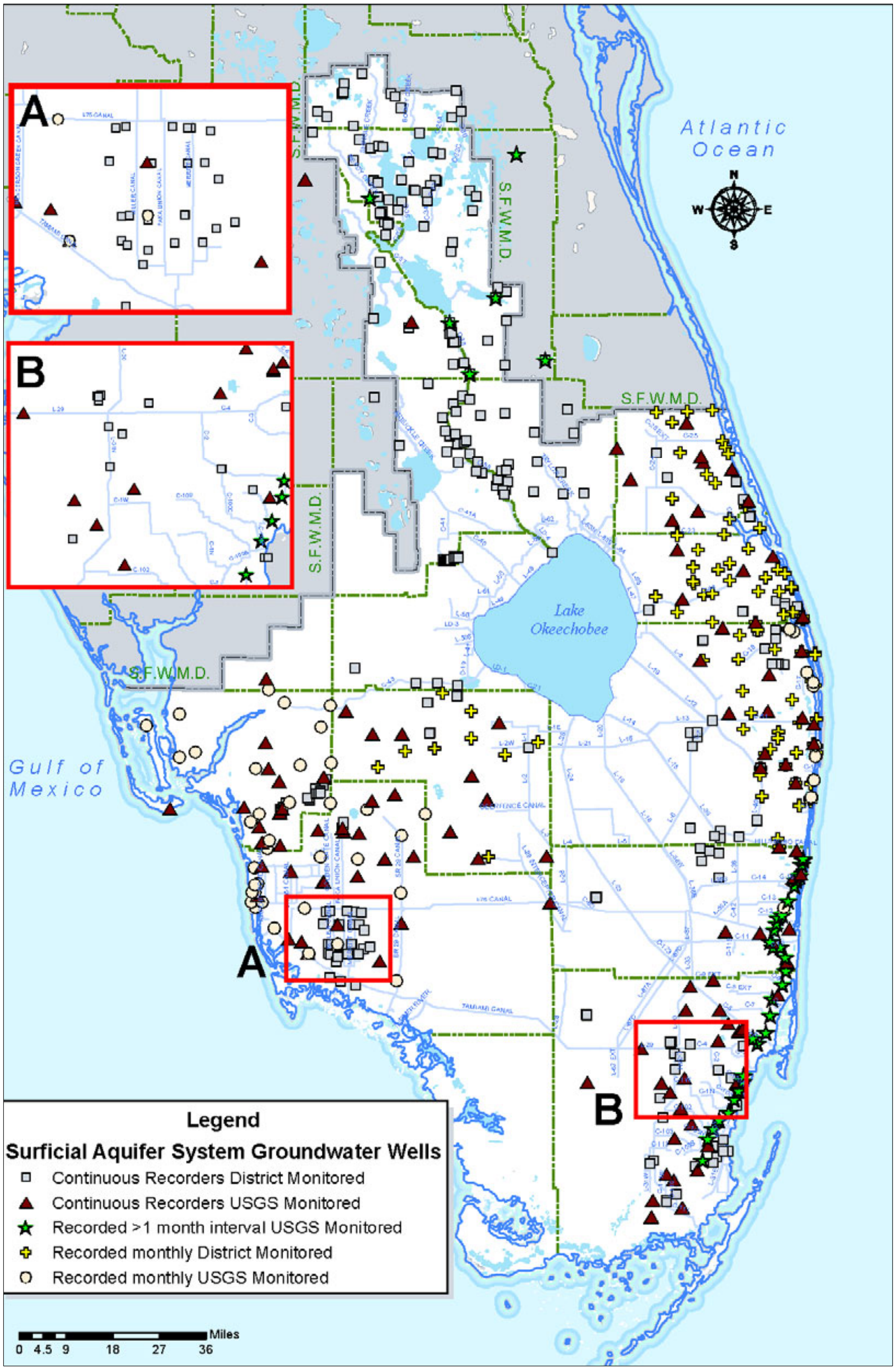

Figure 54. Surficial aquifer system wells.

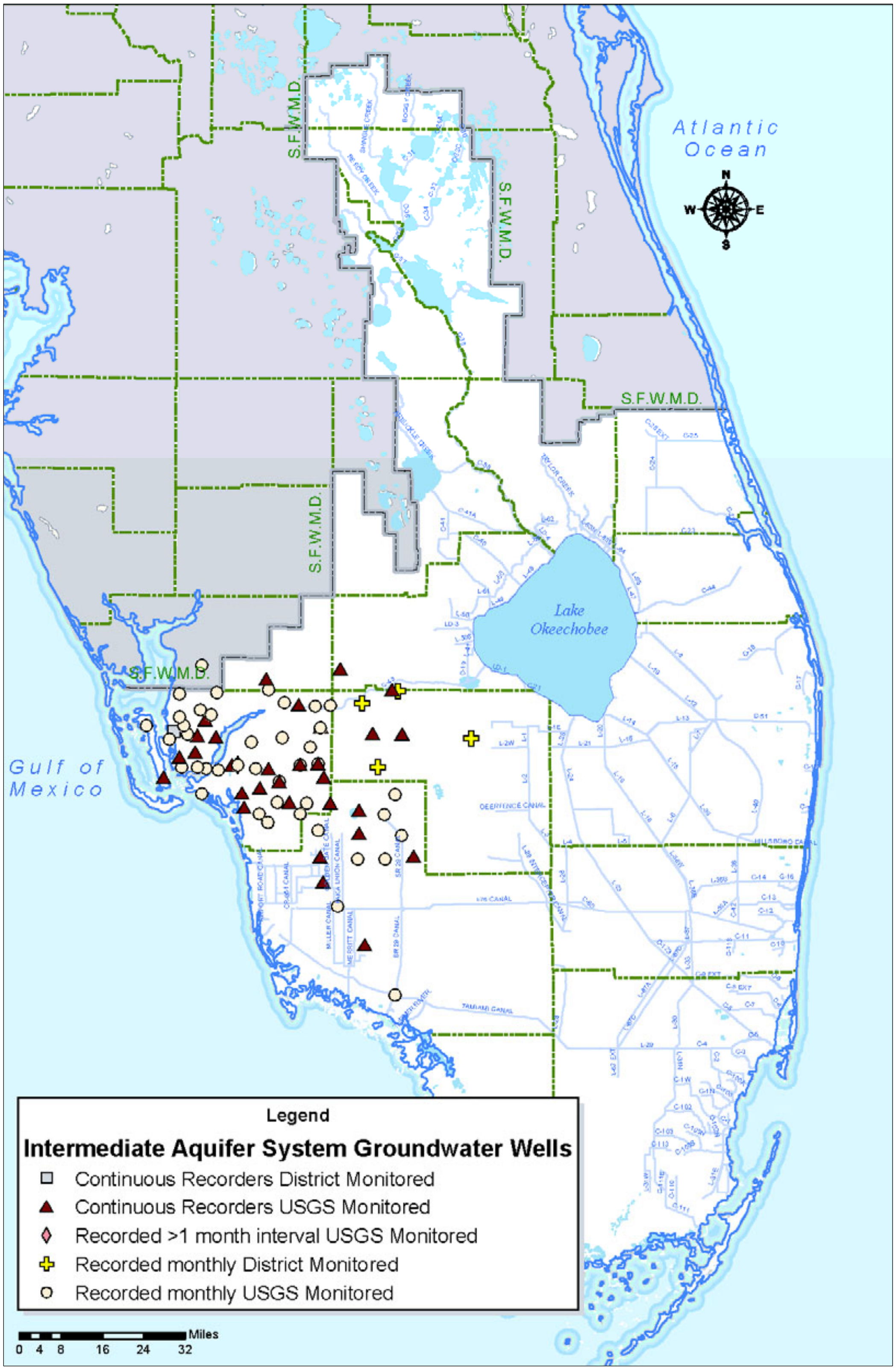

Figure 55. Intermediate aquifer system wells.

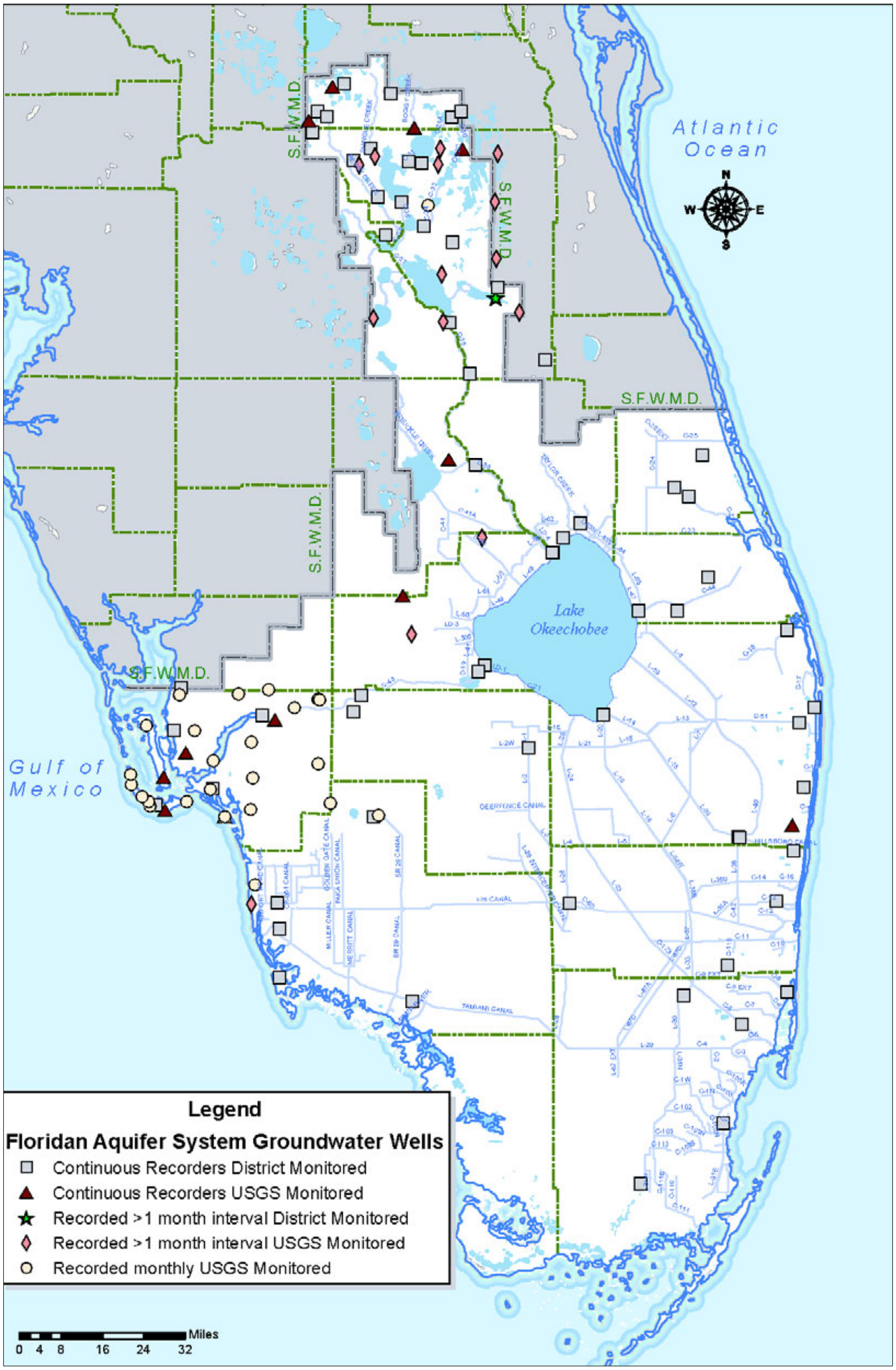

Figure 56. Floridan aquifer system wells.

2. *Field Instrumentation Used at the Sites*

The District measures groundwater levels by using a pressure transducer, which is typically connected to a Campbell Scientific® CR10 data logger (**Figure 57)**. In-Situ® Level Troll pressure transducers are commonly used in non-artesian or water table aquifer wells (**Figure 58)**. The In-Situ® Level Troll pressure transducer is a fully submersible instrument that measures accurate head pressures (water levels) above the sonde.

Artesian or confined aquifer wells are typically equipped with pressure transducers. The In-Situ Level Troll 500 transducer (Figure 59) is used for current and replacement artesian wellhead installations, while some of the older artesian wells are equipped with Rittmeyer pressure transducers. The In-Situ Level Troll 500 pressure transducers are installed at the top of the wellhead and measure head pressure. The transducers communicate with the CR10 data loggers through an electronic cable. The data logger then converts measured pressure values into water levels and records these data for subsequent downloads via laptop computers. Alternatively, data from some of the wells connected to the CR10s are sent via telemetry to the District's headquarters. A non-artesian well site that transmits data via telemetry is shown on **Figure 60.**

Figure 57. A Campbell Scientific® CR10 data logger (attached to pressure transducer in a non-artesian well).

Figure 58. An In-Situ® Level Troll pressure transducer.

Figure 59. The In-Situ Level Troll 500 transducer connected to a Floridan Aquifer well.

Figure 60. A non-artesian well site connected via telemetry.

Some wells in the groundwater network are measured by a well sounder (**Figure 61)**, an instrument that measures water levels by means of an electronic sensor. The sensor is lowered into the well, and a light and buzzer indicate when contact between the sensor and water is made. Along the sensor cable are permanently stamped depth markings to indicate the depth of the water from the top of casing (TOC). To obtain a water level elevation, the depth measurement is subtracted from the TOC elevation. An example of a well measured with a well sounder is shown in **Figure 62**.

Figure 61. Electronic well sounder used for measuring groundwater levels.

Figure 62. An un-instrumented groundwater monitoring well (typically measured with a well sounder).

The majority of USGS groundwater wells are equipped with continuous recorders such as Sutron® 8400 automated data recorders, Stevens® automated data recorders, or data collection platforms. With the exception of data collection platforms, these recorders measure daily groundwater levels at 1-hour frequencies. Data collected by data collection platforms use the Geostationary Operational Environmental Satellite (GOES), which permits water levels to be transmitted to the USGS on a near real-time basis. All data collection platforms are linked to the Internet at http://www.sflorida.er.usgs.gov, and allow users to query the data and produce hydrographs.

3. Frequency of Water Level Measurements

The frequency of water level measurements is not the same at all wells. About 68 percent are fitted with continuous recorders, about 26 percent have measurements taken monthly, and about six percent have measurements taken at more than one-month intervals. **Table 17** shows the frequency of water level measurements of the wells and is classified by aquifer system. **Table 18** shows the frequency of water level measurements classified by county and aquifer system. **Figures 63** through **65** show the location of the wells by frequency of water level measurements: continuous, monthly, and greater than 1 month, respectively.

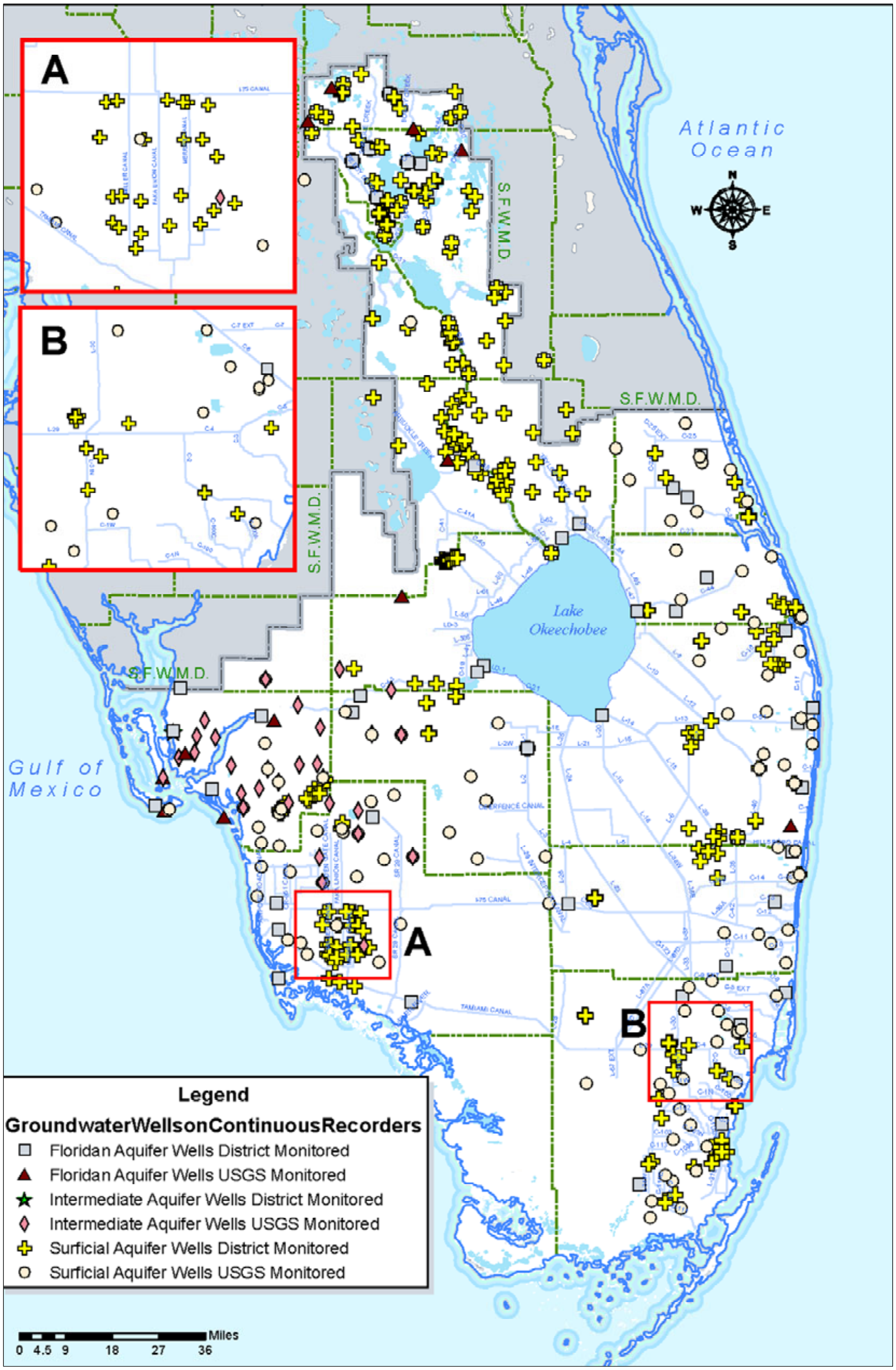

Figure 63. Location of wells on continuous recorders.

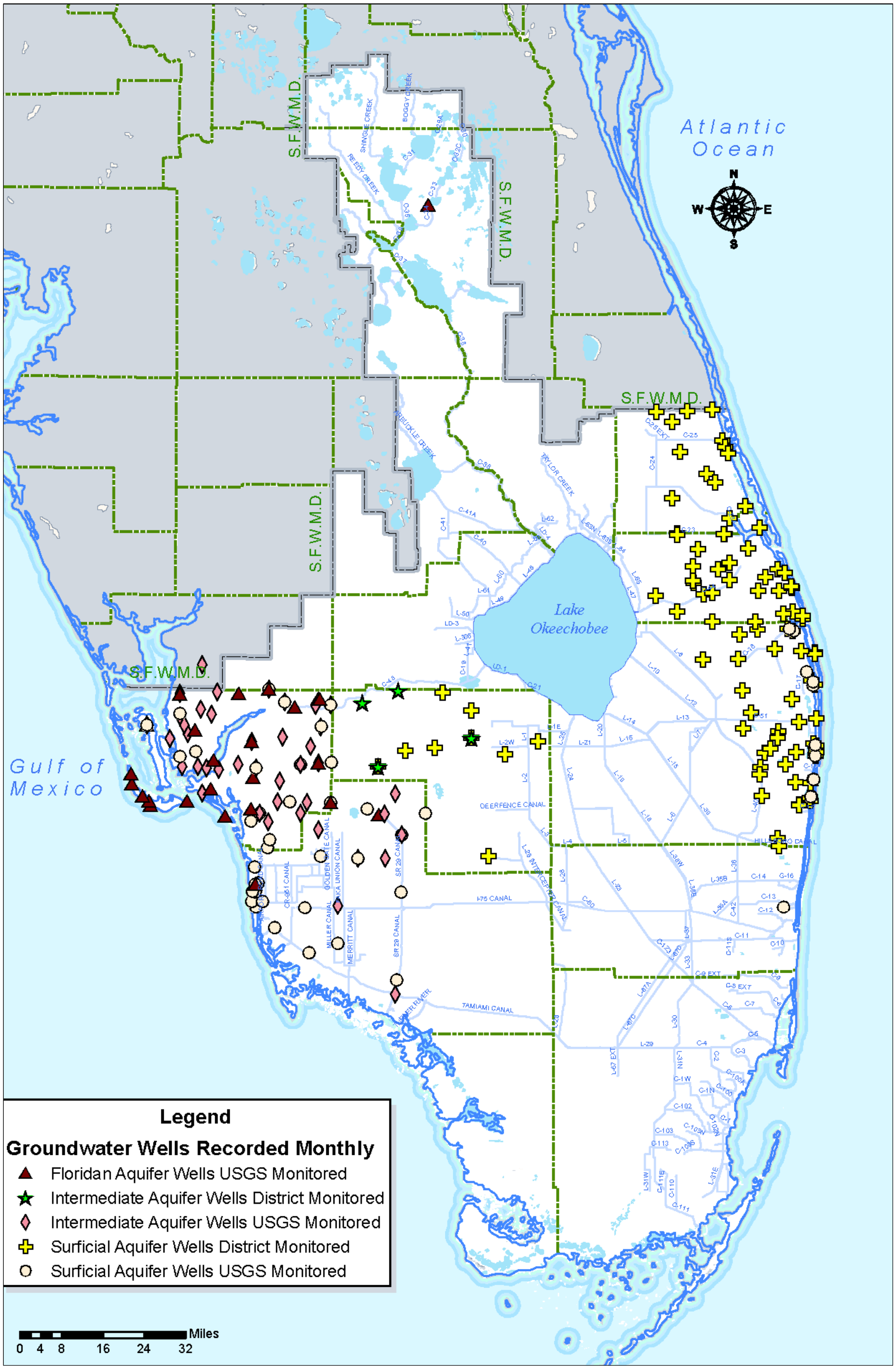

Figure 64. Location of wells recorded monthly.

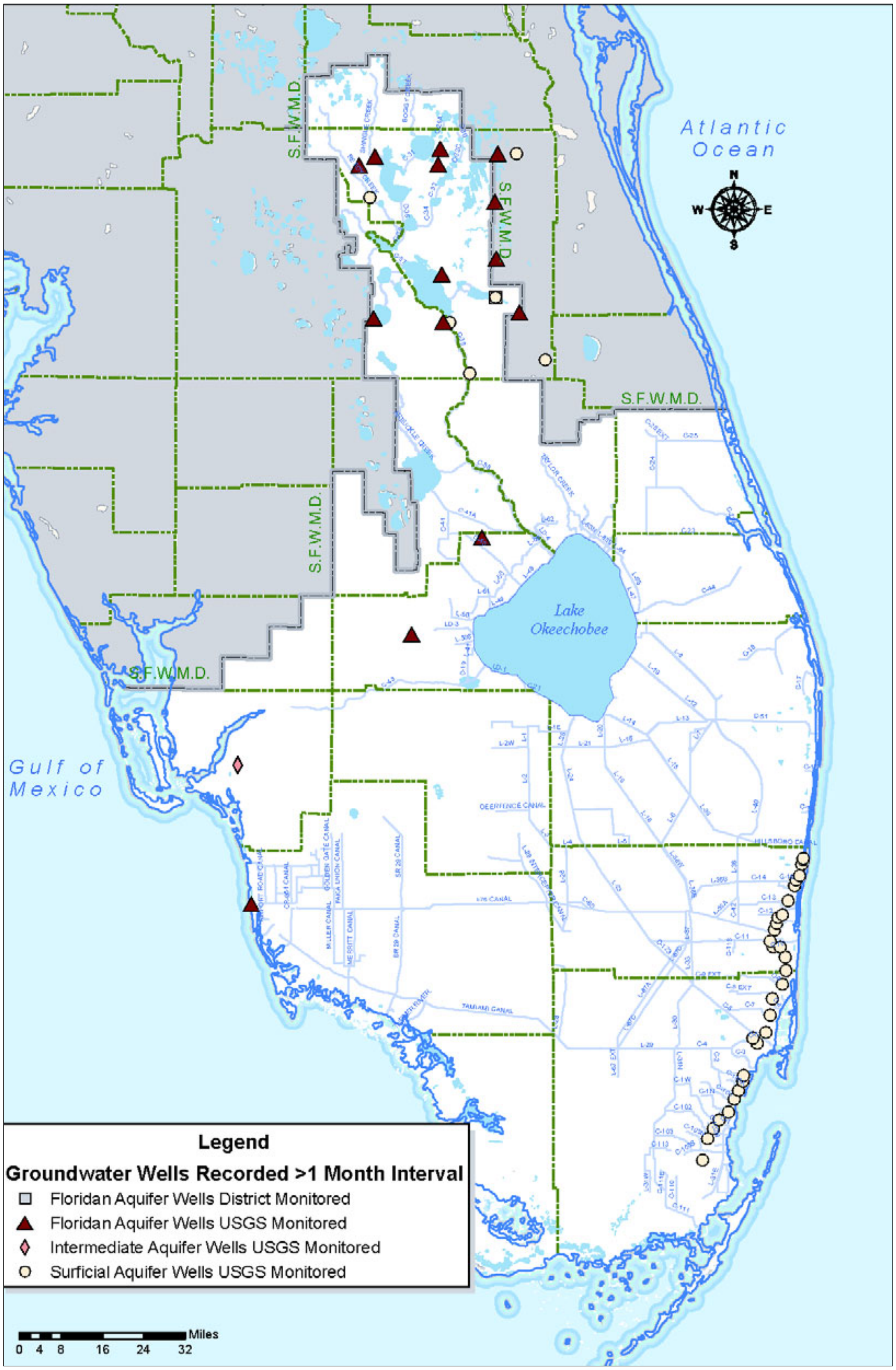

Figure 65. Location of wells recorded at greater than 1-month intervals.

Table 17. Wells classified by frequency of water level measurements and aquifer system.

Aquifer System	Aquifer Unit	Number of Wells by Frequency of Measurements			Total Number	% of Total
		Continuous	Monthly	>1 Month		
Surficial	Water Table Biscayne Lower Tamiami	496	161	37	694	77
Intermediate	Sandstone Mid-Hawthorn	35	47	1	83	9
Floridan	Lower Hawthorn Suwannee Ocala Group	88	27	15	130	14
Total Number		619	235	53	907	100
% of Total		68	26	6	100	100

Table 18. Wells classified by county, frequency of water level measurements, and aquifer system.

COUNTY	SURFICIAL SYSTEM				INTERMEDIATE SYSTEM				FLORIDAN SYSTEM			
	Continuous	Monthly	>1 Month	**Total**	Continuous	Monthly	>1 Month	**Total**	Continuous	Monthly	>1 Month	**Total**
BROWARD	22	2	16	**40**	0	0	0	**0**	5	0	0	**5**
CHARLOTTE	1	0	0	**1**	1	1	0	**2**	1	0	0	**1**
COLLIER	56	24	0	**80**	7	9	0	**16**	5	2	1	**8**
GLADES	14	0	0	**14**	2	0	0	**2**	2	0	2	**4**
HENDRY	29	9	0	**38**	4	4	0	**8**	4	0	0	**4**
HIGHLANDS	47	0	0	**47**	0	0	0	**0**	2	0	0	**2**
LEE	30	17	0	**47**	21	33	1	**55**	10	24	0	**34**
MARTIN	17	34	0	**51**	0	0	0	**0**	3	0	0	**3**
MIAMI-DADE	73	0	15	**88**	0	0	0	**0**	5	0	0	**5**
MONROE	0	0	0	**0**	0	0	0	**0**	1	0	0	**1**
OKEECHOBEE	38	0	0	**38**	0	0	0	**0**	7	0	0	**7**
ORANGE	16	0	0	**16**	0	0	0	**0**	10	0	0	**10**
OSCEOLA	58	0	5	**63**	0	0	0	**0**	15	1	10	**26**
PALM BEACH	50	60	0	**110**	0	0	0	**0**	10	0	0	**10**
POLK	27	0	1	**28**	0	0	0	**0**	3	0	2	**5**
ST. LUCIE	18	15	0	**33**	0	0	0	**0**	5	0	0	**5**
Ground Total	**496**	**161**	**37**	**694**	**35**	**47**	**1**	**83**	**88**	**27**	**15**	**130**

C. Groundwater Data

1. Data QA/QC Procedures

a. District's SCADA and Hydrologic Data Management Department Monitored Wells

The District's SCADA and Hydrologic Data Management (SHDM) Department collects, processes, and archives groundwater data from 454 wells. This department includes the SCADA and Instrumentation Management (SIM) Division and the Operations and Hydrologic Data Management (OHDM) Division. The SIM Division is responsible for installing and maintaining groundwater instrumentation, and ensuring that appropriate data are collected. The OHDM Division is responsible for processing and archiving the groundwater data into the DBHYDRO database.

Groundwater data collected by the SIM Division are reviewed and processed by the OHDM Division following established standard operating procedures (Sangoyomi and Lambright, 2006). Data review includes examination of groundwater data plots using a graphical verification analysis program. Data anomalies, if observed, are reported to the SIM Division for further evaluation. If anomalous data are identified, a request for maintenance and repair (Maintenance Inventory Recorder Malfunction Aid [MIRMAID]) can be generated. This report triggers an email sent to the SIM Division to request review of the suspect data. The email is assigned to an individual who typically must visit the monitoring site to investigate the problem.

A consultant performs additional QA/QC to groundwater data series used in support of the District's reporting, modeling, and regulatory programs. The consultant evaluates groundwater level measurements, performs temporal and spatial statistical analyses of the data, verifies reference elevations, fills missing data, resolves hydrogeologic problems, and documents all analyses in technical reports. This groundwater data is then assigned a new database key (dbkey) that indicates that it has gone through more thorough QA/QC procedures. This project is done annually subject to funding availability.

b. District's Hydrologic On-line Well Inventory (HOWDI) Wells

The District's Water Supply Department collects, processes, and archives groundwater data from 114 surficial aquifer wells located in Palm Beach, Martin, St. Lucie, and Hendry counties that are part of the HOWDI network. The USGS had been responsible for water level collection and data management for these HOWDI wells until 1995. Since that time, various District departments have taken responsibility for the HOWDI well network. Currently the Resource Evaluation and Sub-Regional Modeling Division of the Water Supply Department maintains responsibility of the HOWDI well network. The Division archives the groundwater data and manages contractors who perform monthly manual water level measurements.

c. USGS Monitored Wells under District's Cooperative Agreement

The USGS is responsible for the monitoring and QA/QC of 339 wells in the groundwater network under a cooperative agreement with the District.

Many USGS wells are automated and equipped with automatic data recorders. Other USGS wells are manually measured with well sounders or pressure gauges. The USGS archives the data in their corporate database, which can be accessed at http://nwis.waterdata.usgs.gov/fl/nwis, and portions of the data are migrated into DBHYDRO via an automated download.

2. Groundwater Data Availability

Groundwater data are available in the DBHYDRO database. If some wells do not have active dbkeys, then the Excel spreadsheet file in the appendices shows notes regarding when active dbkeys may become available.

a. Wells to be added to database

Hydrologic On-line Well Inventory (HOWDI) Wells

The HOWDI well data are located in an Oracle database not linked to DBHYDRO. Plans to migrate the HOWDI well data to DBHYDRO include surveying all the HOWDI wells and assigning dbkeys to store historic and future data. These data should be included in DBHYDRO by January 2008.

USGS/District Cooperative Wells

Less than half of the groundwater data currently collected from the USGS/District cooperative agreement and those data are being transferred into DBHYDRO. However, all of the USGS data can be accessed through their website at (http://nwis.waterdata.usgs.gov/fl/nwis). Two alternatives to accessing ADAPS are being considered: (1) assign Dbkeys to the remaining wells and transfer all the ADAPS data into DBHYDRO or (2) provide links from the dbkey to the data located at the USGS website. However, a date for completion of these alternatives was not available at the time of this report.

3. Existing Groundwater Data from Project, Regulation, and Injection Wells

Groundwater data not included in DBHYDRO were collected as part of specific District projects independent of the SHDM Department. Although such projects may involve data collection and processing similar to that performed by SHDM, the data may have quality concerns. However, a portion of this data could undergo QA/QC procedures and be included in DBHYDRO.

A large amount of groundwater data from regulation wells is submitted to the Water Use Regulation Division by approximately 100 permit holders with Water Use Permits issued by the District. While the actual data are collected by the permit holders, the District archives the data. Many permit holders that possess Individual or major General Water Use permits are required to develop and implement groundwater-monitoring programs as conditions of their permits. The objective of these permit conditions is to provide a means of evaluating whether permitted withdrawals may be causing adverse impacts to water resources, protected users, or protected environmental species.

Monthly or quarterly water-level measurements of monitoring wells and/or production wells are typically required of the permit holders. These data are evaluated to ensure compliance with permit conditions. Quality assurance is solely the responsibility of the permit holders; hence, the quality of data in this category may vary and is not included in DBHYDRO. However, future data collected may be added to the DBHYDRO database as more QA/QC procedures are implemented.

The Florida Department of Environmental Protection (FDEP) maintains an injection well groundwater database. Data from this database would be ideal for inclusion into DBHYDRO as it includes deeper portions of the Floridan Aquifer System not normally monitored by District wells. However, the District will need to work with the FDEP to resolve QA/QC and data dissemination concerns before such inclusion takes place.

D. Measured Data Accuracy and Precision

At most of the stations, the ground water stages are measured by stage sensors that have accuracy of 0.01 foot. However, the accuracy of the stage measurement varies due to many factors such as measurement errors caused by mechanism, elevation errors of the reference elevation of the wells, and others; and hence accuracy is estimated to be at 0.1 foot. The precision of the stage during a sampling would be up to one significant digit after the decimal.

E. Groundwater Monitoring Network Design

The purpose of groundwater wells was to obtain groundwater quantity and quality information for various water supply related projects. While the existing groundwater network has evolved over several decades, the design of the network was not performed. However, in 2001, the District's groundwater monitoring network was assessed (Lukasiewicz et al., 2002). In 2004, the District and USGS discussed the possibility of developing a groundwater monitoring network design project. This project is expected to be performed in the next few years depending upon availability of funds at the District and USGS.

1. Proposed Groundwater Wells

a. Floridan Aquifer System wells — South of Lake Okeechobee

Because there is sparse coverage in this region, more wells will need to be installed to monitor the effects of increased Floridan aquifer system use and upcoming aquifer storage and recovery projects in the region. These additional wells will support modeling efforts by providing data to determine circulation and boundary conditions of the Floridan aquifer system.

b. Surficial Aquifer System wells — Interior District Region

The interior portions of the District, away from the heavily populated coasts, have sparse surficial aquifer system coverage. As the District proceeds with designing and implementing CERP and Acceler8 programs, these areas will need more Surficial Aquifer System wells to monitor progress of these projects.

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