Florida Water Resources Research Center
Annual Technical Report
FY 2009

Introduction

The mission of the Florida Water Resources Research Center at the University of Florida is to facilitate communication and collaboration between Florida's Universities and the state agencies that are responsible for managing Florida's water resources. A primary component of this collaborative effort is the development of graduate training opportunities in critical areas of water resources that are targeted to meet Florida's short- and long-term needs.

The Florida Water Resources Research Center coordinates graduate student funding that is available to the state of Florida under the provisions of section 104 of the Water Resources Research Act of 1984. Over the past year (Fiscal Year 2009) the Center supported $1.8 million in research, including agreements with three of Florida s universities (Florida Atlantic University, University of South Florida, and the University of Florida) and four state agencies (South Florida Water Management District, Southwest Florida Water Management District, St. Johns River Water Management District, and the Florida Geological Survey) and has supported the research efforts of 4 post doctoral associates, 15 Ph.D., 8 Masters, and 9 undergraduate students focusing on water resources issues.

During FY 2009, along with providing support to graduate students within the state of Florida, the Center also facilitated development of research at both the state and national level producing 12 peer reviewed publications, 19 proceedings and presentations and 2 PhD dissertations. The Center is a state repository for water resources related publications and maintains a library of technical reports that have been published as a result of past research efforts (Dating back to 1966). Several of these publications are widely used resources for water policy and applied water resources research in the state of Florida and are frequently requested by others within the United States. As part of the WRRC information and technology transfer mission, the library is being converted to digital form and is provided free to the public through the WRRC Digital Library available on the center website (http://www.ce.ufl.edu/~wrrc/).

Research Program Introduction

During FY 2009 the Water Resources Research Center supported five 104B research projects and six center-affiliated research projects. The supported research projects considered a wide range of water resource related issues while maintaining focus on topics specific to Florida.

104B Research Projects

Investigation of the geochemical processes that control the mobilization of arsenic during aquifer storage recovery (ASR). A prior 104B seed project has been extended to a multi-year project with cooperating state agencies (Southwest Florida Water Management District and Florida Geologic Survey) to investigate arsenic mobilization during aquifer storage recovery (ASR). With the topic of alternative water supply becoming a critical issue within the state and nation this is a vital research area to pursue.

Measurement of evapotranspiration, recharge, and runoff in a shallow water table environment characteristic of much of the Gulf of Mexico coastal plain. Results from this study will provide new information and insight into the magnitude and causative mechanisms of runoff, recharge and ET processes and will provide useful parameterization and conceptualization of processes for integrated surface water and groundwater models.

Regional Scale Water resources modeling: multiple student assistantship projects have been established with South Florida Water Management District (SFWMD): Sensitivity Analysis of South Florida Regional Modeling, and Addition of Ecological Algorithms into the RSM Model.

Development of methods for in-filling missing historical daily rain gauge data using NEXRAD. This study investigated the use of spatial analysis techniques to transform existing NEXRAD based rainfall data from one coordinate system to another. This research is highly relevant and critical to a number of water resources management agencies that use NEXRAD based rainfall data for modeling and management of day-to-day operations of water resources systems (SFWMD).

Expansion of Measurement of evapotranspiration, recharge, and runoff in a transitional water table environment

Basic Information

Title:	Expansion of Measurement of evapotranspiration, recharge, and runoff in a transitional water table environment
Project Number:	2006FL142B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	2
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Hydrology, None
Descriptors:	
Principal Investigators:	Mark Ross

Publications

1. Trout, Ken and Mark Ross, Estimating Evapotranspiration in Urban Environments, Urban Groundwater Management and Sustainability, J.H. Tellam, et al., editors, pgs 157-168, Springer 2006.
2. Shah, N., M. Nachabe, and M.Ross. 2007. Extinction Depth and Evapotranspiration from Ground Water under Selected Land Covers. Ground Water, Paper # GW20060417-0057R, doi: 10.1111/j.1745-6584.2007.00302., published online March 12, 2007, awaiting paper publication, submitted 4/17/2006 Accepted December 2006, In Press.
3. Shah, N., M.Ross. 2006. Variability in Specific Yield for Different Drying and Wetting Conditions. Vadose Zone Journal, Submitted 8/18/2006, comments received, revising paper for resubmission.
4. Shah, N., J.Zhang, and M.Ross. 2006. Long Term Air Entrapment Affecting Runoff and Water Table Observations. Water Resources Research, Submitted 10/9/06, comments received, resubmitting paper.
5. Zhang, Jing and Mark A. Ross, 2007. Conceptualization of a 2-layer Vadose Zone Model for Surface and Groundwater Interactions, J. Hydrologic Engrg., HE/2005/022952 (Revised Paper), Accepted with revision, in press.
6. Nilsson, Kenneth A., Ken Trout and Mark A. Ross, 2006. Analytic Method to Derive Wetland Stage-Storage Relationships Using GIS Areas, J. Hydrologic Engrg., manuscript number HEENG-07-55, submitted February 12, 2007.
7. Shah, N., J.Zhang, and M. Ross, 2006. Long Term Air Entrapment Affecting Runoff and Water Table Observations, Water Resources Research, AGU Paper # 2006WR005602, Submitted 10/13/06. Comments received, revising paper for resubmission.
8. Rahgozar, Mandana, Nirjhar Shah, and Mark Allen Ross, 2006. Estimation of Evapotranspiration and Water Budget Components Using Concurrent Soil Moisture and Water Table Monitoring, Journal of Hydrology, paper no. HYDROL5813, submitted Feb 2, 2007.
9. Nilsson, Ken, Trout, K., Ross, M., Stage-Storage Model Application to Predict Multiple Wetland Storage Behavior with Minimal Survey Data, ASCE Journal of Hydrologic Engineering, accepted publication summer 2010.
10. Shah, N. and Ross. M. A. (2009). Variability in Specific Yield under Shallow Water Table Conditions. Journal of Hydrologic Engineering, ASCE, Vol. 14, No. 12, pp 1290-1299, December

2009.
11. Zhang, J., Shah, N., and Ross, M. A. (2009). Observations of long term air entrapment affecting runoff and water table. Int. J. Water, Vol. 5 No. 2, pp. 140-162.

Measurement of Evapotranspiration, Recharge, and Runoff
in
Transitional Water Table Environments

Progress Report Year 4
2010

Prepared by
Center for Modeling Hydrologic and Aquatic Systems
Department of Civil and Environmental Engineering
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Brooksville, Florida

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Executive Summary

A supplemental (fourth year) of the USF eco-site hydrology study have been completed. The overall objective of this study is to instrument, measure and analyze surface runoff, groundwater recharge, and Evapotranspiration (ET) from a characteristic transitional deep water table environment in west-central Florida though a range of meteorological conditions dry to wet. However, the project period still only incorporates measurements and observations from a below average rainfall epoch. Data have been collected for more than three years that now have a combined rainfall deficit from mean conditions of more than 40 inches.

Observations, made at the highest practical resolution and recorded at 10-minute time intervals, include: 1) surficial and Floridan aquifer monitor wells at sites chosen along a transect ranging from deep to shallow water table; 2) vertically resolved soil moisture probes at each well site; 3) an evaporation pan configured to measure high resolution open-pan evaporation; 4) a weather station to continuously monitor atmospheric conditions and precipitation; and 5) field survey and GIS-based background topologic and hydrogeologic data to characterize the site. The wells were installed by the Southwest Florida Water Management District (SWFWMD) and USF. Well core samples were recovered during installation, characterized and logged for at each location.

This report summarizes data and study of recorded data complete for 2009. The project database has been updated with 2009 record. Analysis of the first through third year of complete data collection is ongoing and more detailed computer simulation modeling is presented.

Even though external funding was completed in, active data collection continues. USF personnel visit the site weekly to download data and maintain the equipment. Water levels in the wells and in the evaporation pan are measured manually and compared to the transducer measurements for validation. Also the total rainfall recorded by the tipping-bucket gauge is compared to a manual gauge.

The first complete year of data collection, 2007, was exceptionally dry. Total rainfall measured at the study site from mid-January, 2007 through December 31, 2007 was approximately 41 inches. This followed a dry year experienced in 2006. The year 2008 was slightly wetter than 2007 with 46 inches of rainfall recorded. Last year (2009) continued a three year deficit rainfall period with an annual total of 44.4 inches. Typical annual rainfall for this area is approximately 52 inches. This represents a cumulative three year deficit of 25 inches. This dry period provided an opportunity to examine recharge characteristics for drought conditions but may not be representative of recharge during normal weather conditions.

Introduction

New instrumentation and field procedures have been developed to measure hydrologic processes of runoff, recharge and evapotranspiration (ET). Demonstration of the benefit and application in shallow water table environments characteristic of much of the Gulf of Mexico coastal plain has been shown by Ross et al. (2005), These environments are typified by west-central and southern Florida concave and convex floodplain riverine systems. However, limited testing in deeper water table or transitional hill slope; deep-to-shallow water table, environments has been conducted to date. The objective of this research is to test the methodologies developed at USF (Ross et al., 2005; Trout et al., 2005 and Rahgozar et al., 2005) to measure hydrologic processes in a small but variably vegetated ecological study area. The proposed site is in west-central Florida, adjacent to and maintained by USF, lying within the Hillsborough River watershed.

Objectives of the study

There are multiple objectives for this study. Foremost is the direct measurement of runoff, recharge and evapotranspiration (ET) in a deep water table and transitional water table environments that represent a significant portion of the SWFWMD domain; determine causative processes and rates through dry and wet transitions; test methods developed at USF to estimate ET for different plant communities; and determine parameters and expectations for integrated surface and groundwater simulation models.

Methodology

To meet the objectives of this project and develop a better understanding of the hydrology of deep and transitional water-table systems, substantial amounts of data must be obtained through dry and wet periods. The data collection design must assure that the necessary and sufficient data are collected in the most efficient and cost-effective manner possible. The project collects soil moisture monitoring down through the extinction (no moisture change) depth. It also provides observation of coupled water-table wells with soil moisture for the evolution of saturation excess and Hortonian runoff. Evaporation pan, rainfall and full meteorological instrumentation are included.

Mapping and GIS

Topographic maps, GPS and site inspection have been used to delineate surface-water basins. The maps have been imported into a Geographic Information System (GIS) for further analysis and presentation.

Rainfall and Evapotranspiration

The time scales of infiltration and Hortonian surface runoff are minutes to hours which require the temporal resolution of rainfall to be similar. A tipping-bucket rainfall gauge, which samples every ten minutes, has been installed. Manually-read rain gauge are used as backup and verification of the automatic gauge.

Evapotranspiration cannot be measured directly, and it is wise to approach the problem from as many directions as possible. Therefore, evapotranspiration is being estimated using three independent methods: soil moisture balance, the Penman-Montieth combination equation, and an evaporation pan. The Penman-Montieth combination equation combines direct measurement of the energy required to evaporate water and an empirical description of the diffusion mechanism by which energy is removed from the surface as water vapor (Allen et al. 1989, Montieth 1965, Penman 1948). These measurements are provided via a central weather station. The weather station installed at the Eco Site continuously measures air temperature, humidity and barometric pressure, solar radiation, atmospheric pressure, air temperature, and wind speed and direction. An evaporation pan is also installed near the tipping-bucket rain gauge to measure actual evaporation and to estimate potential evapotranspiration using pan coefficients.

Soil Moisture

To estimate the profile of soil water storage and measure encapsulated air, six EnviroSMART soil moisture probes (manufactured by Sentek, Adelaide, Australia) will be installed on a flow transect. Each probe has eight soil moisture sensors mounted vertically on a rail installed into a dry well next to the water-level monitoring wells. The sensors permit continuous monitoring of soil moisture profiles at 10-minute time intervals at various depths in the soil column. The soil moisture measurements are important for two reasons: 1) with the continuous records at various depths, movement of soil moisture can be directly measured, and 2) through integration and differencing, ET rates can be measured.

At close proximity to each probe is a continuously recording surficial well to provide water-table elevations at the same time interval as the soil moisture data. The wells are made with 2 inch PVC pipe, with a slotted PVC screen extending below a bentonite clay seal. Silica sand is installed around the screen to prevent the screen from clogging with the fine-grained sand and clay present at the site. A data logger at each station stores soil moisture measurements and water-table elevation data from pressure transducers.

Monitor Wells

Groundwater monitoring wells are associated with the soil moisture sensors to record changes in the elevation of the water table. This is necessary to associate changes in soil moisture with changes in the water table. Because the confinement above the Floridan aquifer is discontinuous in the study area, two Floridan aquifer monitor wells were installed to measure the head gradient between the surficial and Floridan aquifer. Each well has a water-elevation measurement at the same temporal resolution as the soil moisture data. Rapid water-table fluctuations due to recharge events in shallow water-table environments necessitate high-frequency data collection

Soil types and the presence or absence of confinement influence soil-moisture movement and water-table response to infiltration and Floridan aquifer recharge. For this reason, soil cores were recovered to characterize the subsurface geology.

Study Area

The study site is the University of South Florida ecological preserve (Figure 1), about two miles east of the campus on Fletcher Ave. The site is owned and maintained by the University of South Florida and is secured with a 6-foot fence and locked gates. The site is currently used for biological and hydrologic research. SWFWMD recently completed a low-flow study transect across the Hillsborough River at the site.

The sites selected for aquifer water level and soil moisture data were chosen by topography and accessibility and so that they would lie on a general down-slope flow path. The sites range from the top of a ridge, approximately at 55 feet in elevation, to a low-lying area near the Hillsborough River at approximately 28 feet elevation. The vegetative cover transitions from a pine forest at the top of the ridge to a predominately palmetto scrub with scattered slash pine trees.

The upper site is characteristic of a deep water table. It is covered by dry very-fine (D_{50} ~ 0.5 mm) dune sand. The predominant vegetative cover is pine and scrub oak forest. The two upper-most shallow wells have not contained water since they were installed. Both of those wells are in a relatively thin unit of very-fine dune sand overlying a thick clay lens. Precipitation has been unusually light this year and the sand unit has remained unsaturated. All other shallow wells have contained water since installation.

A Florida aquifer monitor well was installed next to the upper-most dry surficial well. The purpose of this Floridan well was to evaluate the geologic structure of the ridge, determine if any actual or potential aquifer units exist above the Floridan aquifer and below the surficial, and to obtain measurements of Floridan aquifer water elevations from a second location. No additional aquifer units were located in the unconsolidated sediments above the Floridan limestone. Below the top 14 feet of dune sand were primarily clay and sandy-clay lenses. If a water table forms on the upper portion of the ridge, it will probably be an ephemeral appearance, present only during the wet season and perched above the underlying clay.

The well at the lowest elevation is approximately ¼ mile from the Hillsborough River and is in a high (shallow) water-table environment. A second well, screened from the bottom of the well to the ground surface, was installed approximately 20 feet away. The purpose of the second well is to compare the water levels in a well fully screened to water levels in a monitor well of standard construction where the well screen is present only at the bottom portion of the well. If the water level in a well is influenced by air pressurization due to an infiltrating wetting front, the water level in a cased well should be more responsive than the water level in a fully-screened well where the air pressure inside the well can equilibrate to the air pressure outside of the well.

A Floridan aquifer monitor well was installed next to the ECO-4 surficial aquifer well to measure the head gradient between the surficial and Floridan aquifers. The ECO-4 well was drilled to a depth of 27 feet, where limestone was encountered. No significant clay (confinement) was detected. For the Floridan well installed approximately 18 feet from ECO-4, limestone was encountered at 44 feet with a total depth of 58 feet. Significant clay units were found at 22 and 37 feet bls. Despite the difference in depths to the limestone (and the difference in clay content) between the two wells, the water elevations in the wells are almost identical. It is believed that both wells reflect the Floridan aquifer water elevations.

The topographic elevation at the site varies from a high of greater than 55 feet on a dune-sand ridge to less than 25 feet at the Hillsborough River flood plain. The preserve contains a wide variety of soil types. The dune ridge is classified as Candler Fine Sand which is a hydrologic group A soil (see Table 1) with a seasonal-high depth to water table of greater than 6 feet. Surrounding the base of the dune are Myakka Fine Sand and Malabar Fine Sand, both of which are in the B/D hydrologic group and have a seasonal-high depth to water table of 0.5 - 1.5 feet. Also at the base of the east side of the dune is Pomello Fine Sand, a C hydrologic group soil with a seasonal-high depth to water table of 2 – 3.5 feet. The flood plain is covered by Chobee Sandy Loam which is a D hydrologic group soil with a seasonal-high water table at or above land surface.

Table 1. Hydrologic Grouping of Soils

Group	Description
A	High infiltration rates. Soils are deep, well drained to excessively drained sands and gravels.
A/D	Drained/undrained hydrology class of soils that can be drained and are classified.
B	Moderate infiltration rates. Deep and moderately deep, moderately well and well drained moderately deep, moderately well and well drained.
B/D	Drained/undrained hydrology class of soils that can be drained and are classified.
C	Slow infiltration rates. Soils with layers impeding downward movement of water, or soils with moderately fine or fine textures.
C/D	Drained/undrained hydrology class of soils that can be drained and classified.
D	Very slow infiltration rates. Soils are clayey, have a high water table, or are shallow to an impervious layer.

The vegetation at the site is equally varied as a result of the differences in elevation, soil types and the depth to the water table. Pine trees predominate on the ridge and give way to oaks and palmetto scrub moving toward the floodplain.

The wide variety in the depth to the water table, the soils and the plant communities make this study site particularly appealing. Much of the data collected at this site can be directly transferable to other areas in the SWFWMD domain, from sandy areas with deep water tables to loamy areas with high water tables and from xeric to mesic to hydric plant communities. The close proximity to USF also reduces travel costs.

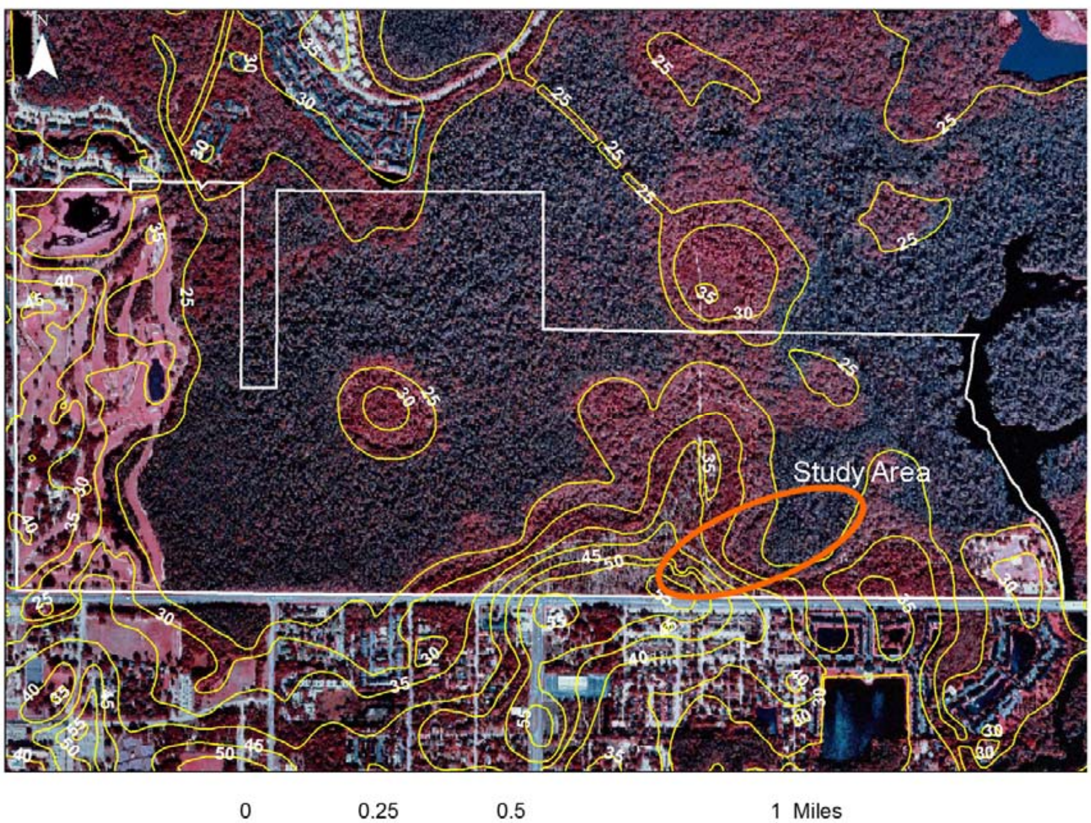

Figure 1. The Orange oval identifies the study area with white line showing the boundary of the USF Eco Area.

Data Collection

The data from all the equipment are collected at a 10 minute intervals and stored in a Microsoft-Access database. Manual measurements are made biweekly for rainfall and water elevations in wells to ensure that the equipment is functioning correctly. Figure 2 shows the locations of the data collection stations. Surficial aquifer monitor wells were installed at the sites labeled ECO-1 through ECO-6 and Floridan aquifer monitor wells were installed at sites FL-1 and FL-2. Cores were obtained from each of the well sites and core logs were completed. The cores and core logs are described in the year two report.

Figure 2. Data collection sites with contour lines showing the land elevation feet above National Geodetic Vertical Datum (NGVD). Floridan wells have an FL prefix.

Weather Station and ET Data

Campbell ET-106 (Campbell Scientific Inc., Logan, Utah) weather station (Figure 3) collects data for rainfall, wind velocity, solar radiation, temperature and relative humidity. In addition, barometric pressure data has been collected at ECO-1 via a Unidata Model 6522B barometric pressure instrument. Hourly average weather data for the year 2009 is presented in Figures 4, 5, 6, 7, 8, 9 and 10. Maximum hourly wind velocity is presented in Figure 6. Solar radiation (Figure 6) is presented as total daily solar radiation in units of kJ/m^2 along with total daily rainfall which is presented on the upper X axis.

Figure 3. Campbell Scientific weather station.

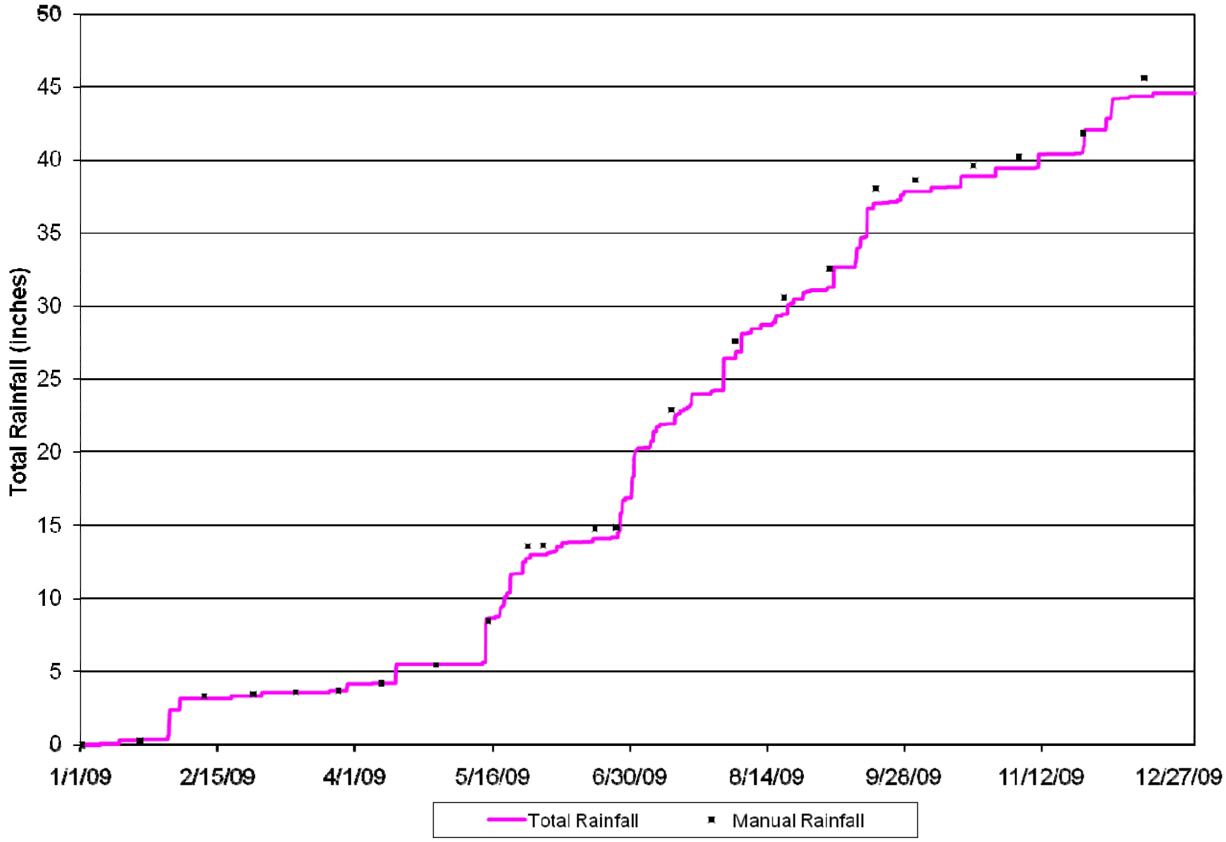

Figure 4. Cumulative and manual rainfall data.

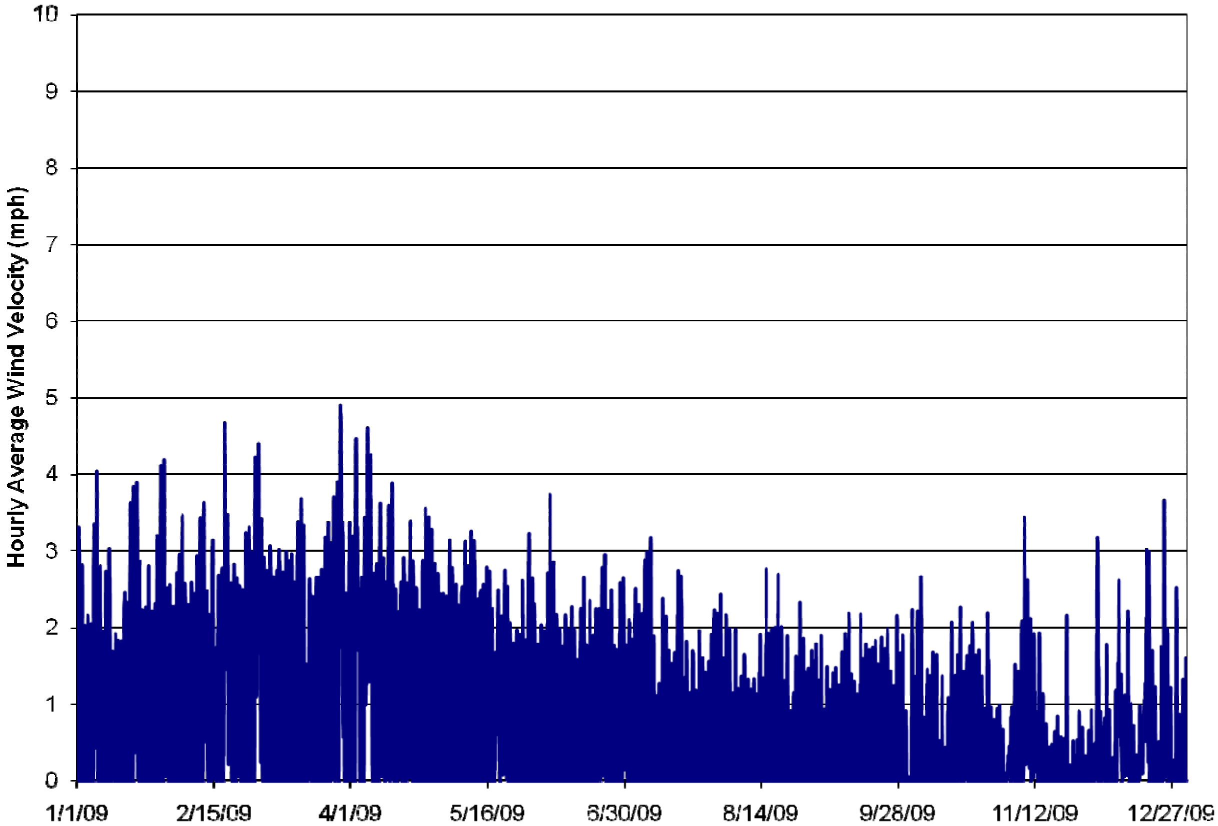

Figure 5. Average hourly wind velocity.

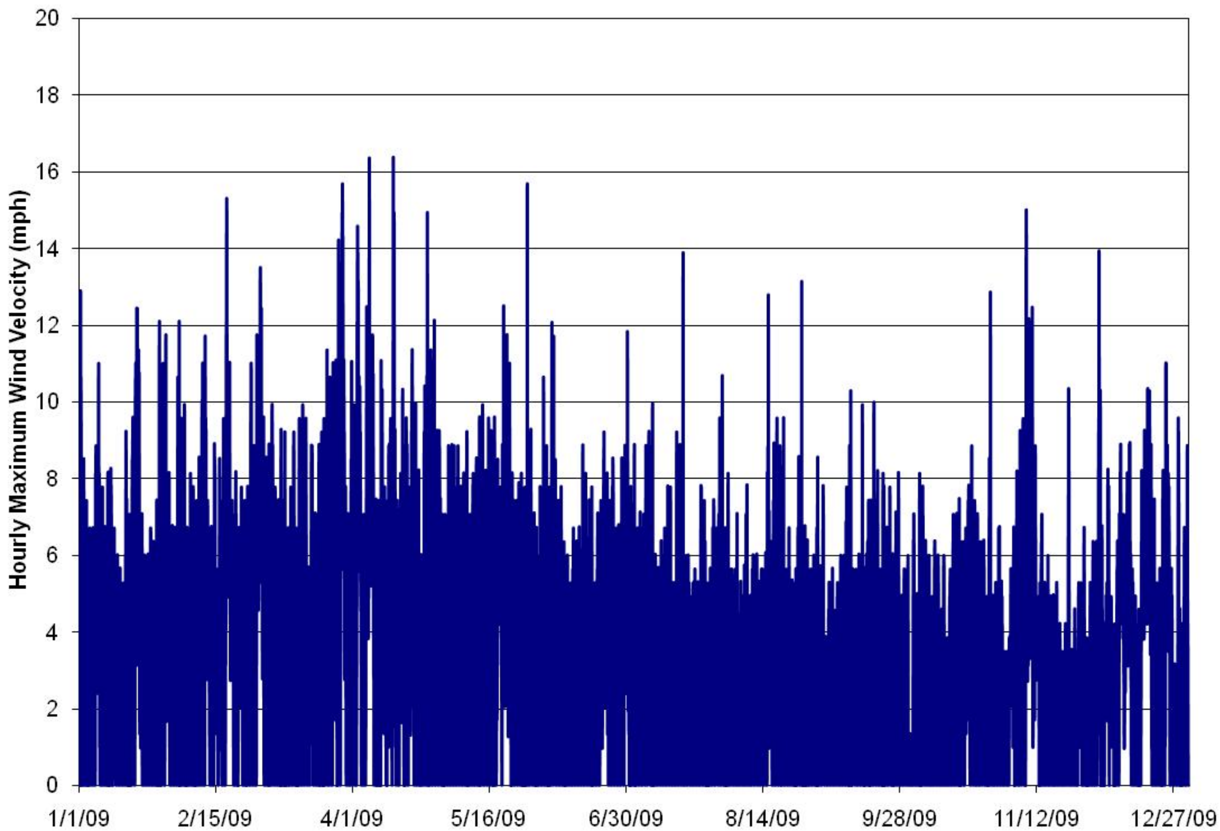

Figure 6. Hourly maximum wind velocity.

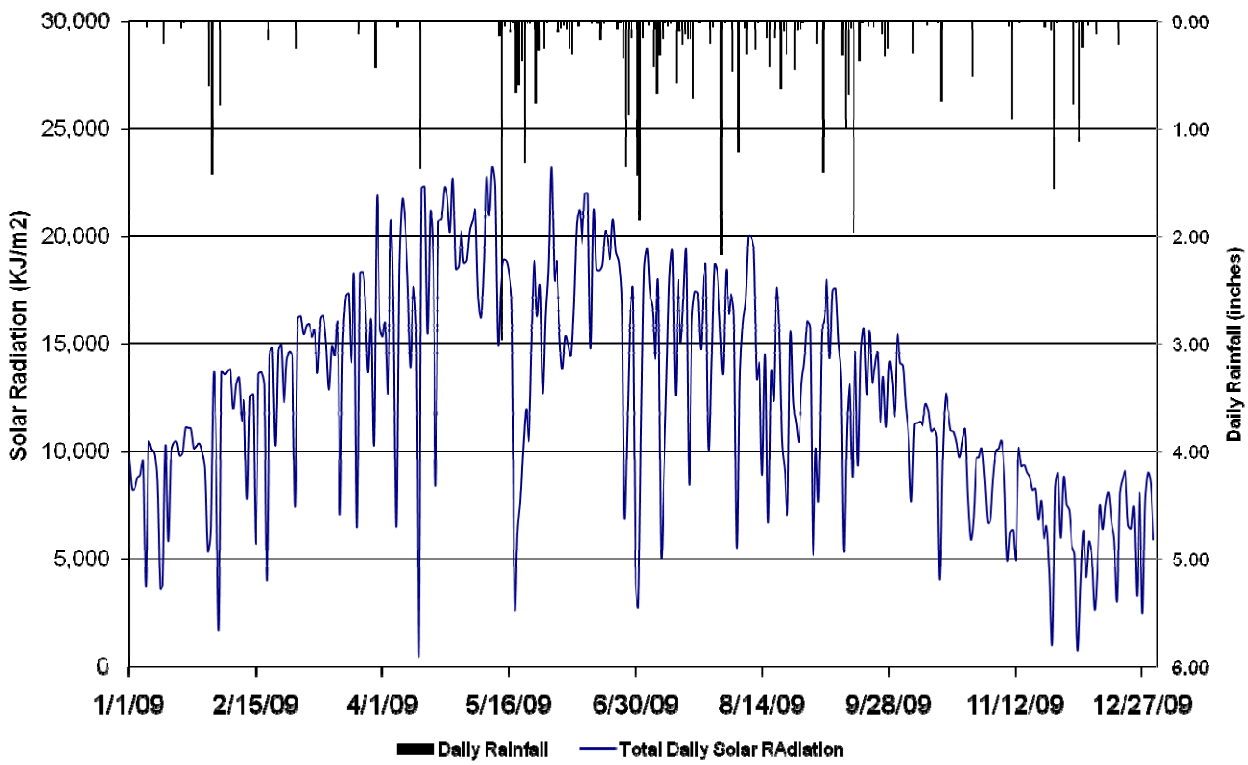

Figure 7. Total daily solar radiation and rainfall

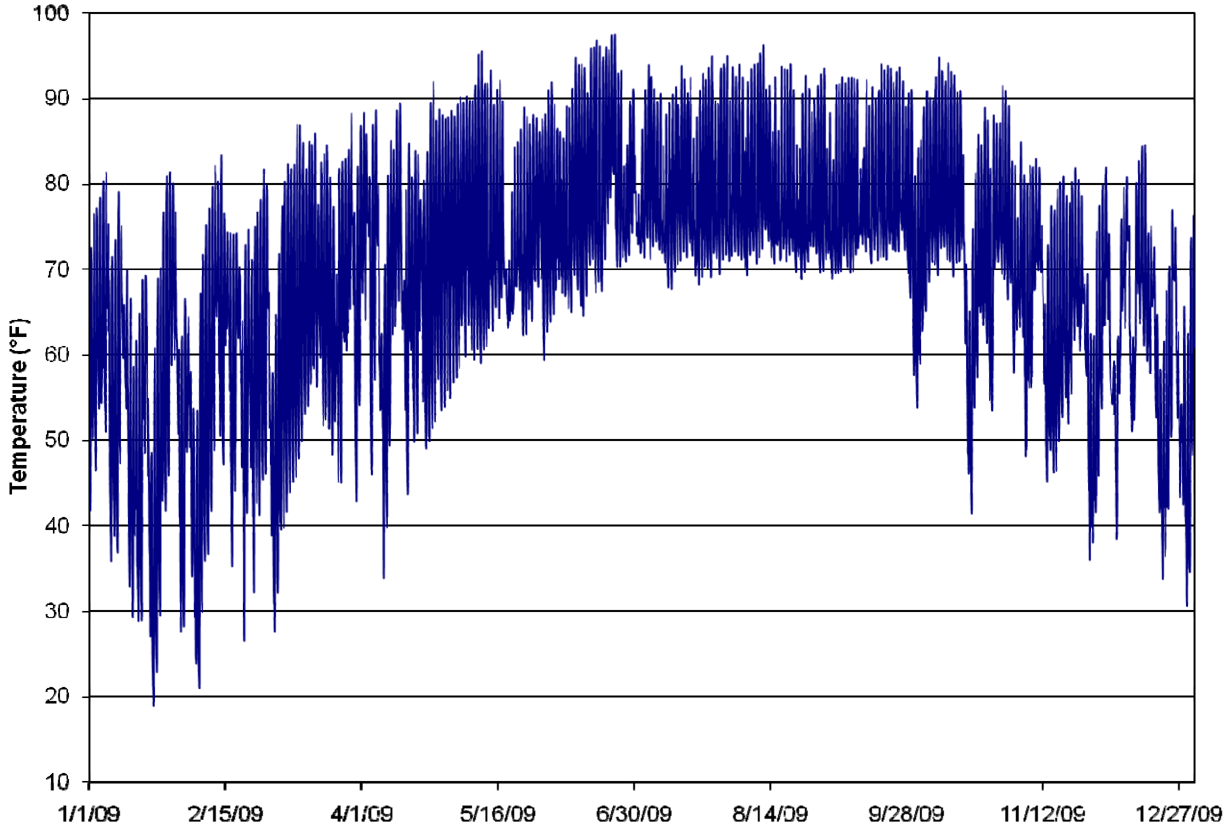

Figure 8. Average hourly temperature.

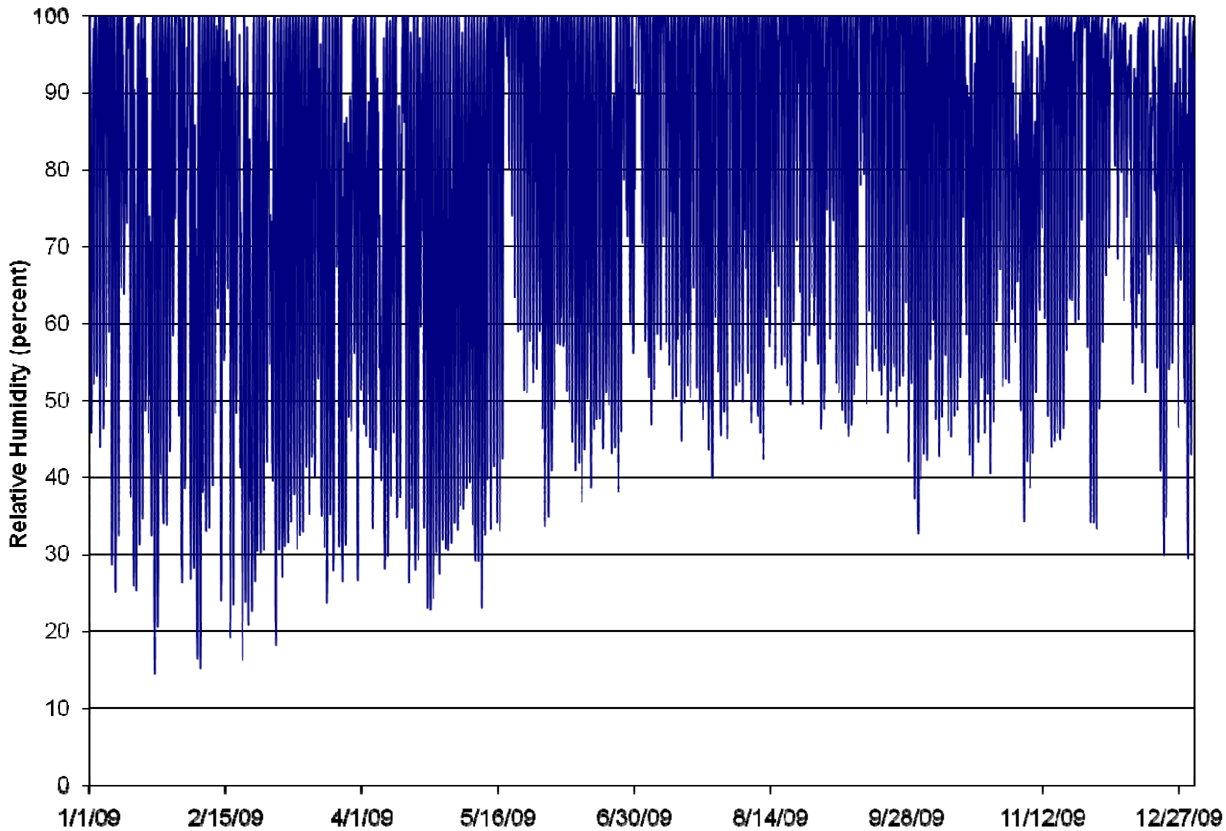

Figure 9. Average hourly relative humidity.

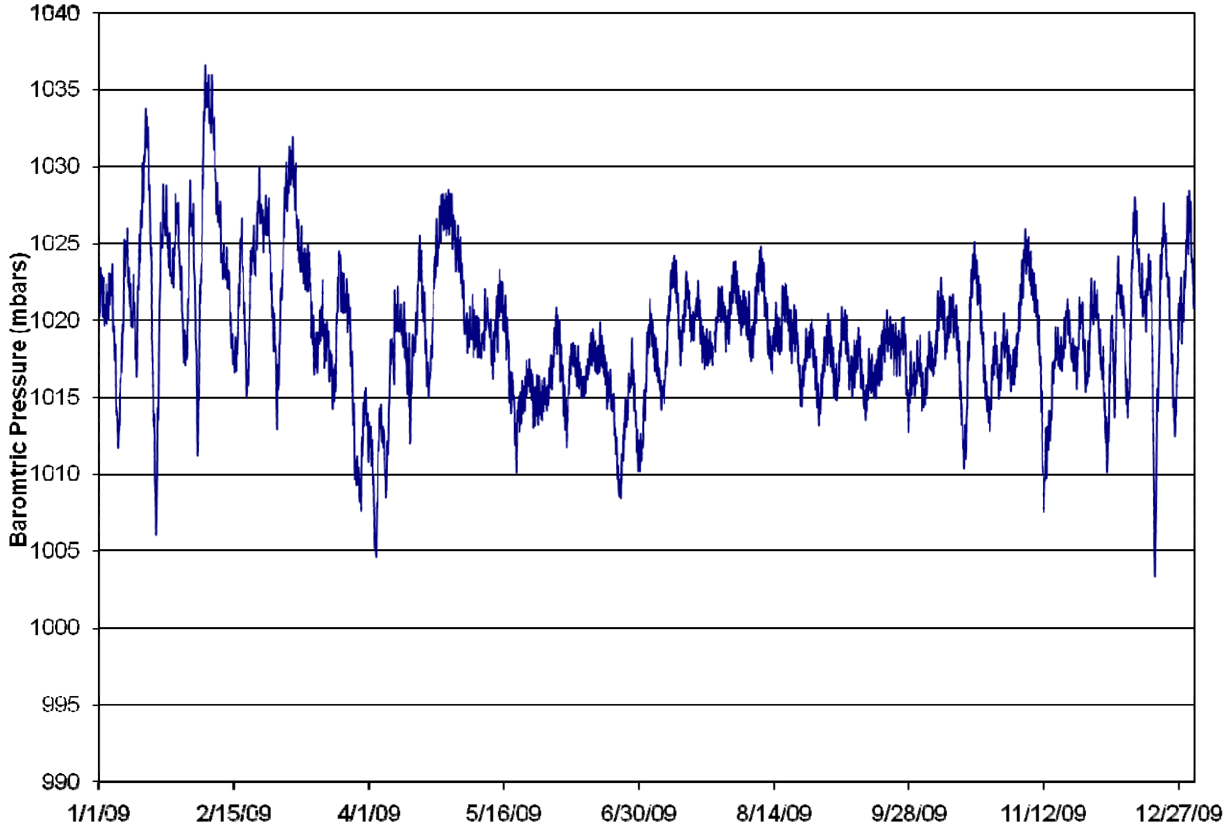

Figure 10. Average hourly barometric pressure.

The raw and cumulative open water evaporation rate data from the standard Class A evaporation pan (Figure 11), which was installed 2/1/07. The blue line in Figure 12 represents the water level from a fixed instrument reference. Thus, increases in this dimension represent declining water levels and, conversely, rapid increases in these values represent rapid water-level rise, most notably from rainfall or water additions to the pan. The red line (secondary axis) represents the derived cumulative evaporation which is the raw data minus the rainfall depth.

Figure 11. Class A ET pan with GeoKon water level monitoring device installed next to the weather station.

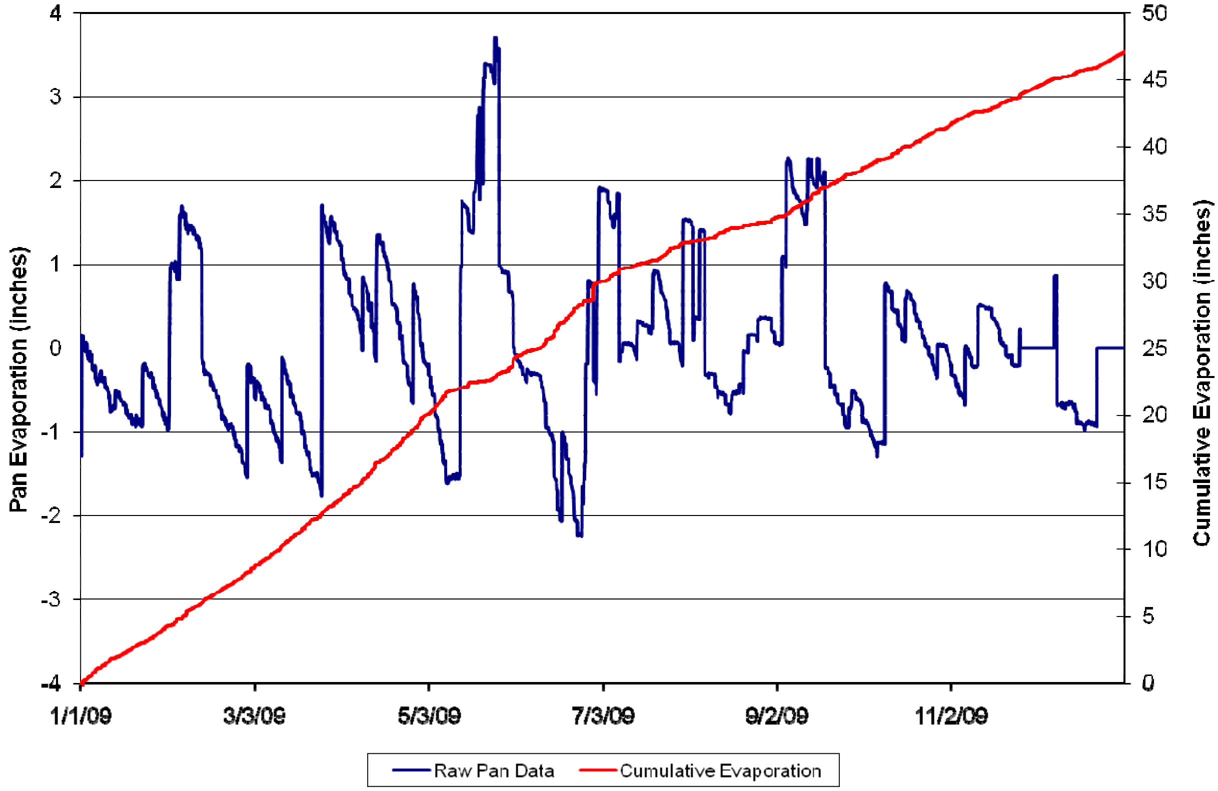

Figure 12. Raw and cumulative open pan evaporation.

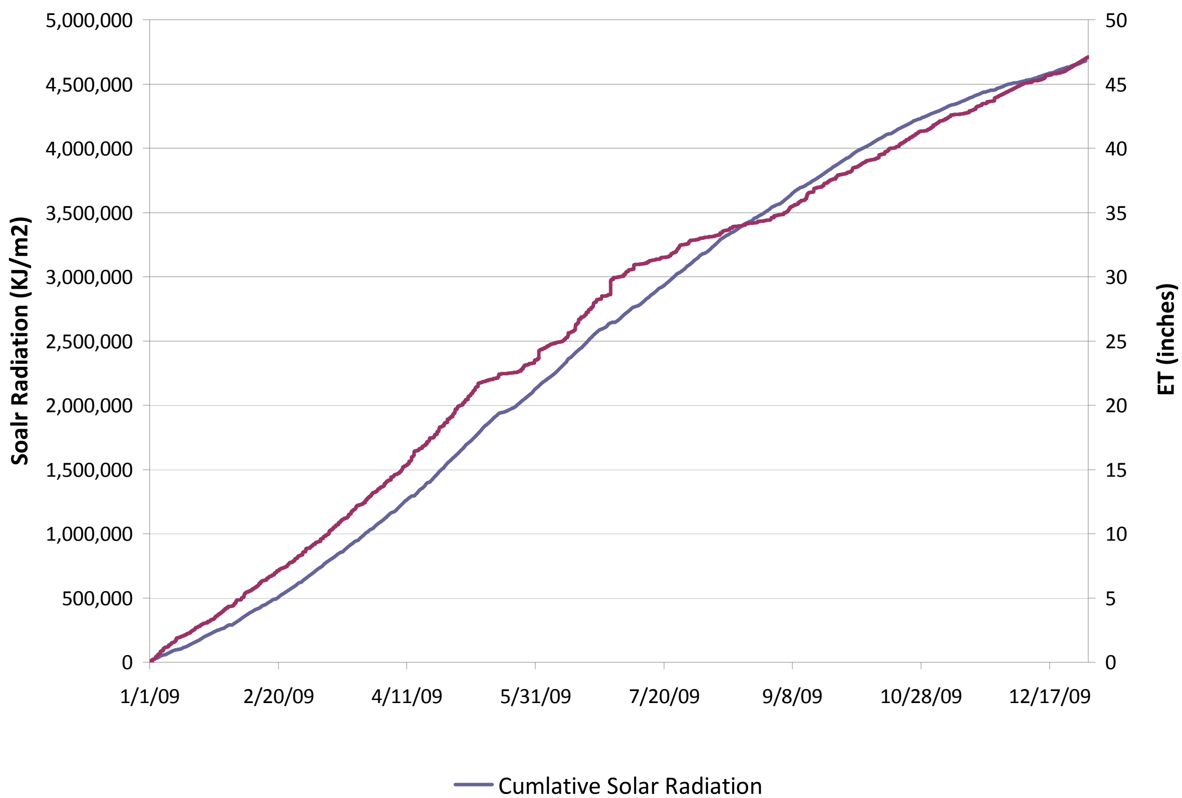

Figure 13. Cumulative solar radiation and cumulative pan evaporation.

Soil Moisture and Aquifer Water-Level Data

Soil moisture sensors and water-table monitor wells are installed at six sites along a down-sloping transect labeled ECO-1 through ECO-6. Sites ECO-1 and ECO-4 also have paired Floridan aquifer monitor wells labeled FL-1 and FL-2 respectively (Figure 14).

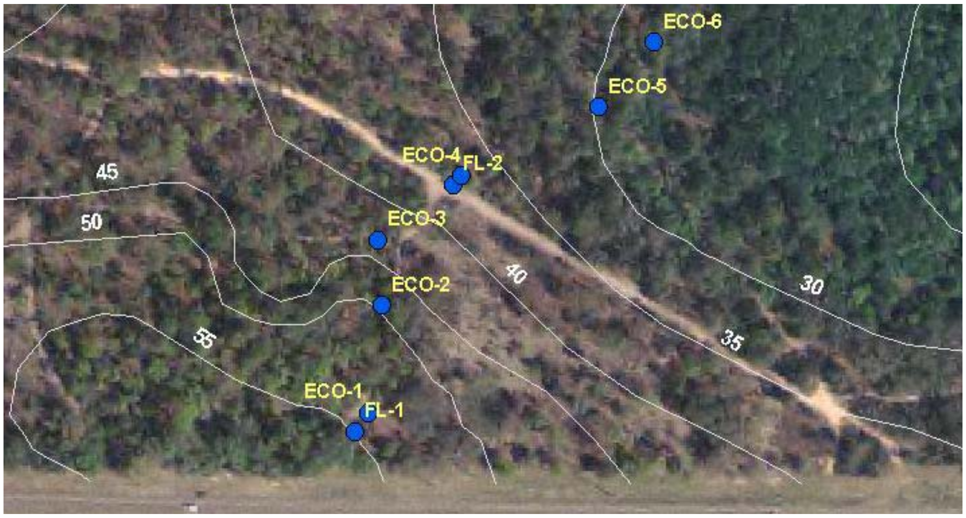

Figure 14. Soil moisture and aquifer monitoring sites.

The USF ECO site exhibits a hillslope convex to concave profile typical of the high-slope, sandy remnant dune feature ridge environments of the coastal plain fringe typified in west-central Florida. Similar environments in the SWFWMD domain include the Pinellas (Lake Tarpon), Brooksville, Brandon and Lakeland Ridge settings. The topographic elevation ranges from 51 feet at ECO-1 to 24 feet at ECO-6. Site ECO-3 is at the base of a hill at an elevation of 37 feet. Down gradient of ECO-3 the slope transitions to a flatter flood-plain type slope (Figure 15). During the wet summer period, the water table reaches land surface at ECO-6. Figures 16-21 are photographs of the monitoring sites.

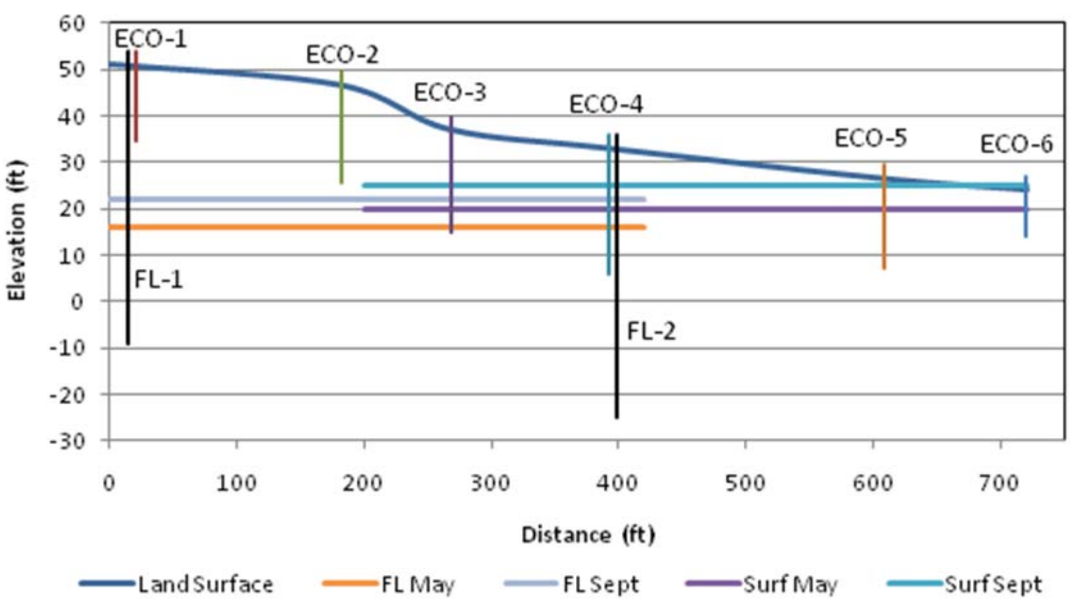

Figure 15. Hillslope profile of data collection sites.

Figure 16. Eco-1 Soil moisture sensor and data logger box.

Figure 17. ECO-2 Soil moisture sensor, data logger box and well (next to stake).

Figure 18. ECO-3 near tree at center of photo.

Figure 19. ECO-4 site. Soil moisture sensor is under the red cup. Flashing was installed around the moisture sensor to prevent overland flow from pooling around the sensor.

Figure 20. ECO-5.

Figure 21. ECO-6.

Soil Moisture Data

Soil moisture probes were installed at sites ECO-1 through ECO-6. Each probe has eight moisture sensors at depths below the land surface of 10 cm to 190 cm, except at ECO-6. Site ECO-6 is in a high water-table environment and the deepest moisture sensor at that site is 140 cm. There was one period of equipment failure during the year at ECO-1 and ECO-2. The failures at both sites were related to problems with the communications board and the boards were subsequently replaced. There were also anomalous measurements for 2/3 of the first quarter at ECO-4 that were resolved by replacing moisture sensors.

Figures 22 through 27 show the observations of hourly average soil moisture through time at each station. Rainfall is displayed on the top axis to allow correlation with changes in soil moisture content. All sensors are seen to show rapid fluctuations from rainfall events followed by more subtle recession periods. Stations in the deep water-table environment (i.e., ECO-1-3) exhibit lower moisture contents generally with no observations of complete column saturation. In contrast, the shallow water table stations, ECO-4-6, exhibit moisture contents consistent with water table observations near land surface with pronounced periods of partial to full column saturation.

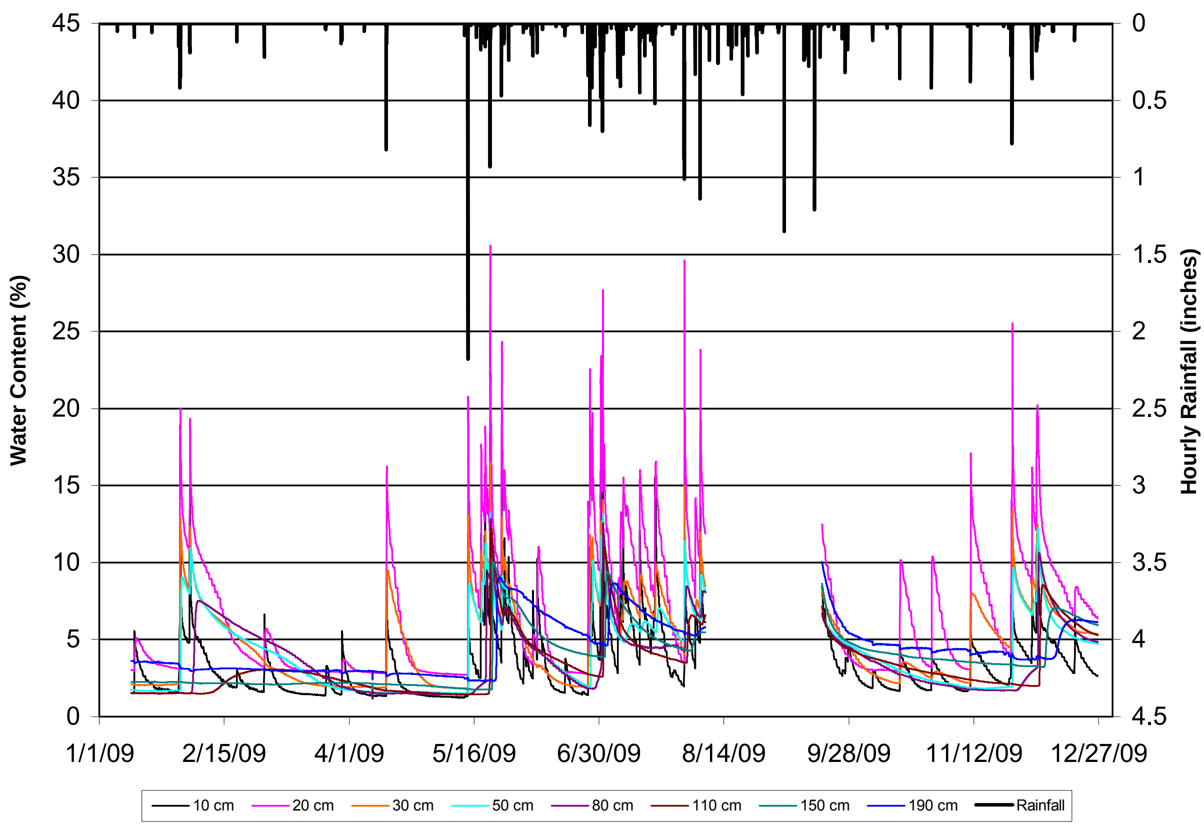

Figure 22. Average hourly soil moisture data from ECO-1.

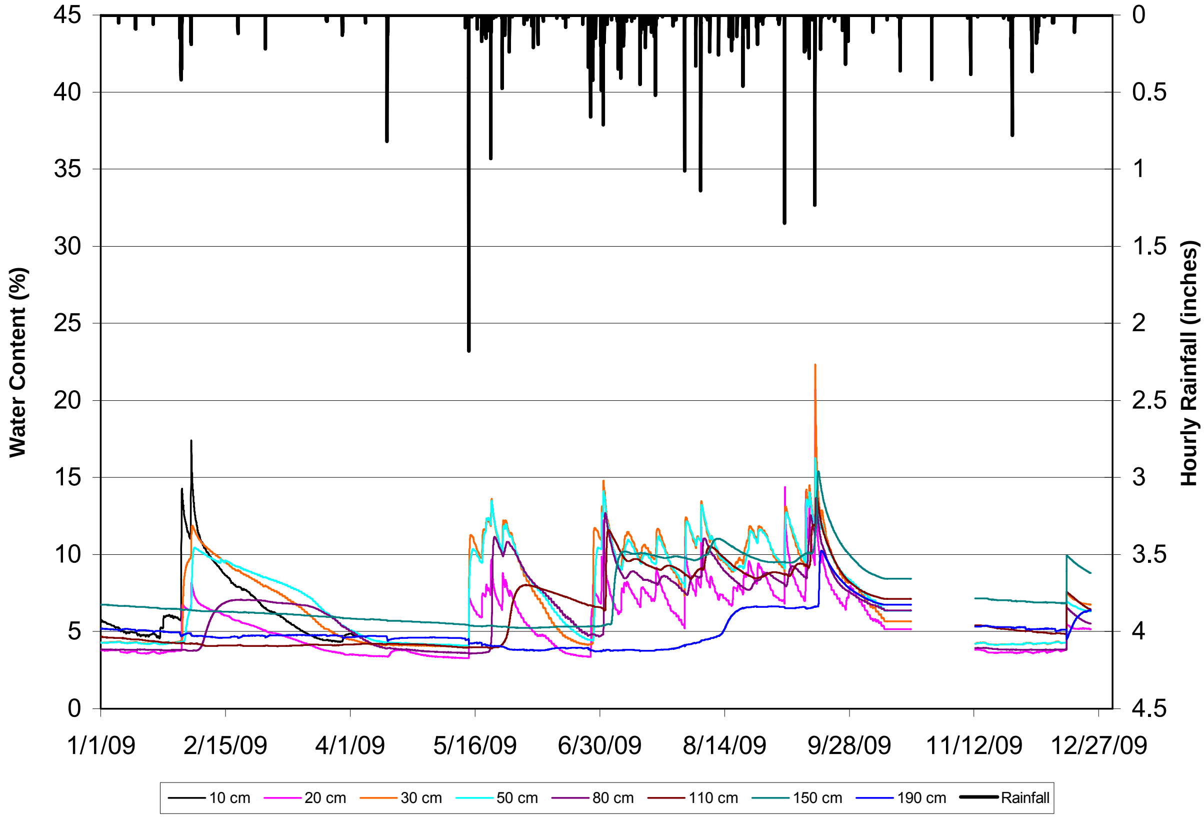

Figure 23. Average hourly soil moisture data from ECO-2.

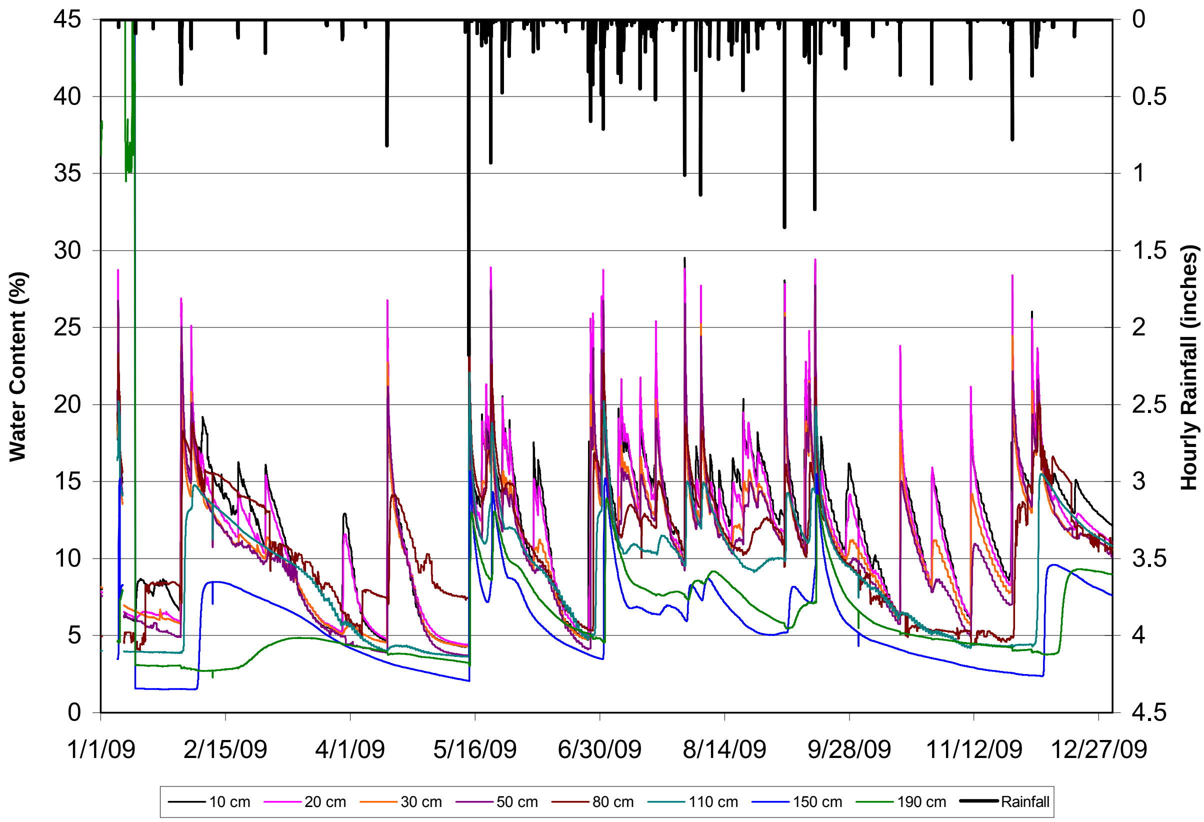

Figure 24. Average hourly soil moisture data from ECO-3.

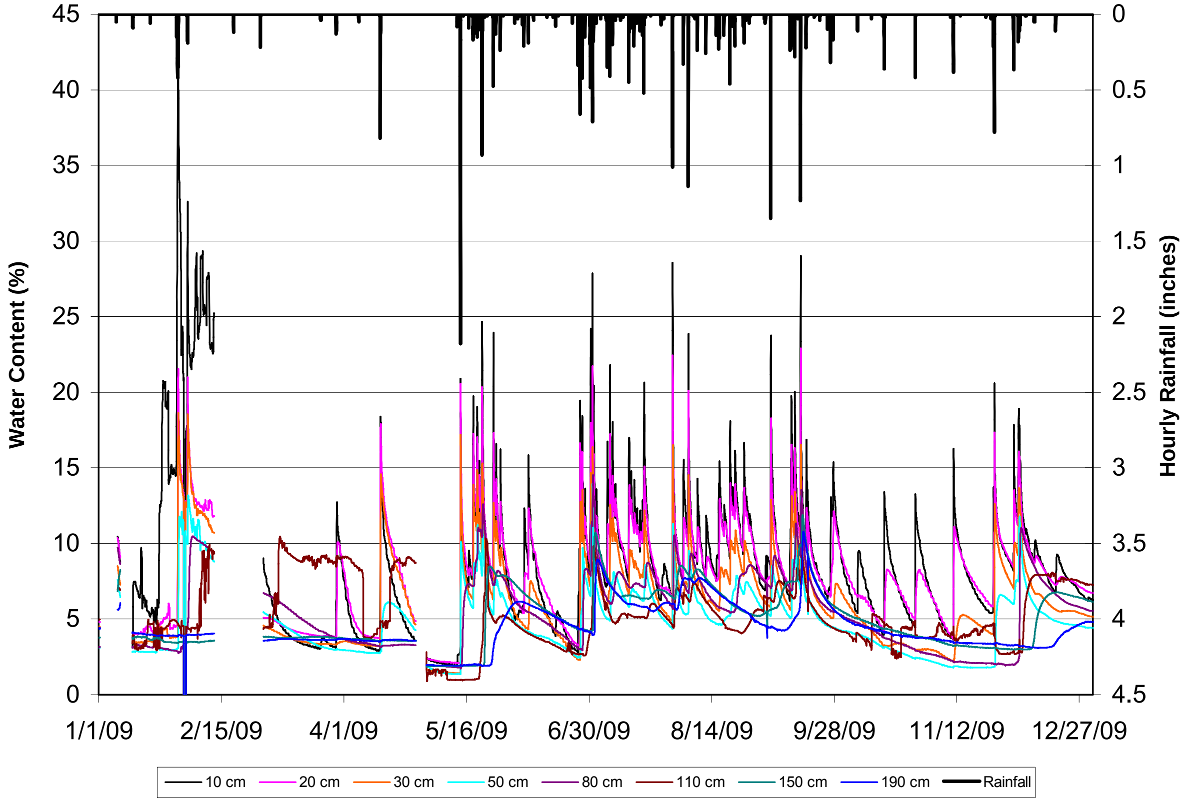

Figure 25. Average hourly soil moisture data at ECO-4.

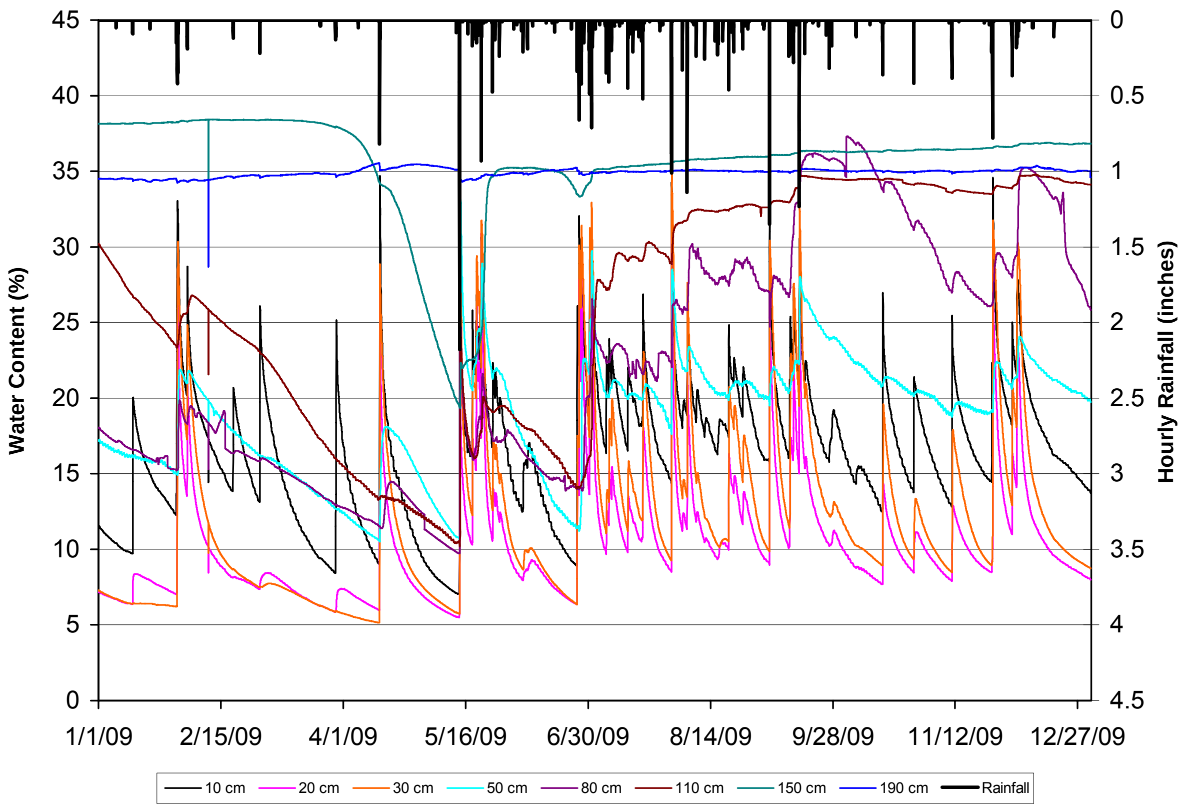

Figure 26. Average hourly soil moisture data at ECO-5.

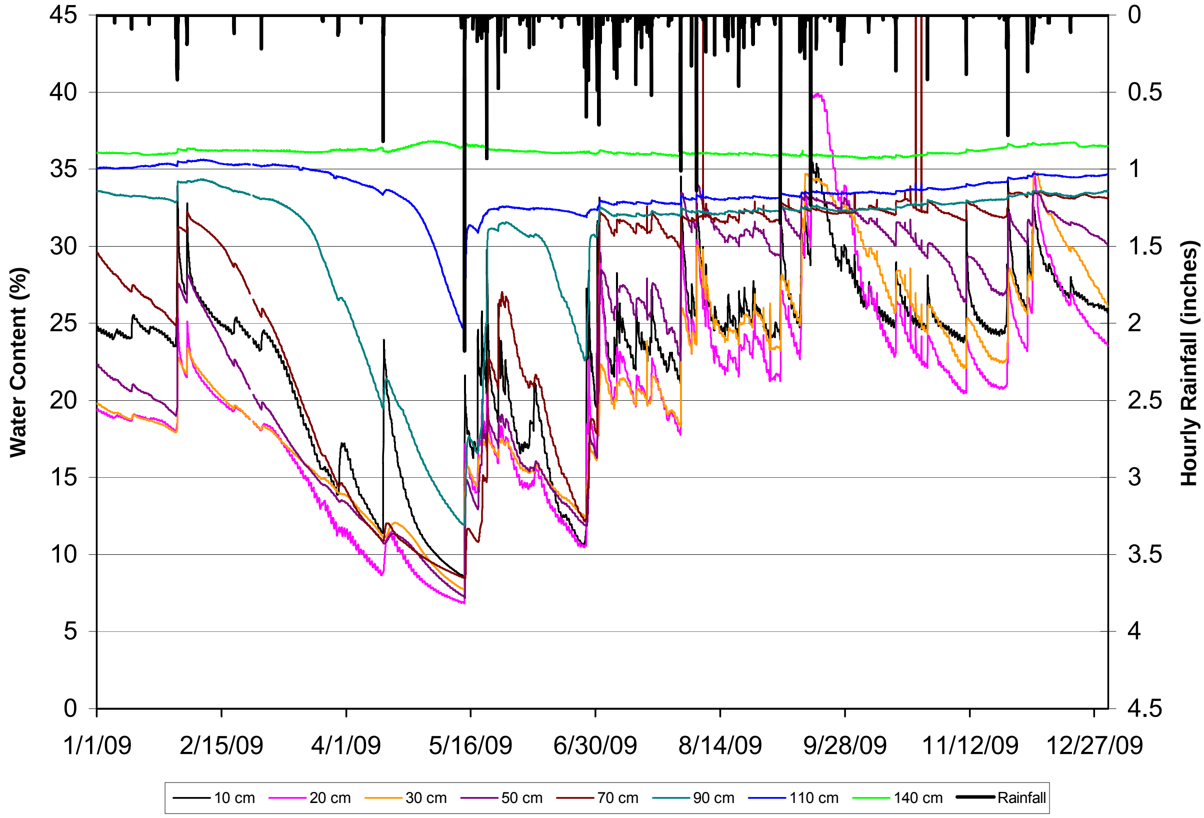

Figure 27. Average hourly soil moisture data at ECO-6.

Total Soil Moisture (TSM)

The vertically displaced soil moisture observations can be integrated over the displacement depth to obtain a direct measurement of total soil moisture (TSM) over the observation depth (2m). In this manner, the units for TSM become inches or cm (volume per unit surface area). Since soil moisture observations are made every 10 minutes, the resultant TSM can be resolved to this same interval. However, the propagation of the wetting front, possibly through macro-pores, during a rainfall infiltration event can result in TSM(t) results that are spuriously noisy during the early stages of the wetting front evolution. Therefore, typically TSM is resolved no more frequent than hourly using hourly averaged soil moisture measurements. In this manner TSM(t) was resolved hourly for the entire 2007 observation period. Results are plotted in Figures 28 to 33. Rapid fluctuations in TSM are seen consistent with each rainfall period followed by gradually decreasing soil moisture consistent with ET uptake. Resolution of TSM in time can be used to estimate infiltration, recharge and ET fluxes from the soil column in the manner of Rahgozar et al. (2005).

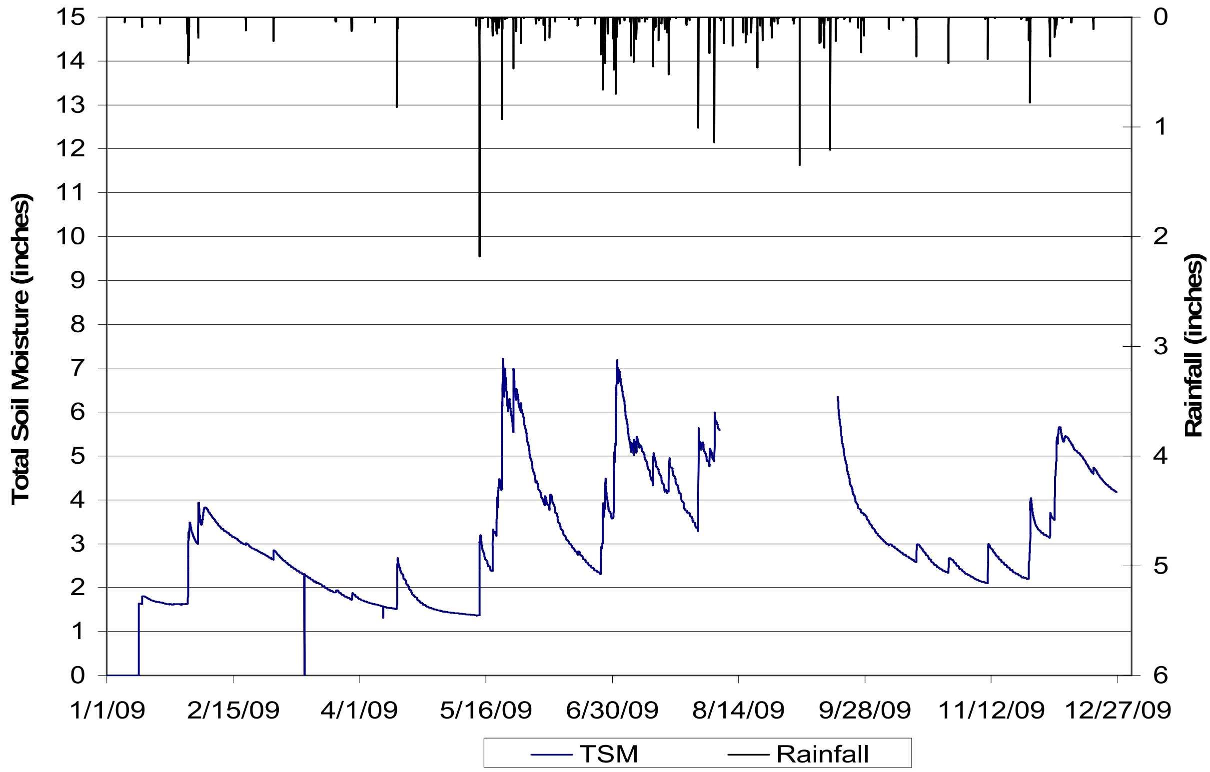

Figure 28. Total soil moisture and rainfall at ECO-1.

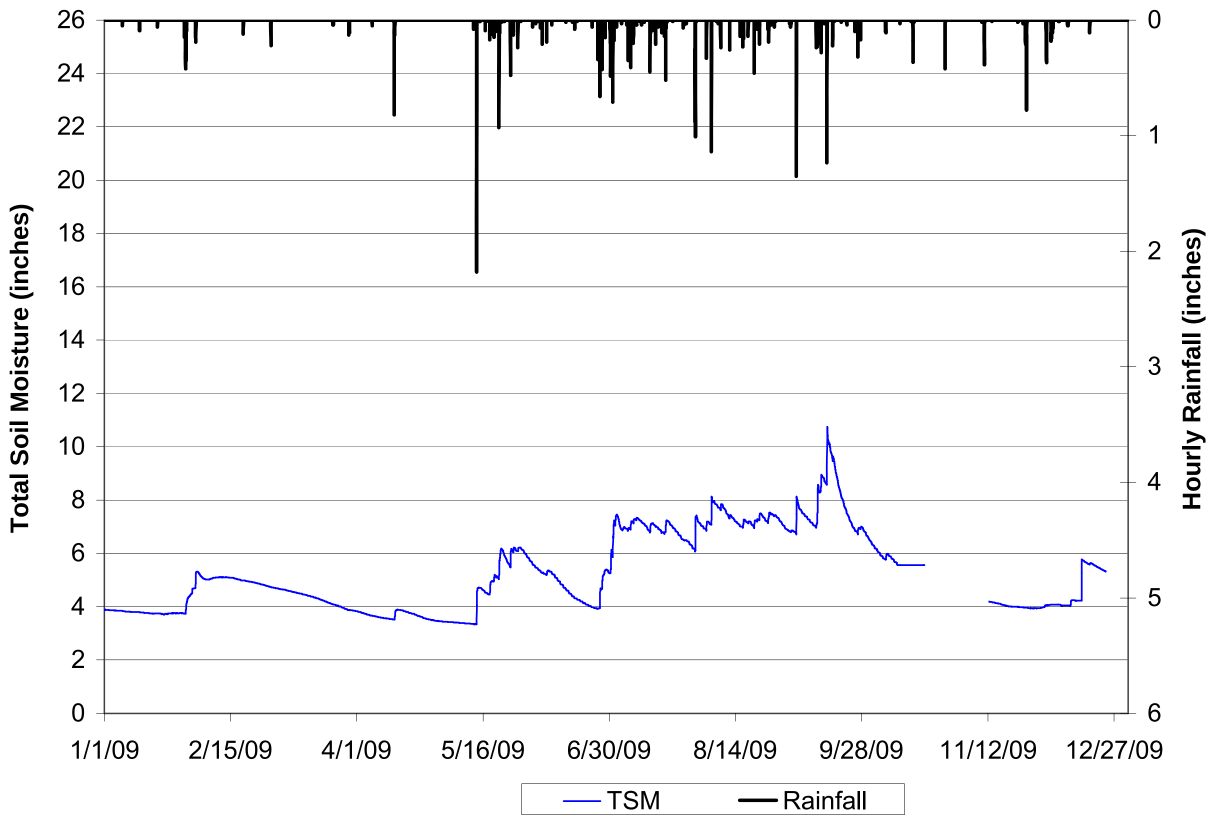

Figure 29. Total soil moisture and rainfall at ECO-2.

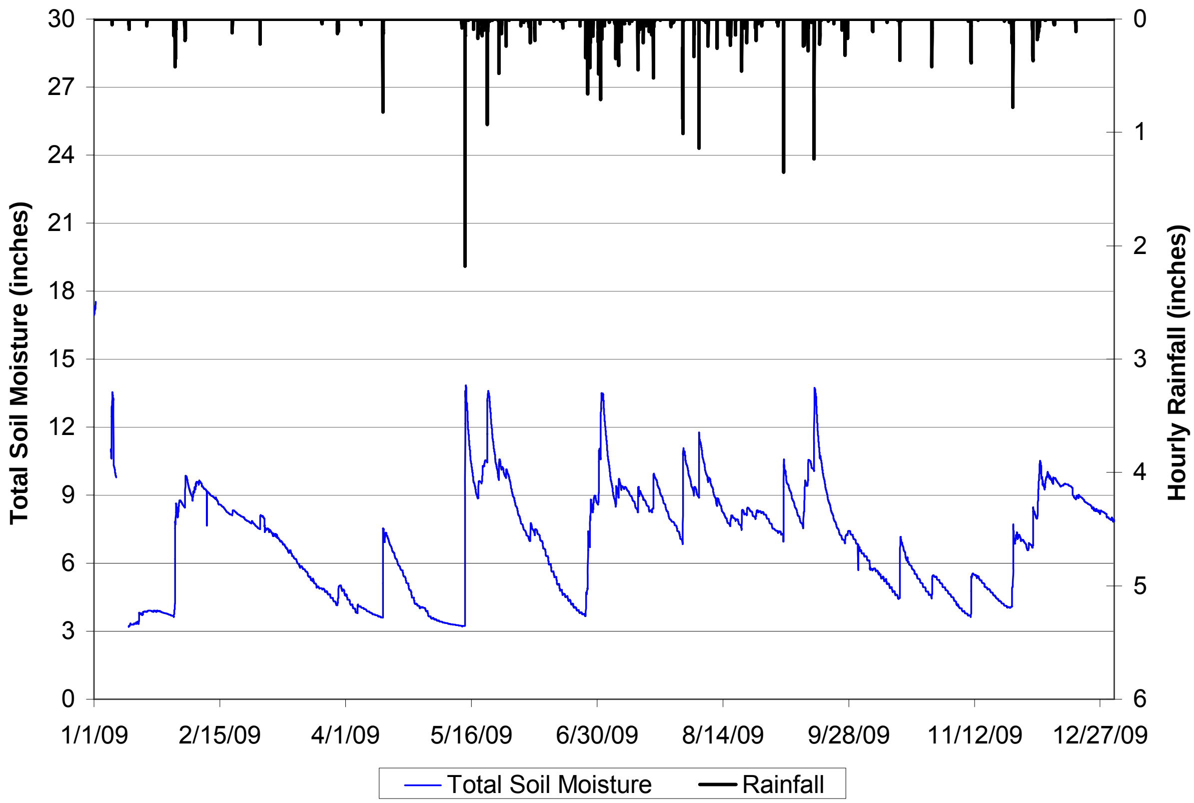

Figure 30. Total soil moisture and rainfall at ECO-3.

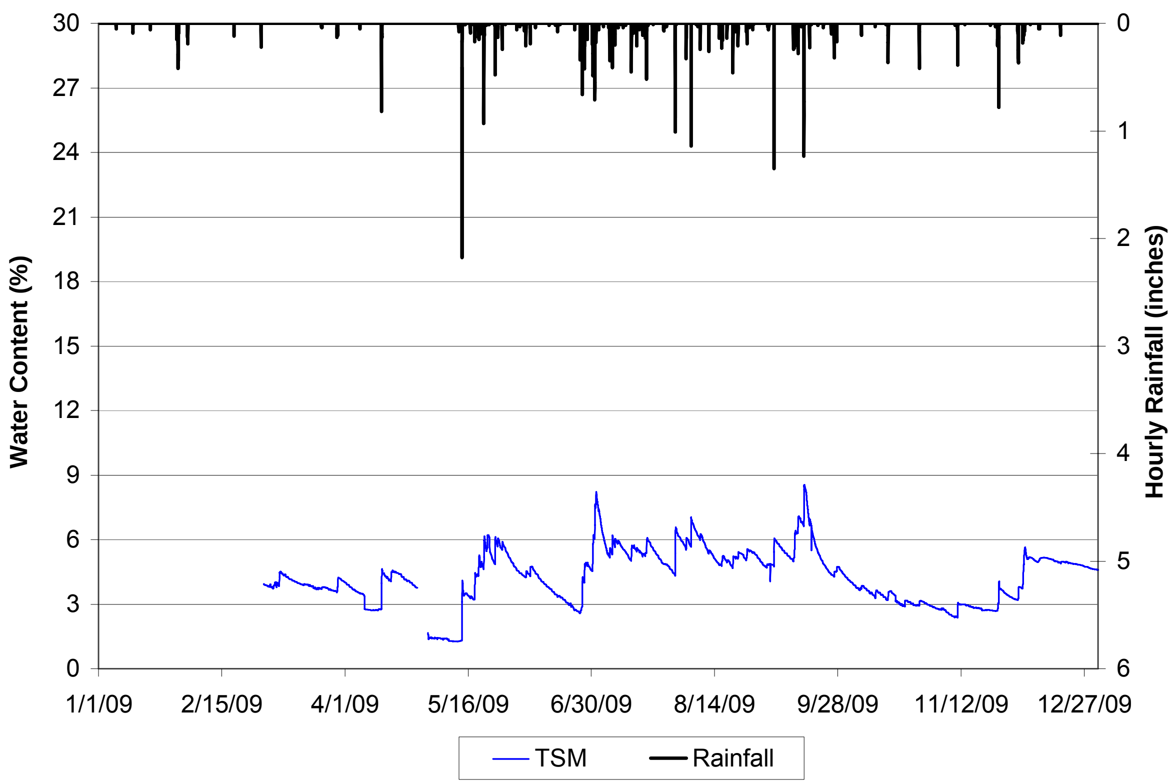

Figure 31. Total soil moisture and rainfall at ECO-4.

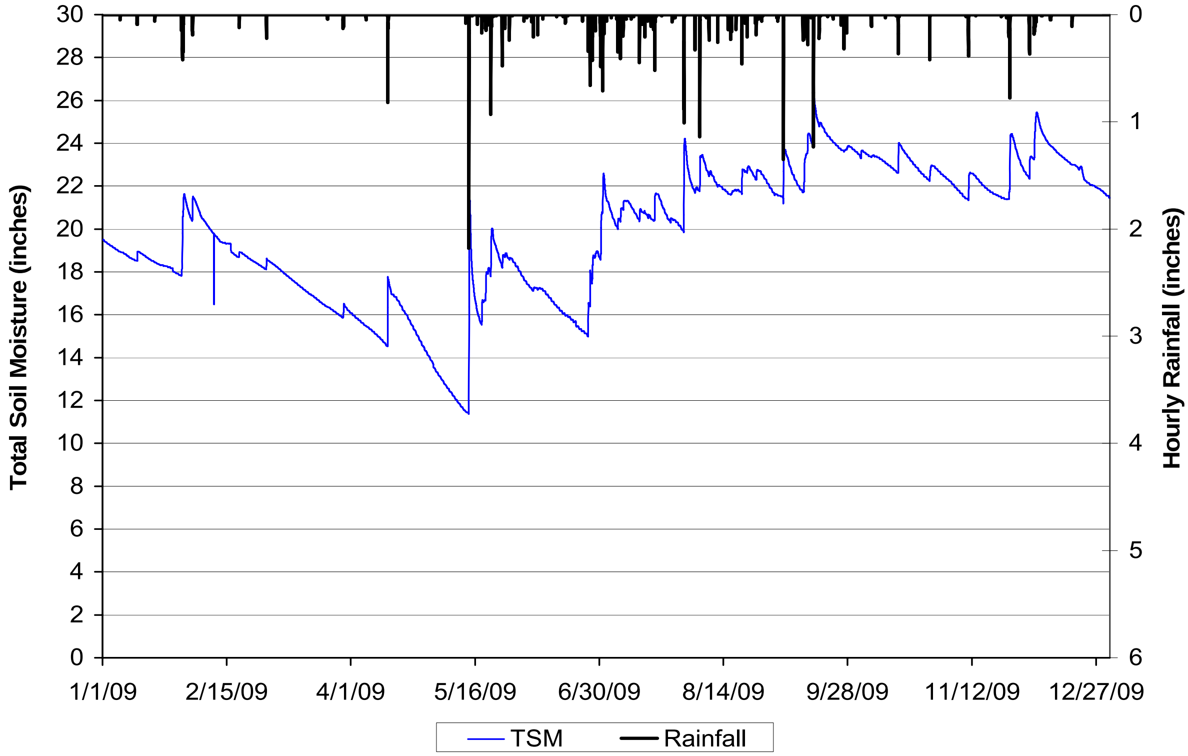

Figure 32. Total soil moisture and rainfall at ECO-5.

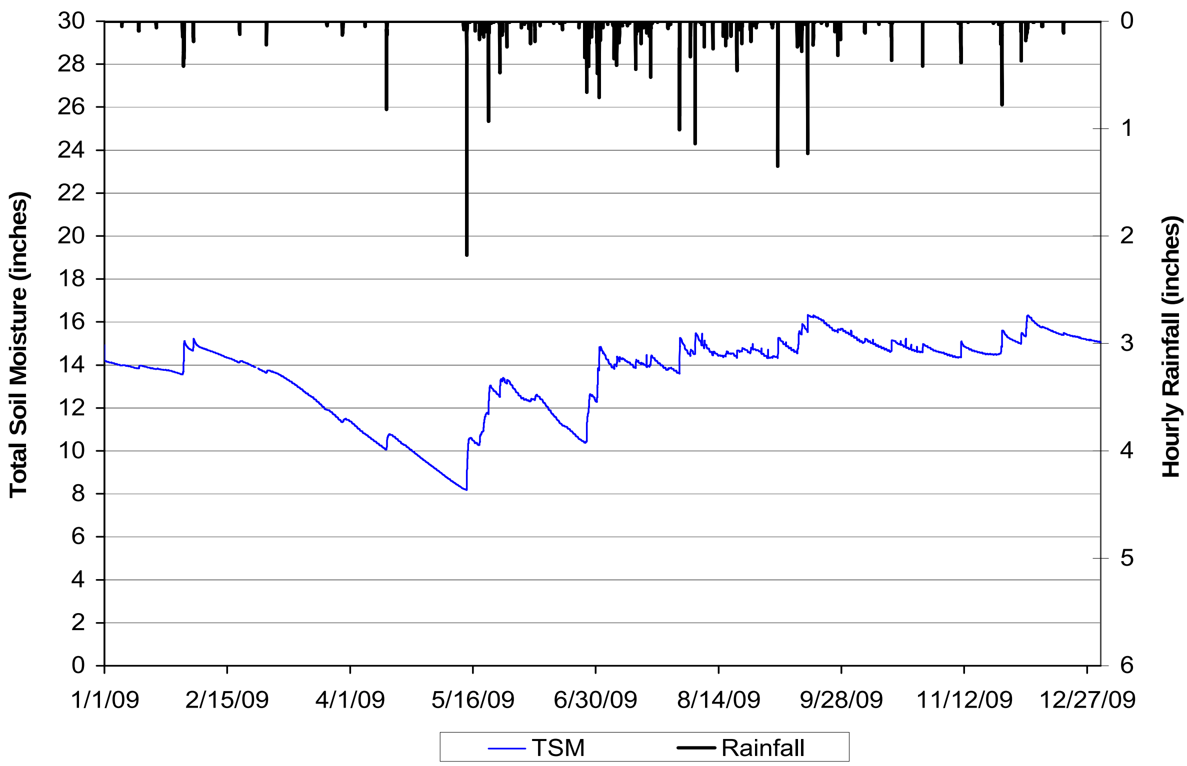

Figure 33. Total soil moisture and rainfall at ECO-6.

Water Table Elevations

Pressure transducers were installed in the monitor wells to record ground water levels. ECO-1 and ECO-2 have been dry since they were installed. Both sites are primarily clay to the Floridan Aquifer. The wells with the ECO prefix were intended as surficial aquifer monitor wells; they were installed to the first competent clay unit or, in the case of ECO-4, to rock as no clay was encountered. The wells with the FL prefix were installed into the first competent limestone unit which is the Upper Floridan Aquifer. Initially, one Floridan well (FL-2) was installed near ECO-4 to provide head gradient information between the surficial and Floridan aquifers. A second Floridan well (FL-1) was then installed near ECO-1. All the wells except FL-1 have been surveyed and their water levels corrected to NGVD. Figures 34-39 display the continuously recorded water-level elevations (blue line), manual measurements (red box) and cumulative rainfall (pink line) for each of the wells.

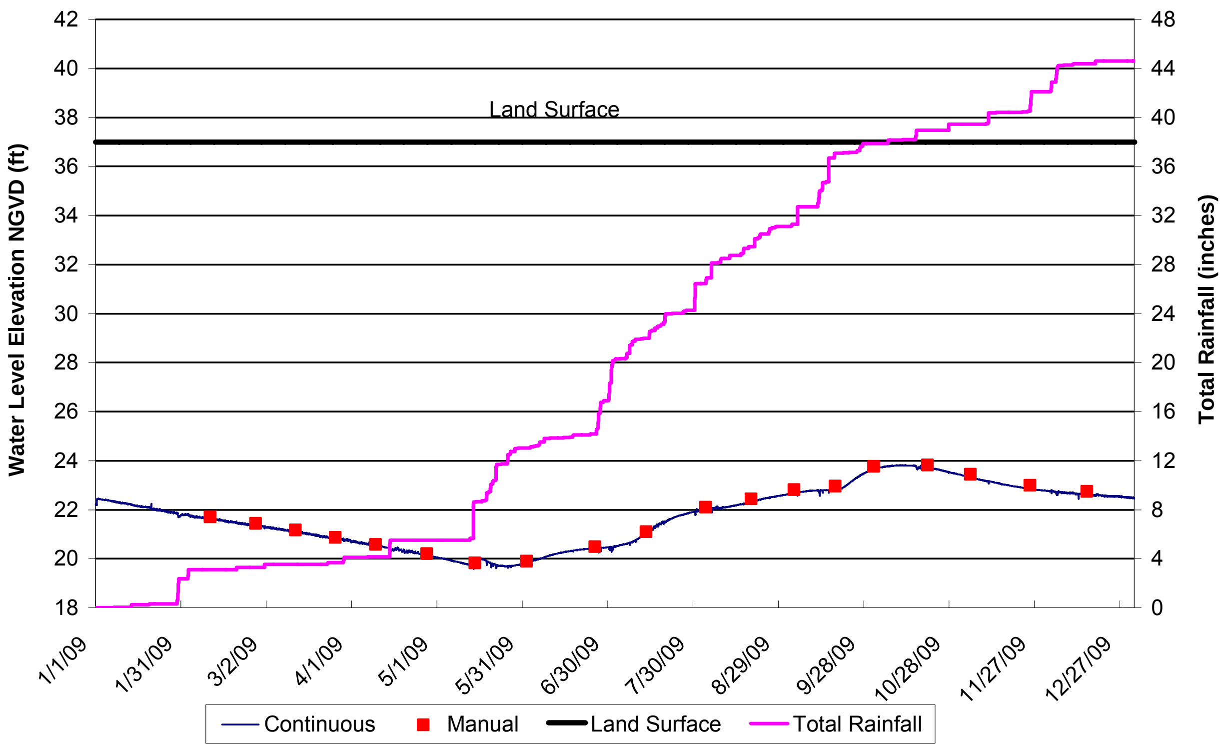

Figure 34. Continuous water-table measurements at ECO-3 with manual measurements and total rainfall.

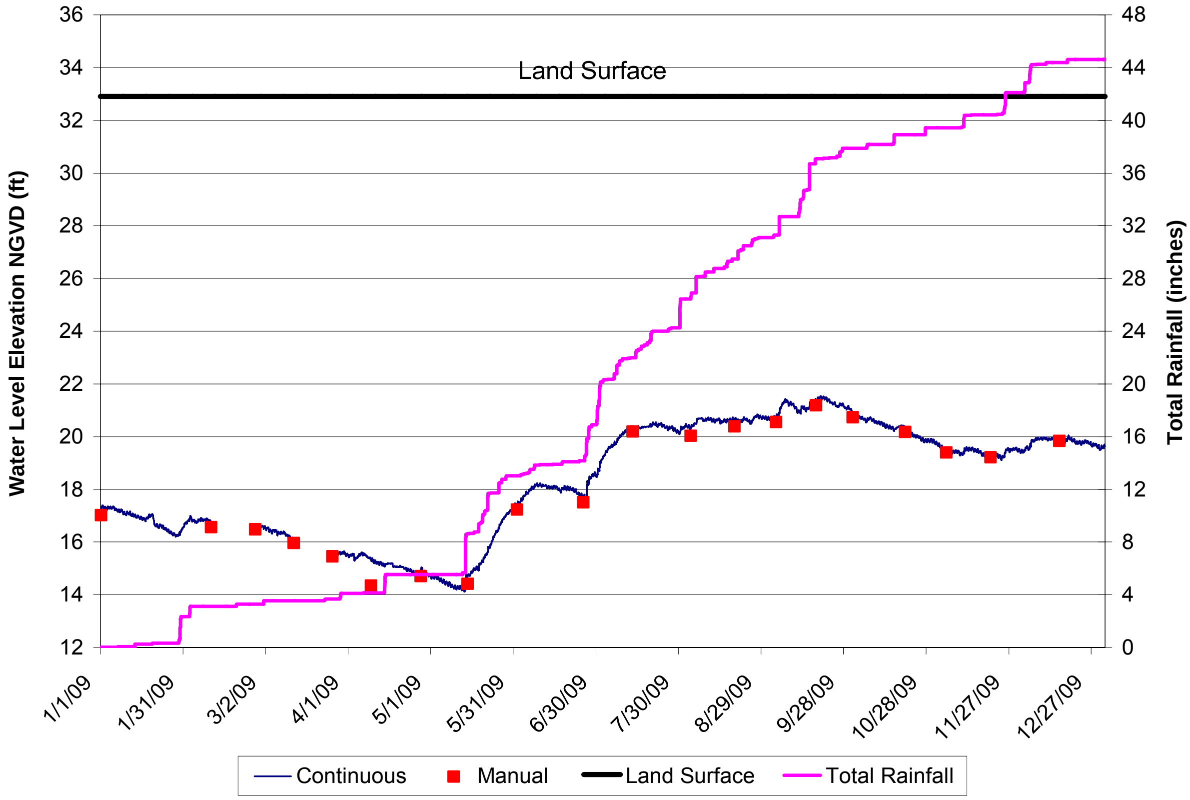

Figure 35. Continuous water-table measurements at ECO-4 with manual measurements and total rainfall.

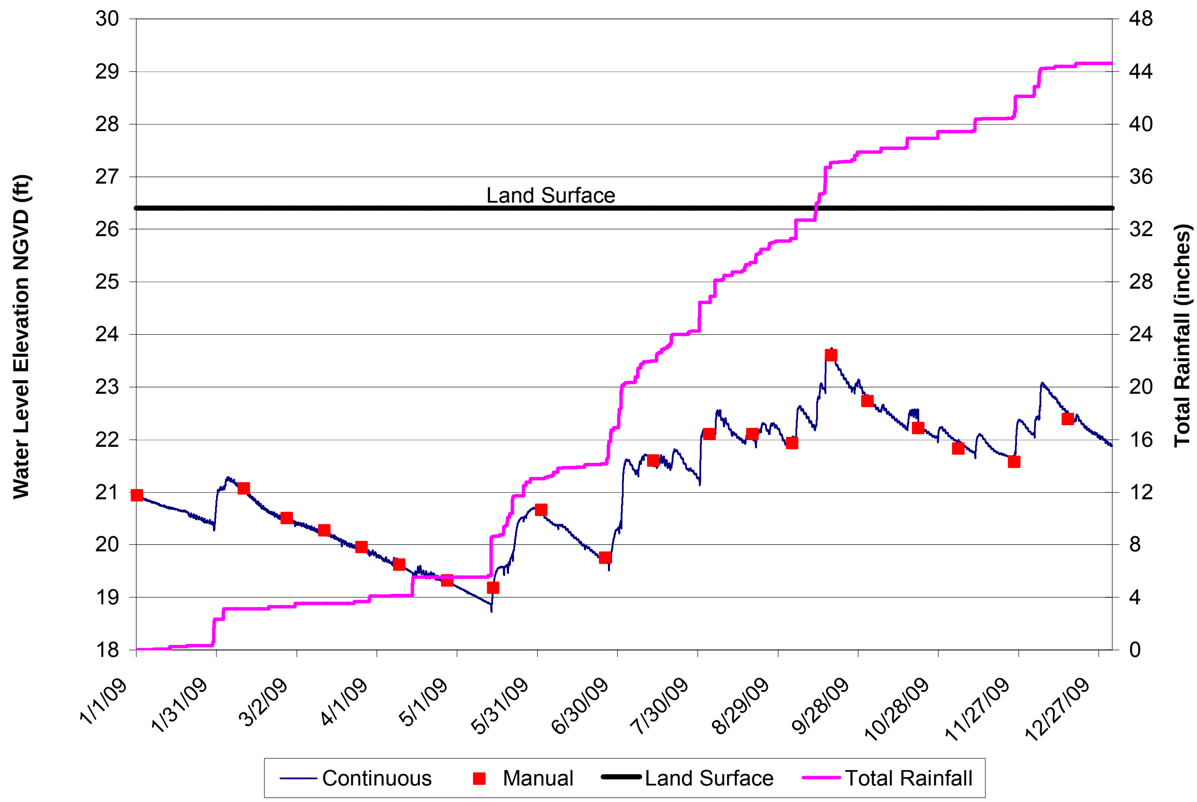

Figure 36. Continuous water-table measurements at ECO-5 with manual measurements and total rainfall.

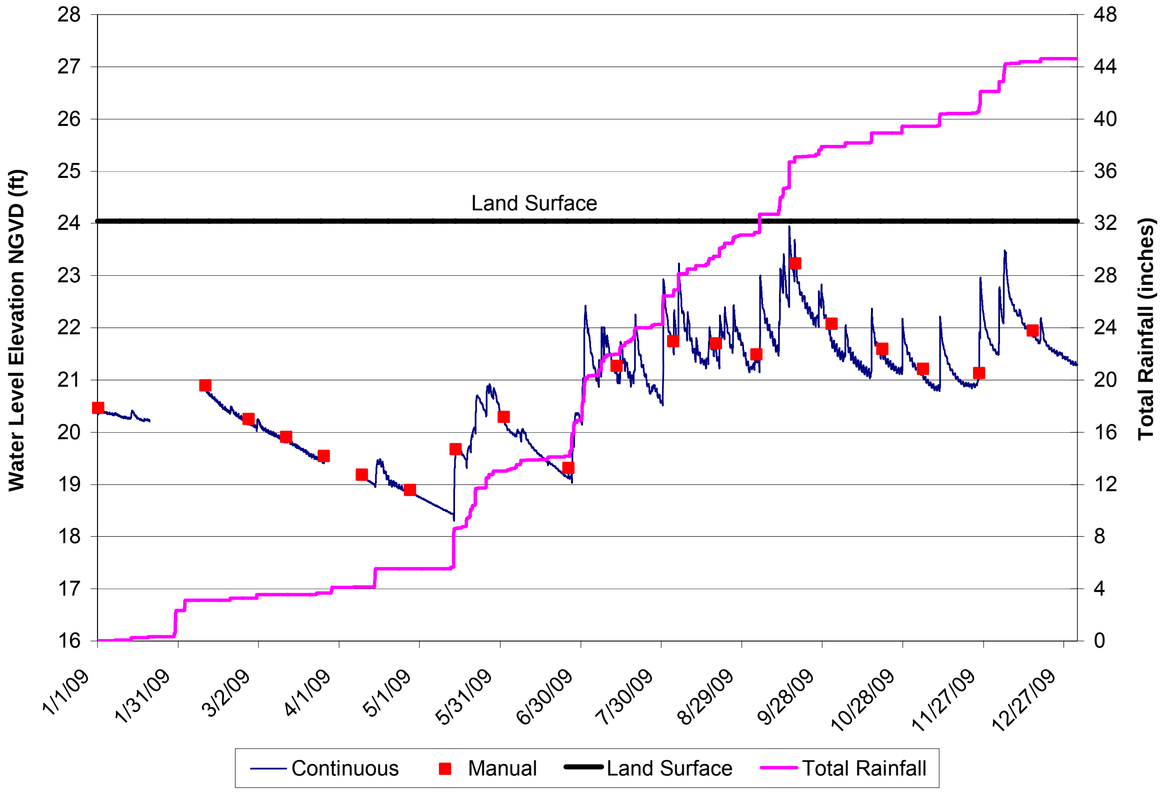

Figure 37. Continuous water-table measurements at ECO-6 with manual measurements and total rainfall.

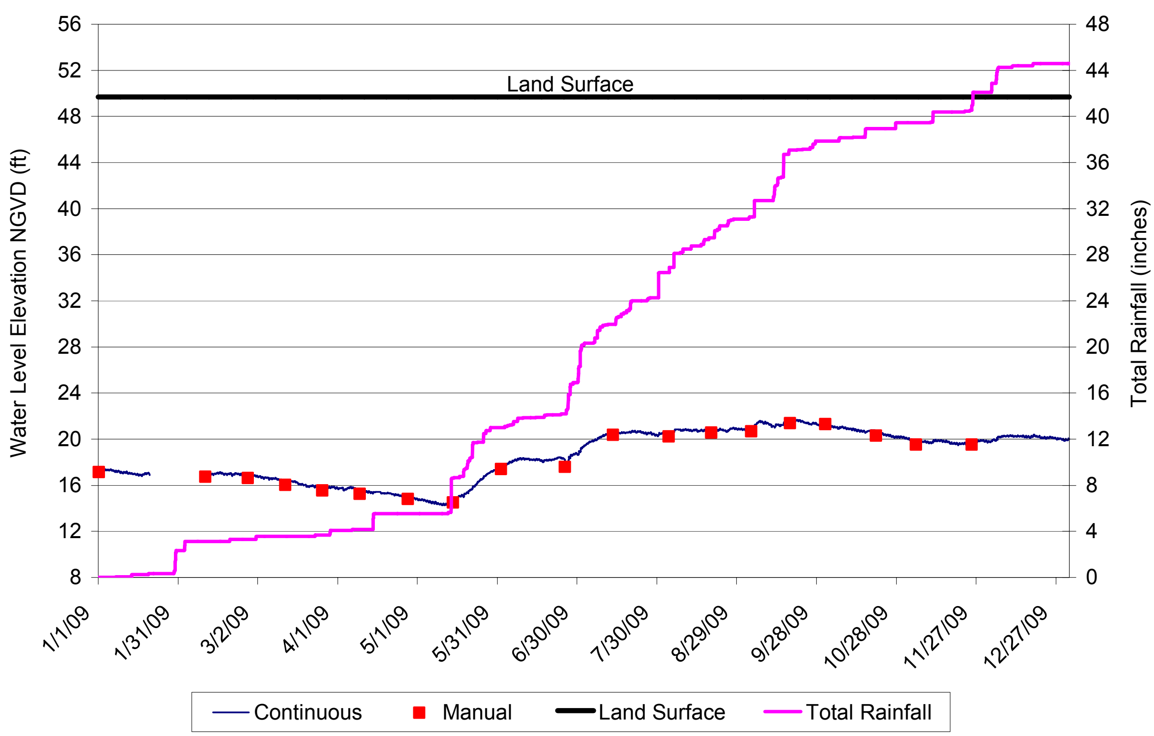

Figure 38. Continuous approximate Floridan Aquifer water levels at FL-01 with manual measurements and total rainfall.

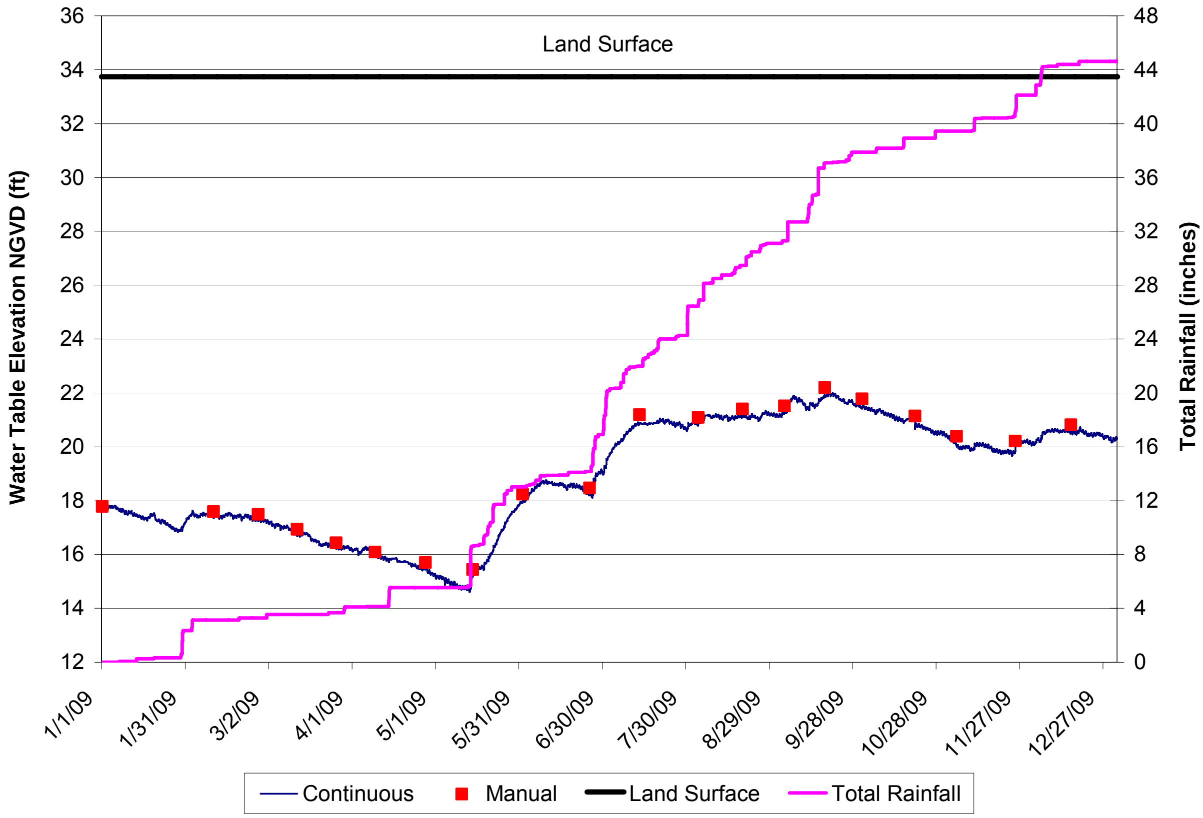

Figure 39. Continuous water-table measurements at FL-02 with manual measurements and total rainfall.

ECO-4 was installed as a water-table monitor well. However, no significant clay unit was penetrated. The well was ended at 27 feet below land surface when rock was encountered. The well was screened from 17-27 feet below land surface (bls).

Approximately 18 feet from ECO-4, a Floridan Aquifer well was installed, FL-2. FL-2 passed through two significant clay units, one between 22 and 32 feet bls and the other between 37 and 44 feet bls. Several smaller clay layers or lenses were encountered between the two thickest clay units. Rock was encountered at 44 feet bls. The well was continued for an additional 20 feet through the limestone to a total depth of 64 feet. A 15-foot well screen was installed in the well, but the bottom six feet of the well was lost when the auger flight was extracted and the well casing pulled up. The final depth of the screen is from 43 to 58 feet bls.

Although ECO-4 is only 27 feet deep while FL-1 and FL-2 are 60 and 58 feet deep and finished in limestone, the water elevations in all three wells match. Figure 40 illustrates the correspondence between the water elevations in the three wells. All three wells reflect water elevations in the Floridan Aquifer. The downward spikes on the graph represent times that the well transducer was removed to download data.

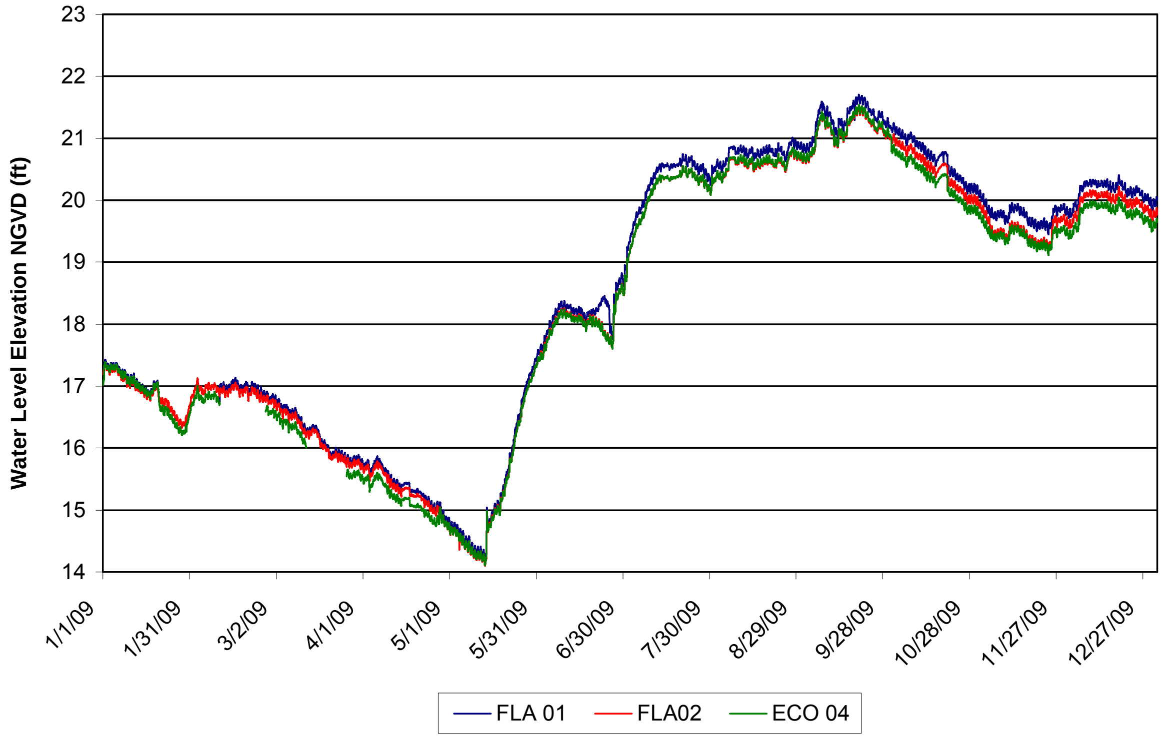

Figure 40. Water elevation comparison between FL-1, FL-2 and ECO-4.

A second well was manually installed at the ECO-6 location to a depth of approximately four feet. This well is screened for its entire length below the ground surface. Because air entrapment and compression is believed to play a role in the rapid water-table response to rainfall events, this second well provides a water-table comparison to the partially screened initial well. A water-table response in the cased well that is not present in the fully-screened well may indicate a water-table change due to air pressurization. Figure 41 presents the water levels recorded in the two ECO-6 wells for that time period when water levels were measurable in the fully-screened well (the fully-screened well was dry during the time that the line is flat). Air pressurization events are likely present when the response to a given rainfall event at the ECO-6 well is greater than the corresponding response in the fully screened ECO-6 well. During 2009, there were numerous possible air-pressurization events, visible where the pink line exceeds the blue line in response to rainfall events.

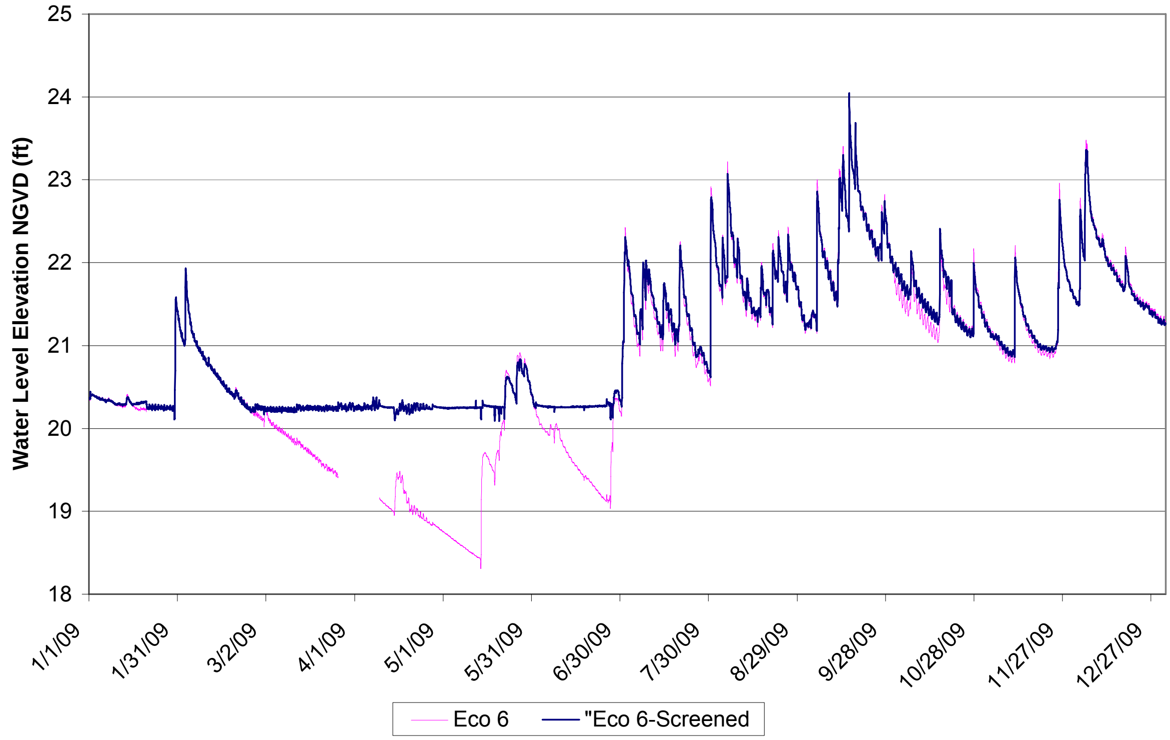

Figure 41. Relative water levels at the ECO-6 wells illustrating possible air pressurization events.

Recharge

Antecedent soil moisture conditions and the depth to the water table play a significant role in aquifer recharge. Figure 42 displays the position of the water table and timing of rainfall events during the dry first quarter of 2009 at ECO-3, a deep water-table environment (depth to the water table varies between 12 and 16 feet). The water table makes a gradual decline through most of the period despite several rainfall events. The largest events, 0.60 inches on January 29th, 1.42 inches on January 30th and 0.78 inches on February 2 for a total rainfall of 2.80 inches over five days had no effect on the rate of decline of the water table. In fact none of the rainfall events made any appreciable change to the rate of the water-table decline. The soil in the vadose zone was sufficiently dry to intercept infiltrating rain water that was not taken up by ET processes, increasing the water content of the vadose zone and preventing recharge from reaching the water table. The total rainfall recorded during this quarter was 4.10 inches and the net decline in the water table was approximately 1.7 feet.

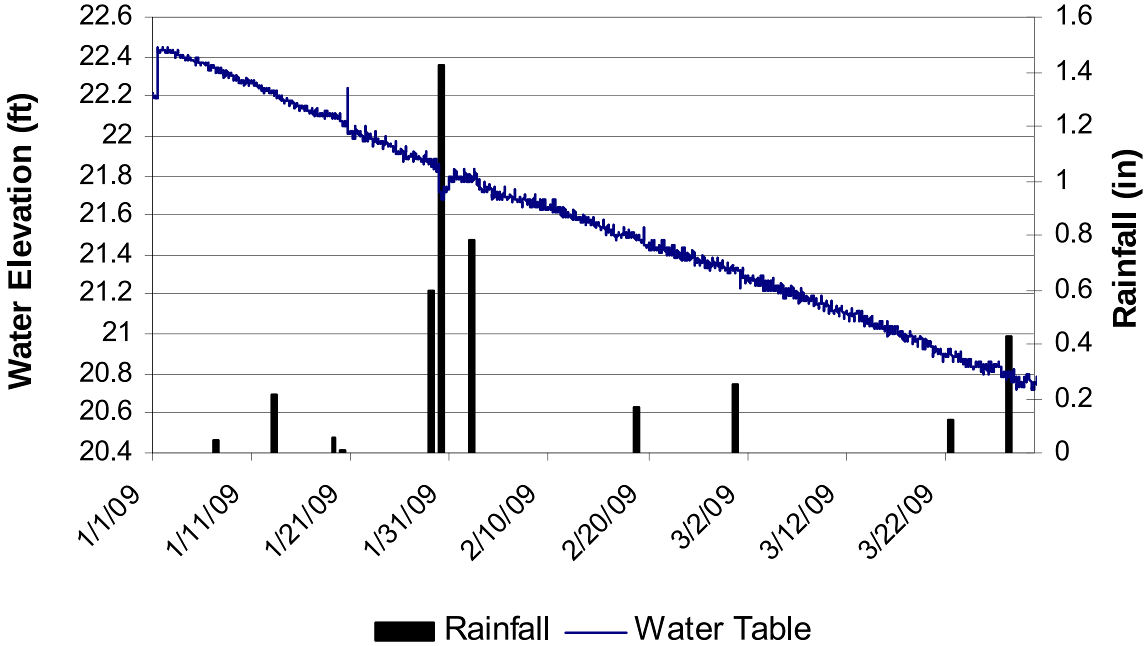

Figure 42. Water-table elevation at ECO-3 and rainfall events during quarter 1.

During the wet summer period from June 1st through August 31st, the water table slope transitioned from declining to increasing (Figure 43). The decline of the water table ceased temporarily following a nearly 3 inch rain event on May 13th. The water table then continued to decline until an additional 4.4 inches of rainfall were added through May 29th. The May rainfall added sufficient moisture to the soil that subsequent 0.25 inch events produced increases in the water table elevation. Between June 1st and June 22nd, 1.08 inches of total rainfall produced an apparent increase in the water-table elevation of 0.6 feet.

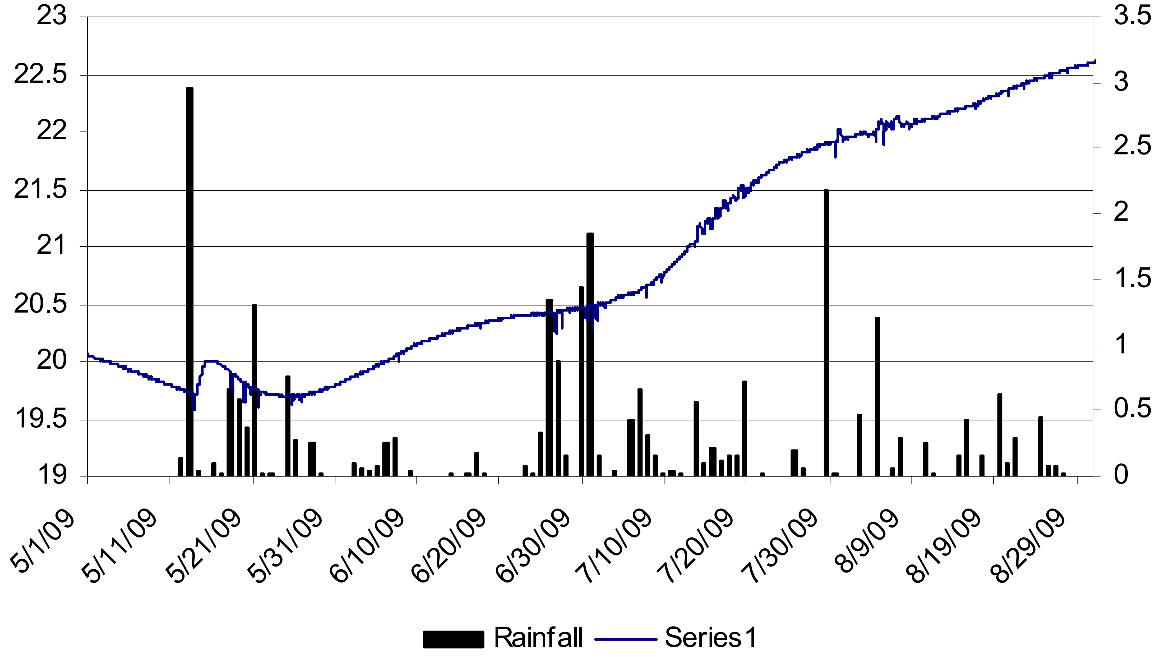

Figure 43. Water-table elevation at ECO-3 and rainfall events during quarter 3. Land surface at ECO-3 is 37 feet.

Increases in the water-table elevation become more difficult to associate with specific rainfall events as the rainfall frequency and the depth to the water table increase. For example, the water table rose from June 10th through June 15th in the absence of almost any rainfall. There is a delay between the time rainfall hits the land surface and the time recharge arrives at the water table. The deeper the water table, the longer the delay.

Figure 44 illustrates this effect. The figure contains the same information as Figure 35 but adds the percent soil moisture content at a depth of 6.25 feet on the same axis as rainfall. Rainfall and soil moisture have different units but the numbers overlap. Land surface elevation at ECO-3 is 37 feet. There appears to be a 2-7 day delay for infiltration to reach the 15-foot deep water table.

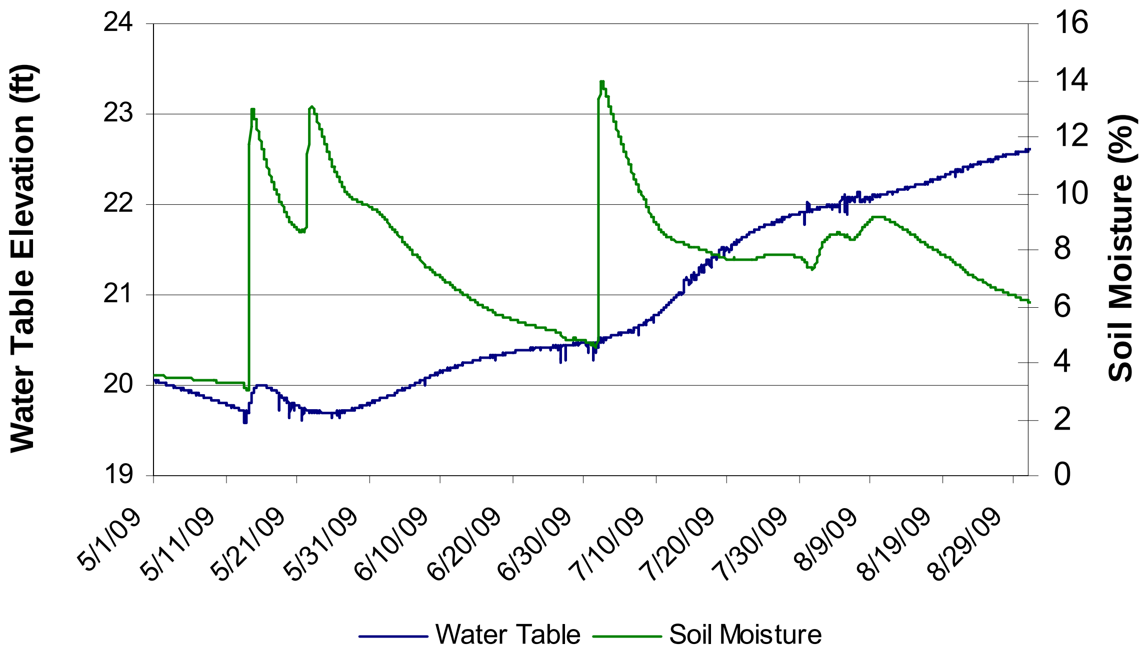

Figure 44. Water-table elevation at ECO-3, rainfall events and percent soil moisture content during quarter 3 Land surface is 37 feet.

In contrast to the relatively deep water table at ECO-3, ECO-6 represents a shallow water-table environment where the position of the water table varies from land surface to five feet below land surface. During the first quarter when the water table at ECO-3 was essentially unaffected by rainfall, the water table at ECO-6 increased immediately at almost every rainfall event (Figure 45). The water-table increases were, however, quickly followed by a water-table decline. Because the water table is deep at ECO-3, most of the plants at ECO-3 can only transpire water from the vadose zone, plants at ECO-6, with the help of the capillary fringe, can transpire water directly from the water table. This plant transpiration offsets the quick response of the water table to rainfall and, for the first quarter, the net result is no change in the water table position from the beginning of the quarter to the end of the quarter despite numerous recharge events. For this quarter, ET matched recharge.

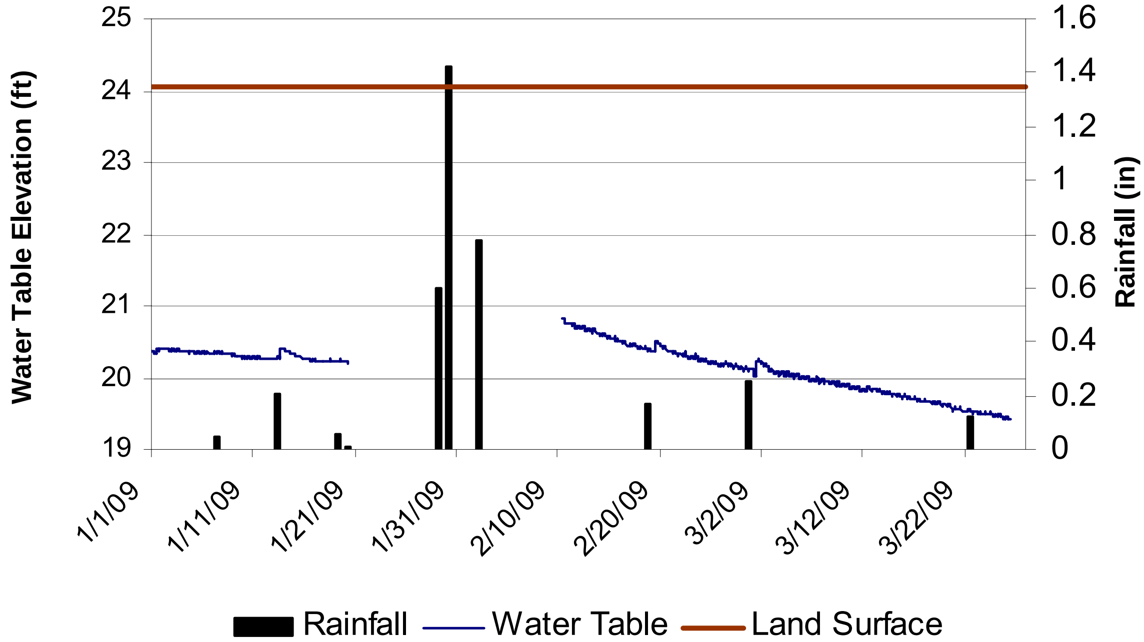

Figure 45. Water-table elevation at ECO-6 and rainfall events during quarter 1.

Figure 46 illustrates the water-table response to rainfall at ECO-6 during the wet summer quarter. As was evident for the first quarter, the water responds rapidly to rainfall events and quickly declines due to ET. During this quarter, however, due to the frequency and intensity of rainfall events, recharge to the water table exceeds ET and the water table rises throughout the quarter.

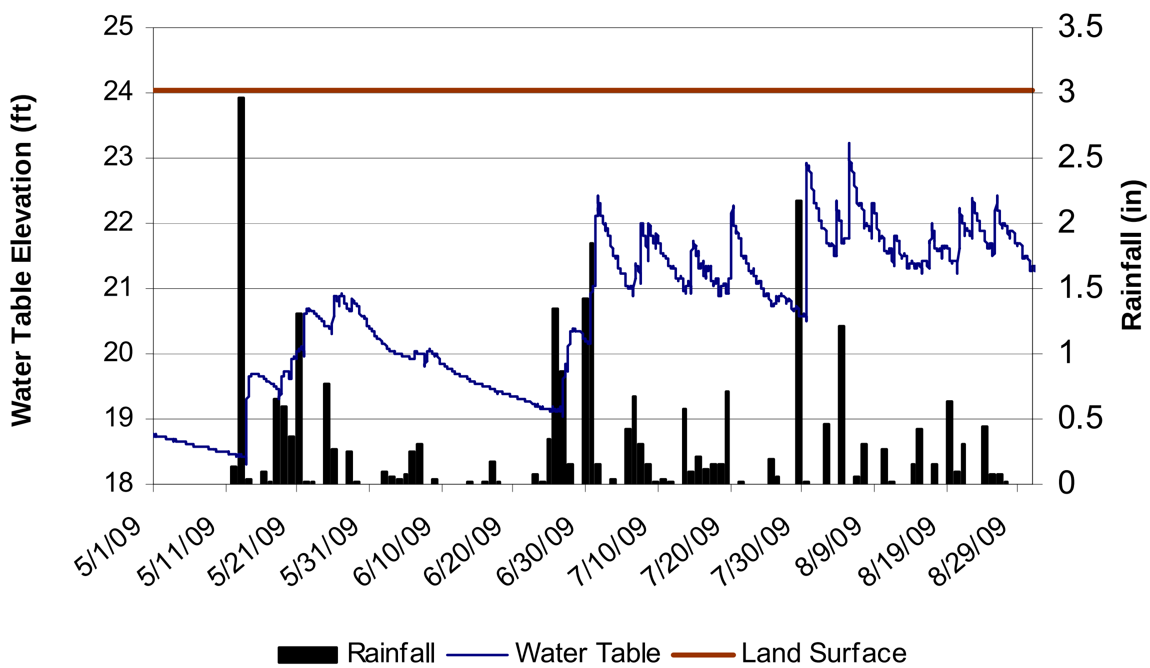

Figure 46. Water-table elevation at ECO-6 and rainfall events during quarter 3.

Eco-area Water Budget Analyses

Soil moisture is monitored continuously at discrete elevations down to 2m depth and recorded as average hourly values. Numerical integration over depth of the measured values yields a time series of total moisture contained in the effective uptake horizon (soil/plant vadose zone). Hourly changes in total soil moisture yield net flux rates of infiltration (increases), and combined ET and deep leakage losses. Considering the time of day and the rapid uptake potential of plants, an estimation method of Trout and Ross (2006) can be utilized to separate the daytime dominated ET flux rate from the vertical leakage. Resultant water budget fluxes of infiltration, rhizosphere (root zone down to 2m) ET uptake, deep leakage and net lateral groundwater flow can be derived for all periods of complete data.

In addition, by comparing smaller event rainfall with net infiltration, especially for dry antecedent conditions, an estimate for the interception capacity for each station can be derived in the manner of Rahgozar et al. (2005). Interception capacity is hereby defined as the maximum storage associated with surface wetting (initial abstraction of rainfall) that does not show in soil moisture monitoring. Rainfall events greater than interception capture contribute to net infiltration, runoff and recharge. Interception capture storage then forms the priority ET support in the post-rainfall period.

Figure 47 is an example of the derivation of the 0.15” interception capacity value for Station ECO-3. From these derived interception capacity values, an estimate of the annual interception ET budget can be found using the annual rainfall time series considering inter-event dry periods.

Figures 48 to 53 are graphs of cumulative water budget results from integrated soil moisture differences for each of the transect monitoring stations ECO-1 through ECO-6, respectively. Included in the graphs are rainfall, total soil moisture (TSM), lateral groundwater (GW) support, gross infiltration, soil zone evapotranspiration (ET), vertical flow (deep recharge), interception ET, and total ET. The 45” of accumulated rainfall (red lines in the figures) for the period (calendar year 2009) was dryer than normal but roughly starts and ends in similar antecedent moisture condition indicated by the starting and ending TSM values (grey lines in the figures). Instrument failure and other data gaps are indicated as discontinuous periods in the lines.

Integrated Soil Moisture Water Budget Methodology

Soil moisture sensors are generally placed at 10, 20, 30, 50, 80, 110, 150, and 190 cm depth at each station. Each of the eight sensors determines the soil water content present in the surrounding soil over a range +/- 5 cm. The sensor’s observed values are taken every ten minutes and then averaged over every hour. This averaged water content is then converted to inches of water present within the surrounding soil. From this total soil moisture (TSM) value, the differences between successive hourly values are used to determine either a net increase or net decrease in the soil moisture surrounding the column. From these hourly fluctuations, positive changes in TSM are indicative of either infiltration if in the presence of a rain event, or groundwater support if in the absence of a rain event. Conversely, negative changes in TSM are indicative of groundwater evapotranspiration (GWET), vertical processes, or a combination thereof.

Due to the time it takes a rain event to infiltrate through the soil column, it was determined that large increases in TSM are observed on average four hours following a rain event less than 0.25 inches (small event) and 12 hours following a rain event greater than 0.25 inches (large event). Because of this, these four and 12 hour periods following rain events are used to calculate infiltration and those hourly changes outside of these time frames are used to calculate vertical processes and ET.

The first step in determining the water budget, is establishing an estimate of the vertical processes which are present at all times of the day. For this, only the changes in TSM between 12 am and 6 am are used because of the negligible values of ET during this period. In the case in which a rain event is to occur during or around this time frame, the changes observed are ignored. In order to determine this time frame a period of 6 hours is used for small events and a period of 12 hours is used for the larger events. In the event in which rain is present during midnight to 6 am, these changes in TSM are also ignored. The net changes between these six hours are then taken to arrive at a rate which can be said to apply to the entire day. In order to account for days in which no rates are calculated due to rain events, every daily rate is then calculated by averaging the current daily rate, the previous day's rate, and the following day's rate. Furthermore, in order to ensure a smooth transition in these rates, the three day averaged values are then averaged once more over a 24 hour period ranging from a period six hours before and 18 hours after. This final smoothed average is then used for each hour of every day.

In the absence of a rain event, ET and groundwater support values are calculated by taking the difference of the hourly change in TSM and the vertical process rate calculated for the same time step. In a case in which the TSM increases, there is said to be groundwater support either by later flow or an increasing water table. More often occurring during the day however, is a larger net decrease in TSM than the vertical process rate. This difference is used to arrive at the hourly ET values. In order to eliminate large changes in TSM outside a rain event that are said to be caused by pulling the sensors during data collection, a maximum negative change of 0.06 inches and maximum positive change of 0.1 inches are used as thresholds.

For both small and large rain events, a period of four and 12 hours, respectively, are used to determine the net increase in TSM. During a rain event, the TSM at both the beginning and end of the four or 12 hour period is observed. The differences in TSM over these gaps are used to arrive at the total infiltration for a rain event. Moreover, in order to calculate the interception evaporation at each site, an average for the differences between an event's total rain amount and the observed infiltration is determined in order to arrive at an interception capture rate. This rate is then applied to all rain events. For those rain events which are less than this said rate, the total amount of rainfall is thought to be completely intercepted. Conversely, for those rain events larger than this rate, the calculated interception is set to this maximum rate.

Also calculated by the comparing the soil moisture sensor fluxes to that of the water which reaches the sensors directly from rainfall, surface runoff values are determined. In order to derive runoff both flowing into and out of a site, a difference between rainfall, the calculated interception rate, and the corresponding sensor flux is taken. For cases in which rainfall minus the interception capture exceeds the positive soil moisture change, and net flow of runoff leaving the site is calculated. Conversely, for an event where the positive flux in the sensors exceeds that of the rainfall amount minus the interception, a net flow of runoff entering the site is determined. Thereafter, it is possible to compare the runoff leaving and entering nearby sites.

Moreover, for periods in which there are data gaps, a net difference between the TSM for the last collected value and that for the next collected value is taken. This net difference, whether positive or negative, is taken as either infiltration or GWET, respectively. Also summed are any erroneous changes in TSM that are filtered while calculating groundwater support and GWET. Those changes in TSM either more negative than -0.06 inches or more positive than 0.1 inches are calculated by either adding 0.06 or subtracting 0.1 inches, respectively. These outliers are summed up and a net difference for the year is either added to or subtracted from the positive fluxes. In arriving at a water budget balance, the difference in TSM at both the beginning and end of the year is taken. These changes in storage for the entire year are used in order to verify either the positive or negative net fluxes for a particular site. The steps used for this analysis are summarized in Appendix 1.

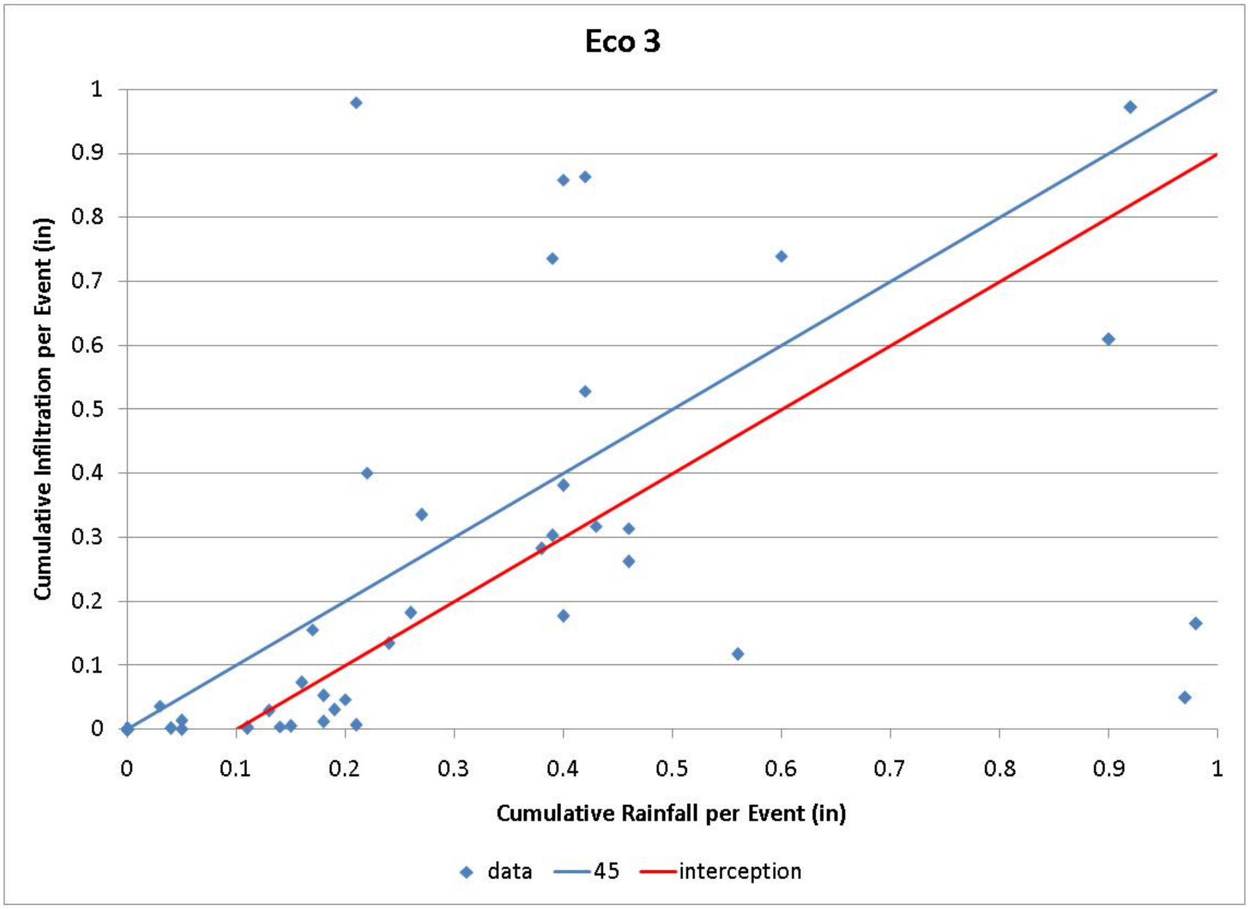

Figure 47. Derivation of 0.15 inch interception capture capacity at ECO-3.

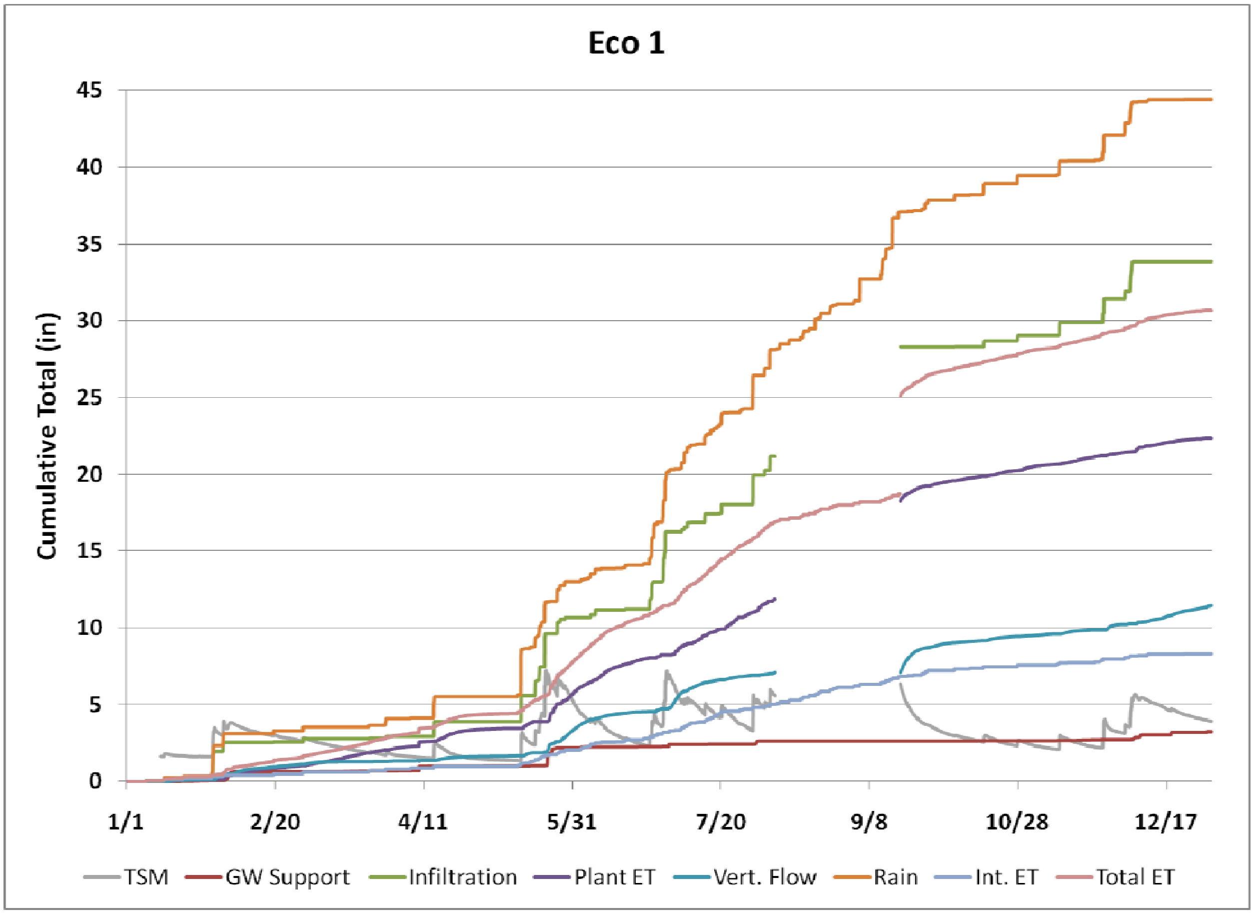

Figure 48. 2009 Cumulative water balances for ECO-1.

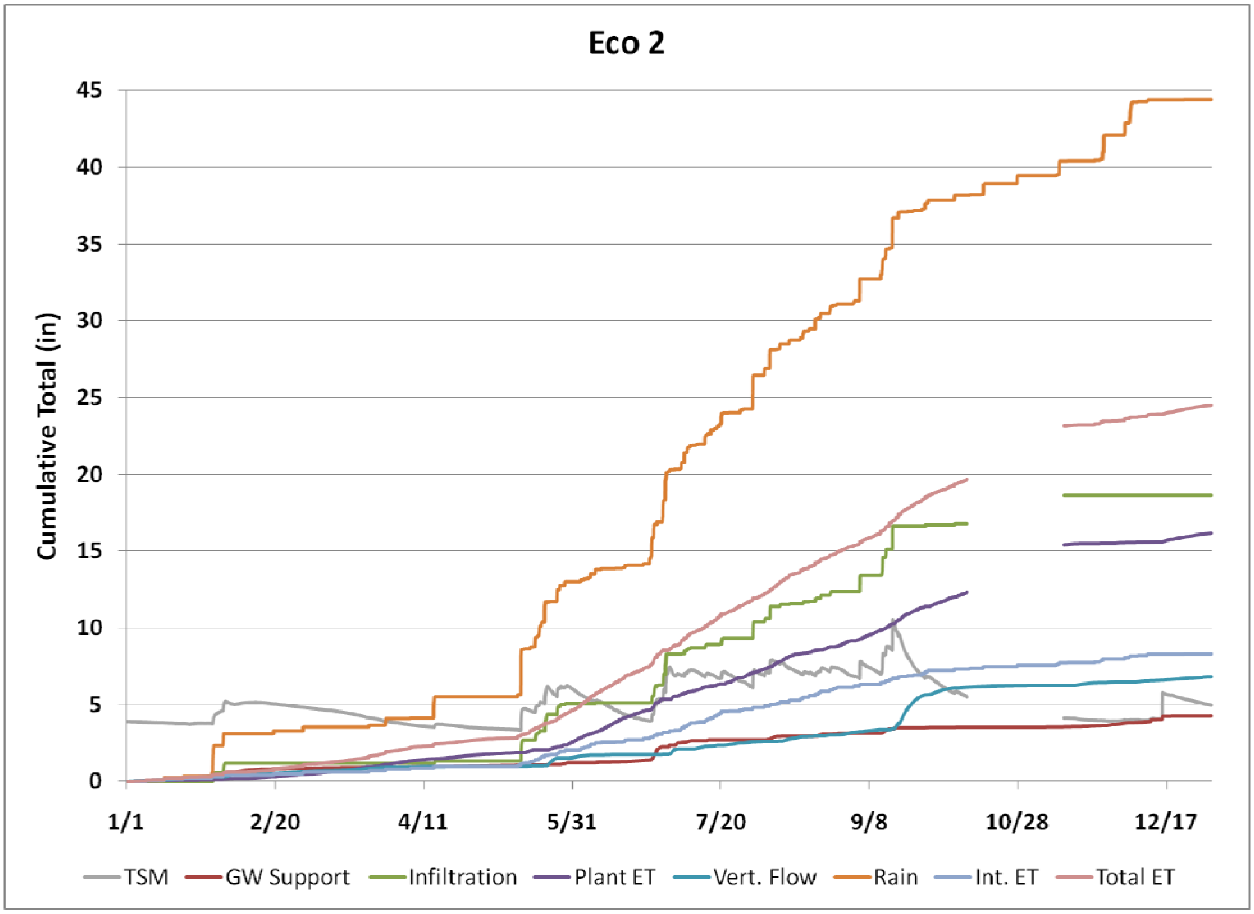

Figure 49. . 2009 Cumulative water balances for ECO-2.

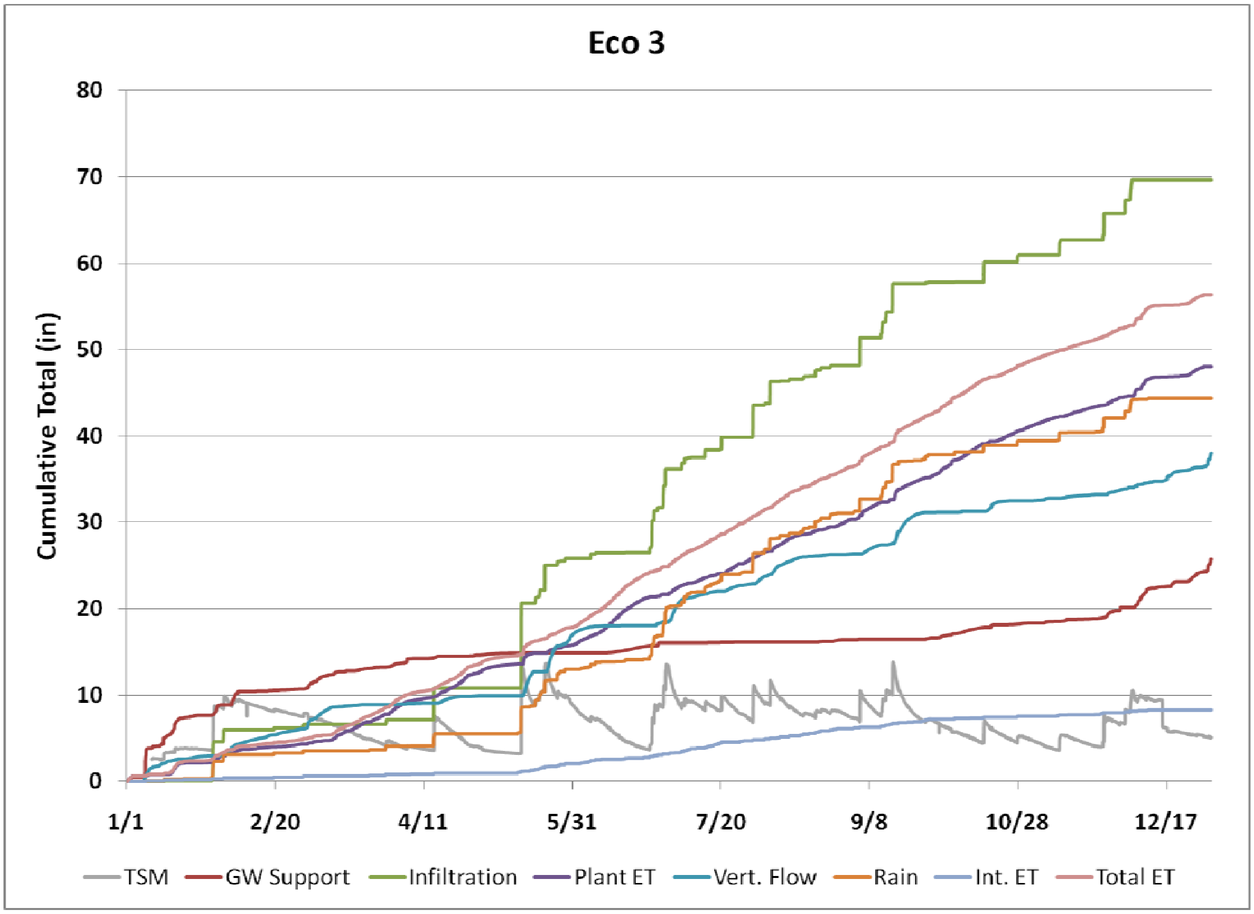

Figure 50. 2009 Cumulative water balances for ECO-3.

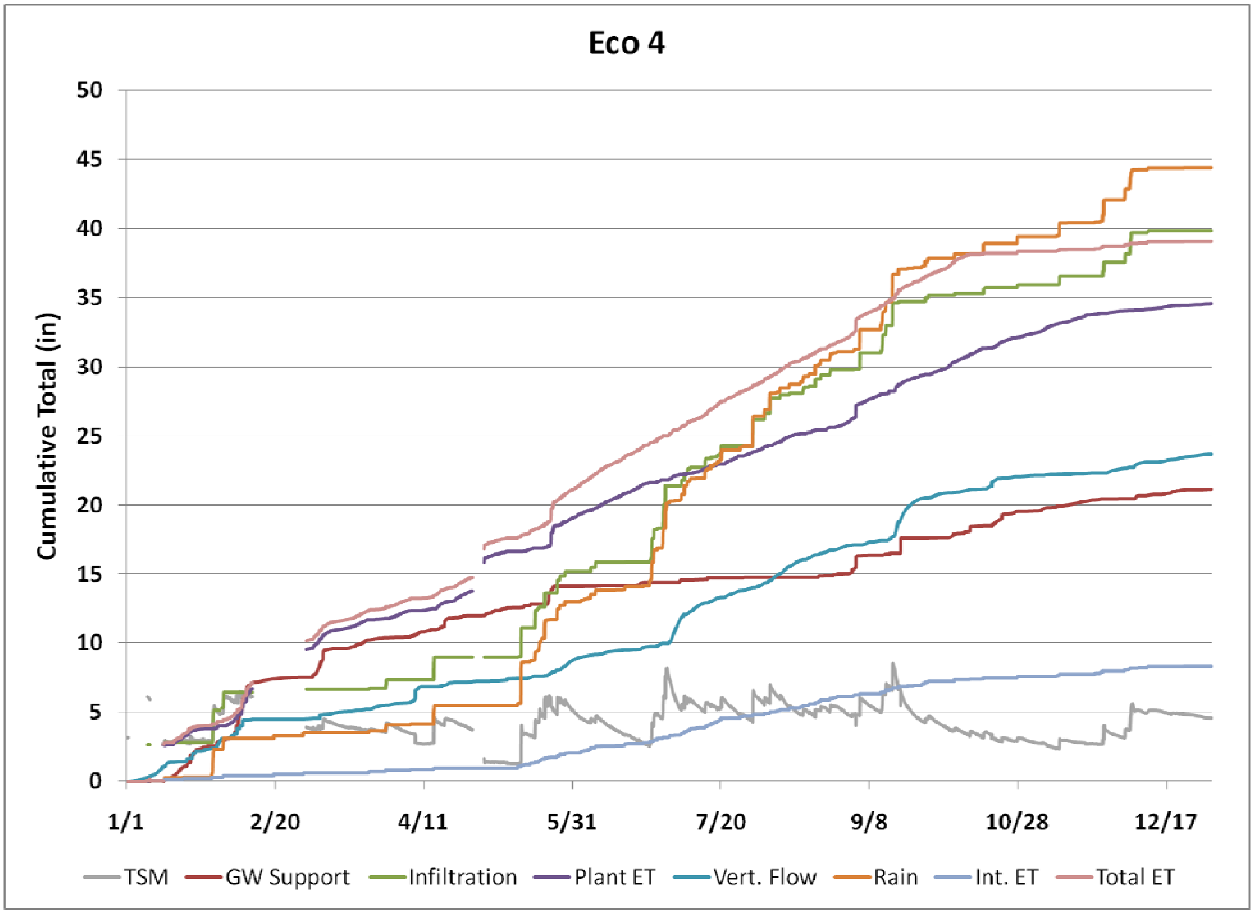

Figure 51. Cumulative water balances for ECO-4.

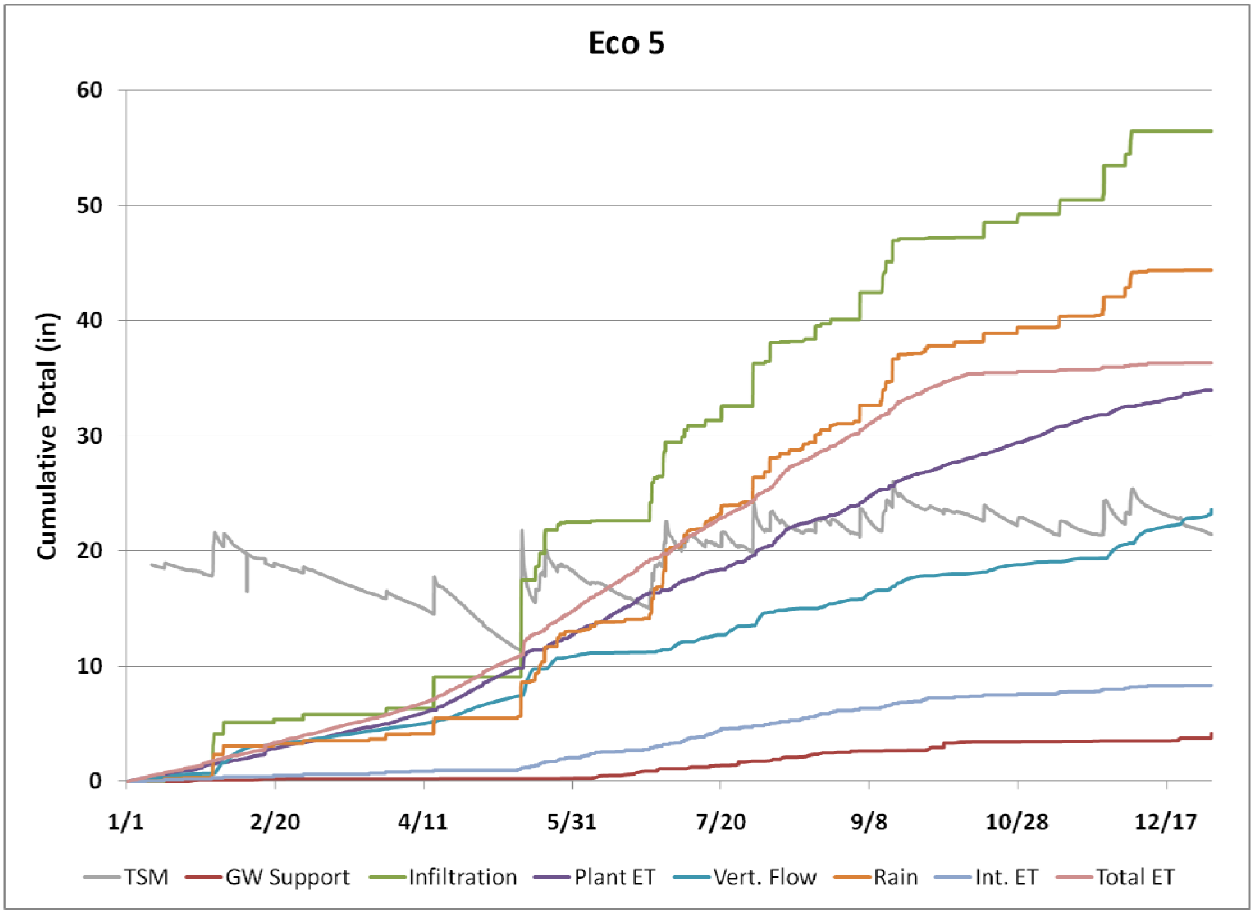

Figure 52. Cumulative water balances for ECO-5.

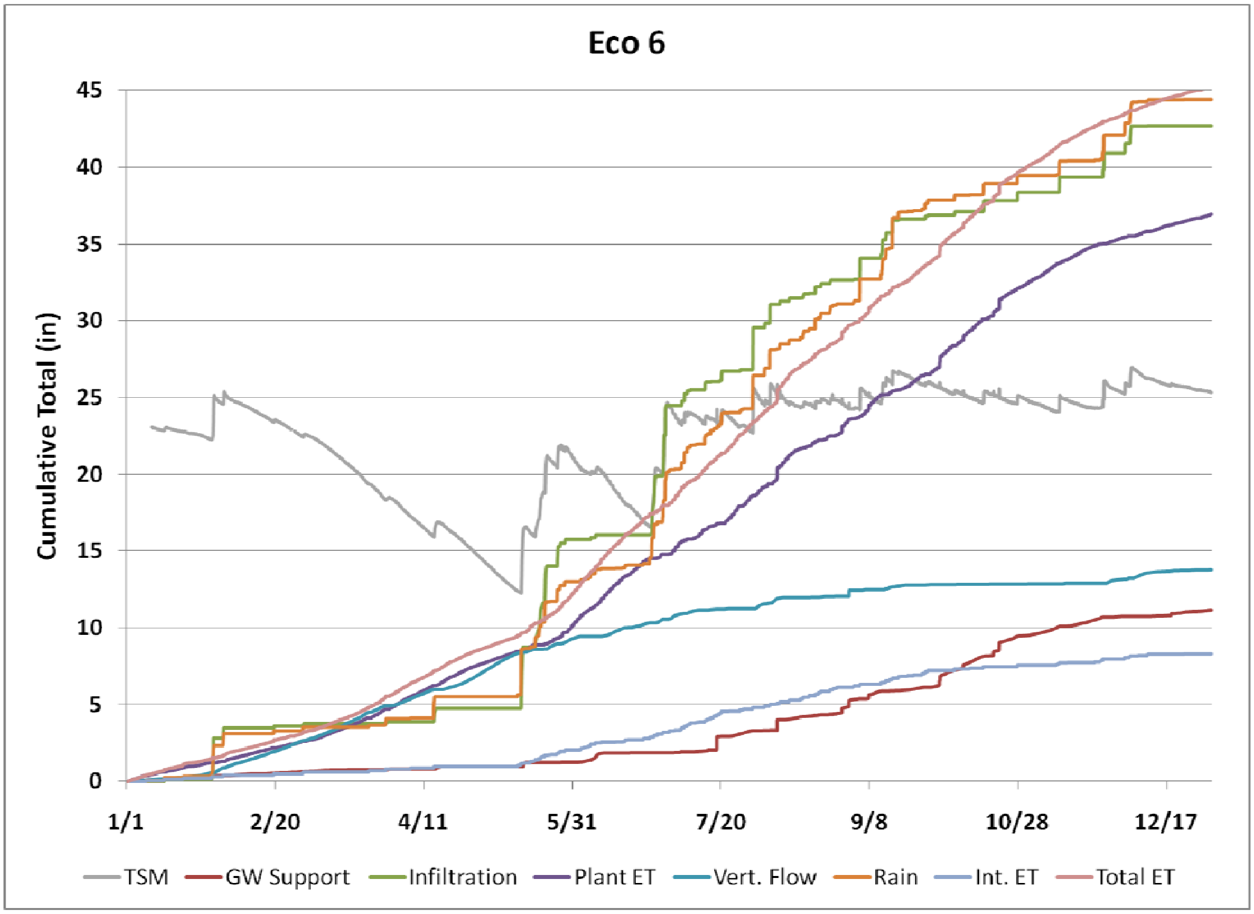

Figure 53. Cumulative water balances for ECO-6.

Tabulated results for water budget are included in Tables 2 to 7 which are separated into fluxes, storage changes and signal filtering constituents. For this procedure data gaps, equipment maintenance and other spurious instantaneous signal perturbations in the record must be filtered and, for complete mass balance closure for the record, must be accumulated. The results are tabulated to evaluate their magnitude. Note, there was a considerable period of missing data (last quarter) for station ECO 1 and shorter duration missing record periods at 2 and 5 which should be considered when discussing results for these stations.

Table 2. Water Budget at ECO-1.

Site Balance

Eco 1 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	2.942	Surface RO (out)	5.14
		Infiltration	33.862
Total In	47.342	Total Out	47.310
Net Inflows I-O (in) =		0.0	

Sensor Balances

Eco 1 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	37.6	GWET	18.5
GW Support	3.4	Int. ET	8.7
Gap ET	-0.6	Vert. Flow	18.2
Total In	40.4	Total Out	39.8
Net Inflows I-O (in) =		0.6	

Eco 1 Storage Change			
Water Table FL 1 (ft)		2m Soil Moisture Storage (in)	
1/1/2009	17.3	1/1/2009	1.63
12/31/2009	20	12/31/2009	3.92
Difference	2.7	Difference (ΔS)	2.29
Residual ΔS-I+O (in) =		1.726	

Eco 1 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
-3.239	0.163
Net Difference	-3.076

Table 3. Water Budget at ECO-2.

Site Balance

Eco 2 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	0.01	Surface RO (out)	17.74
		Infiltration	18.641
Total In	44.41	Total Out	44.688
Net Inflows I-O (in) =		-0.3	

Sensor Balances

Eco 2 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	18.6	Plant ET	16.2
GW Support	4.2	Int. ET	8.3
		Vert. Flow	6.8
Total In	24.4	Total Out	23.0
Net Inflows I-O (in) =		1.4	

Eco 2 Storage Change		
Water Table FL 2 (ft)	2m Soil Moisture Storage (in)	
1/1/2009	1/1/2009	3.9
12/31/2009	12/31/2009	5.0
Difference	Difference (ΔS)	1.1
Residual ΔS-I+O (in) =	-0.3	

Eco 2 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
0.0	1.5
Net Difference	1.5

Table 4. Water Budget at ECO-3.

Site Balance

Eco 3 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	35.938	Surface RO (out)	2.35
		Infiltration	69.642
Total In	80.338	Total Out	80.296
Net Inflows I-O (in) =		0.0	

Sensor Balances

Eco 3 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	58.9	GWET	33.6
GW Support	14.9	Int. ET	8.7
Gap ET	-3.3	Vert. Flow	36.8
Total In	70.5	Total Out	72.3
Net Inflows I-O (in) =		-1.8	

Eco 3 Storage Change			
Water Table (ft)		2m Soil Moisture Storage (in)	
1/1/2009	22.2	1/1/2009	4.44
12/31/2009	22.5	12/31/2009	5.07
Difference	0.3	Difference (ΔS)	0.63
Residual ΔS-I+O (in) =		2.41	

Eco 3 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
-5.100	3.200
Net Difference	-1.900

Table 5. Water Budget at ECO-4.

Site Balance

Eco 4 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	4.437	Surface RO (out)	3.66
		Infiltration	37.043
Total In	48.837	Total Out	49.016
Net Inflows I-O (in) =		-0.2	

Sensor Balances

Eco 4 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	39.9	Plant ET	34.6
GW Support	21.1	Int. ET	8.3
		Vert. Flow	23.7
Total In	61.0	Total Out	58.6
Net Inflows I-O (in) =		2.4	

Eco 4 Storage Change			
Water Table (ft)		2m Soil Moisture Storage (in)	
1/1/2009	17.1	1/1/2009	3.2
12/31/2009	19.7	12/31/2009	4.6
Difference	2.6	Difference (ΔS)	1.4
Residual ΔS-I+O (in) =		-1.0	

Eco 4 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
-4.193	3.910
Net Difference	-0.283

Table 6. Water Budget at ECO-5.

Site Balance

Eco 5 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	23.083	Surface RO (out)	2.66
		Infiltration	56.472
Total In	67.483	Total Out	67.442
Net Inflows I-O (in) =		0.0	

Sensor Balances

Eco 5 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	56.5	Plant ET	33.9
GW Support	4.1	Int. ET	8.3
Gap Infiltration	0.0	Vert. Flow	23.7
Total In	60.6	Total Out	58.6
Net Inflows I-O (in) =		2.0	

Eco 5 Storage Change			
Water Table (ft)		2m Soil Moisture Storage (in)	
1/1/2009	20.85	1/1/2009	19.505
12/31/2009	21.9	12/31/2009	21.456
Difference	1.05	Difference (ΔS)	1.951
Residual ΔS-I+O (in) =		0.0	

Eco 5 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
-1.305	0.277
Net Difference	-1.028

Table 7. Water Budget at ECO-6.

Site Balance

Eco 6 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Rain	44.4	Int. ET	8.309
Surface RO (in)	9.585	Surface RO (out)	3.24
		Infiltration	42.698
Total In	53.985	Total Out	54.244
Net Inflows I-O (in) =		-0.3	

Sensor Balances

Eco 6 Fluxes			
Positive Changes (Inflow)		Negative Changes (outflow)	
Infiltration	42.7	Plant ET	36.9
GW Support	11.2	Int. ET	8.3
		Vert. Flow	13.8
		Gap ET	0.1
Total In	53.9	Total Out	50.8
Net Inflows I-O (in) =		3.114	

Eco 6 Storage Change			
Water Table (ft)		2m Soil Moisture Storage (in)	
1/1/2009	20.36	1/1/2009	23.527
12/31/2009	21.29	12/31/2009	25.331
Difference	0.93	Difference (ΔS)	1.804
Residual ΔS-I+O (in) =		-1.31	

Eco 6 Major Changes in TSM w/o Rain	
Neg Chgs <-.06	Pos Chgs >.1
-2.853	2.869
Net Difference	0.016

Interesting expected and unexpected findings are noted from the graphical and tabulated results. Observations are offered in the follows paragraphs

Expectedly, deep water table ridge vegetative areas exhibit expectedly lower ET (e.g., 26.61" total ET for ECO 1) compared to mid-hill, topographic convergent regions (42.35 and 29.70" for ECO 3 and 4, respectively) and further downhill hillslope discharge high water table environments (41.41" and 45.97" total ET from ECO 5 and 6, respectively). Total ET at ECO 2 appears to be anomalous at 17.91" of total ET and will be discussed separately. In general, the ET rates derived from all sites are lower than expected and are probably a consequence of a dryer than normal rainfall year.

Perhaps more inconsistent for the hillslope was the net groundwater inflow defined as the deep vertical flow minus the groundwater support. This value could be considered net groundwater recharge to the deep (>2m depth) system. For the site, net groundwater inflow ranged from expectedly higher values of 14.21" at ECO 1 (note this should be higher without the missing final quarter) to -6.36" (net discharge) at ECO 6. However, there was considerable variation in the values in between from 4.75" at ECO 2 to 21.82"and 16.88" at ECO 3 and 4, respectively to 9.17" at Eco 5. Again, ECO 2 should be considered anomalous and is discussed separately. The high recharge rates at the down slope stations 3 and 4 appears to the result of high runoff from uphill (i.e., ECO 2) areas with repeatedly higher than rainfall infiltration values observed at these stations for larger (>1") rain events. Note that total infiltration at ECO was 60.3" (15' greater than annual rainfall).

Concerning the anomalous behavior exhibited at ECO 2 for infiltration, vertical flow and ET, lower values for fluxes observed at this station appear to be as a result of the station placement on the high slope region of the hill slope profile. During field visits following rainfall it was noted that wash runnel evidence is present and the high infiltration and other fluxes observed just downhill at station 3 both support the hypothesis that this high slope (~10%) environment exhibits considerable locally generated runoff at the expense of infiltration (only 14.27", with some data gaps in 2008). The milder slopes at stations 3 and 4 would appear to offer an environment conducive to higher infiltration and recharge. Soils and subsoil hydrogeologic conditions at ECO 2 due not appear to be otherwise special or substantially different from other stations (higher clays or low permeability regions) to preclude infiltration. Finally, the absence of a water table (does not exist or is greater than 40' depth) for this station also supports a lack of prevalent recharge. Further investigation of this region, prevalent in deep water table ridge settings throughout the District, is strongly warranted to understand if this is the dominant hydrologic behavior for these settings.

Conclusions and Recommendations

The hydrologic study of the USF Eco site is completing the third year of a four year study. All instrumentation is deployed and operational. The first year was mostly site selection, setup, well drilling, procurement and setup of instrumentation. Therefore, two calendar years of data are available for analysis. The project will continue to collect data through the summer 2009 wet season and the fall transition to dry season.

Infiltration, Recharge, runoff and ET Fluxes measured from this site should prove very useful for further hydrologic studies and understanding this very important and common landscape of west-central Florida. ET rates derived from soil moisture observations should be useful for calibrating hydrologic models and further understanding the hydrology and water budgets of these environments/land covers.

There is a pronounced difference is water-table response to rainfall events between deep water-table environments and shallow water-table environments. In a deep water-table environment, if the vadose zone is sufficiently dry, significant rainfall events may have no effect on the water-table position. As the moisture content in the vadose zone increases, infiltration can reach the water table but there is a delay between rainfall and recharge to the water table. The delay is a function of the depth to the water table and the moisture content in the vadose zone. The deeper the water table the greater the delay and the greater the moisture content the less the delay. In a shallow water-table environment, where the capillary zone is near the land surface, rainfall can produce an almost immediate rise in the water table. The quick rise of the water table is quickly reduced by ET demand. Thus, deeper water tables show a delayed and subdued response to rainfall and shallow water tables show an active and vigorous response to rainfall and ET.

Using soil moisture weather data and water-table water elevations to calculate water budgets at the observation sites identifies the contributions made by the different flux components. This is an important contribution to the understanding of recharge and evapotranspiration.

It would be useful to further investigate the timing of recharge to rainfall in a range of deeper surficial wells. Currently, the soil moisture sensors are limited to two meters in depth. A more thorough investigation would require that moisture sensors be placed closer to the water table so that the wetting front could be tracked to the water table. Additionally, soil moisture appears to respond differently at the high-slope site ECO-2. Total infiltration and ET are quite low probably due to a greater fraction of water being lost to runoff. Data collected at another high-slope site could increase the understanding of water-table response in high-slope environments.

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Appendix 1

Procedures for Smooth Vertical Flow Estimate

- Both small and big rain events are analyzed
  - Events generally under 0.1” are thought to be completely captured by interception therefore do not need to be filtered since effects on TSM are minimal
    - This 0.1” value can fluctuate based on the interception capture observed for each individual site
  - Threshold for small events is 4 hours thereafter for events generally .1”<x<.4”
  - Threshold for big events is 12 hours thereafter for events >.4”
  - This only affects SVF in rain event occurred within 4/12 hours of midnight to 6 am
    - In the event rain occurred within this time frame, only some of the data is erased, not necessarily all of it.
- Next column is made that takes the changes in TSM that occur between 12 am – 6 am for each time step
  - Time steps that are within the 4hr/12 hr time frame are “blanked”, therefore no change in TSM is detected
- Table is then generated that detects the individual hourly changes between midnight to 6 am for each day
- Column then averages these 6 hourly changes for each day
  - If major rain event caused all 6 hours to be “blanked”, the average for the entire day is also “blanked”
- 2 more columns are generated that show the average midnight – 6 am VF rate for both the previous and next day.
  - Each average daily value is then further averaged with the previous days and next day’s average values in order to obtain a 3 day centralized average
  - This helps to smooth out values and account for days with “blanked” averages due to major rain events
- This final average value is taken and applied for every hour of that respective day
- Further smoothing is then applied by one of two ways:
  - If it is between 12am – 6 am VF rate is left unaltered
  - Between 7 am and 11 pm a 24 hour average is done by averaging the past 6 hours and the next 18 hours.
    - This helps ensure the calculated value around 7 am is very similar to 6am’s value and 11pm’s is close to that of the next day’s 12 am value

Evaluation of the Geochemical and Microbial Processes Controlling Arsenic Mobilization during Artificial Recharge (AR) and Aquifer Storage and Recovery (ASR)

Basic Information

Title:	Evaluation of the Geochemical and Microbial Processes Controlling Arsenic Mobilization during Artificial Recharge (AR) and Aquifer Storage and Recovery (ASR)
Project Number:	2006FL143B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	6
Research Category:	Ground-water Flow and Transport
Focus Category:	Hydrogeochemistry, Hydrology, Water Supply
Descriptors:	
Principal Investigators:	Mike Annable

Publications

There are no publications.

Project Status Update

Investigating Arsenic Mobilization During Aquifer Storage Recovery (ASR)

May 26, 2010

Student: Stuart B. Norton – U.F. Environmental Engineering Sciences
Advisor: Dr. Mike Annable – U.F. Environmental Engineering Sciences

Student's Dissertation Topic

Evaluating Trace Metal Mobilization During Managed Aquifer Recharge

Project Background

Due the growing demand on water resources within the State of Florida, Managed Aquifer Recharge (MAR) has become an increasingly attractive water storage option for many municipalities. MAR techniques, such as Aquifer Storage and Recovery (ASR) and Artificial Recharge (AR), have the potential to provide much of the seasonal or long-term storage needed within areas of increased water demand. However, as with any engineered water supply process, these facilities must meet stringent Federal and State regulations to insure the protection of human health and the health of the environment.

Recently, facilities in southwest Florida utilizing the Suwannee Limestone of the Upper Floridan Aquifer for ASR have reported arsenic concentrations in recovered water at levels greater than 112 µg/L (Arthur et al., 2002). On January 23, 2006 the Maximum Contaminant Level for arsenic was lowered from 50 µg/L to 10 µg/L (FDEP: Chapter 62-550 F.A.C., Table 1). Arsenic has become the primary regulator constraint for implementing these MAR techniques.

Research has been conducted to determine the abundance and mineralogical association of arsenic within the Suwannee Limestone (Pichler, et al., 2006). This research suggests that the bulk matrix of the Suwannee Limestone generally contains low concentrations of arsenic. However, according to this research, arsenic is concentrated within the Suwannee Limestone in arsenic bearing minerals such as pyrite.

The potential mechanisms by which arsenic may be mobilized during ASR have been investigated (Arthur, et al., 2002) and suggested by others (Pichler, et al., 2006). The conclusions of this research suggest that the introduction of injectate containing oxidants, such as oxygen and chlorine, into a highly reduced groundwater environment produces a geochemical response that releases arsenic from the aquifer matrix.

Several ASR projects are under testing in southwest Florida. Of these, the recently constructed Bradenton Potable ASR facility presents several benefits for further research including the following:

- Both small volume (40 MG) and large volume (160 MG) recharge and recovery cycles have been performed at the facility, with additional tests planned.
- The data sets collected to date at this facility are fairly extensive.
- The City of Bradenton, in conjunction with the Southwest Florida Water Management District, St. Johns River Water Management District, South Florida Water Management District (SWFWMD) and Peace River Manasota Regional Water Supply Authority are cooperatively developing a pretreatment degasification and dechlorination system for this site. This system is currently being tested at the site.
- The City of Bradenton has authorized the use of the data set in this study.
- Site access has been granted by the City of Bradenton.

Datasets from other ASR sites within SWFWMD may also be available.

Project Status

The following research was completed during Fiscal Year 2009 or are currently underway:

Model Review

A review of reactive transport (geochemical transport) models is complete. The reactive transport model PHT3D appears best suited for modeling arsenic mobilization during ASR. PHT3D couples the geochemical model PHREEQC-2 with the multi-component transport model MT3DMS. The model is being maintained by Henning Prommer at the University of Western Australia (Prommer 2005). Alternatives to PHT3D include the USGS reactive transport model PHAST, USGS geochemical modeling code PHREEQC and Geochemist Workbench. Geochemist Workbench is currently being used to model the geochemical/reactive components for incorporation into transport models.

Core Collection and Preservation

Over 145 ft of 2-inch core material has been collected and preserved for use during this project. The core was preserved in core-storage vessels designed and built for this project. The core material will be used in batch-studies and preliminary intact core-column experiments, discussed below.

Core-column Design

The design of intact core-column experiments is underway. Falling head permeameters were constructed and tested in the lab to evaluate the hydraulic seal around the outer-wall of the core and to test vertical conductance of the rock. The FHP tests form the basis for the design of core-column experiments.

ASR Batch Studies

Sub-samples of the core material have been collected and prepared for use in batch studies planned for this summer (June through August 2010). These will be conducted in coordination with the Florida Geological Survey and will test core preservation techniques, arsenic release during ASR and the effects of microbes and natural organic matter on arsenic release during ASR.

Qualifying Exam

On May 12, 2010, Mr. Norton successfully completed the Ph.D. qualifying exam, including a written and oral defense of his research proposal.

Presentations

American Groundwater Trust - ASR- 9 Conference:
Stuart Norton, Project Specialist and Seth Kohn, Engineer, City of Bradenton, Bradenton, FL: *Past, Present and Future of the Bradenton Degasification Project*, September 29, 2009

2nd UF Water Institute Symposium - Poster Session:
Stuart Norton and Dr. Mike Annable - *Evaluation of Trace Metal Mobilization during Managed Aquifer Recharge (MAR),* February 24, 2010 - Awarded 1st Place Prize

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Price, Roy E., and Pichler, Thomas, 2006, Abundance and mineralogical association of arsenic in the Suwannee Limestone (Florida): Implications for arsenic release during water-rock interaction: Chemical Geology, Vol. 228, pp. 44-56

Prommer, Henning, and Stuyfzand, Pieter J., 2005, Identification of temperature-dependent water quality changes during a deep well injection experiment in a pyritic aquifer: Environmental Science and Technology, Vol. 39, pp. 2200-2209

In-Filling Missing Daily Rain Gauge Data Using NEXRAD Rainfall Data

Basic Information

Title:	In-Filling Missing Daily Rain Gauge Data Using NEXRAD Rainfall Data
Project Number:	2007FL202B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	19
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Methods, Models
Descriptors:	
Principal Investigators:	Ramesh Teegavarapu

Publications

1. Utility of Optimal Reflectivity-Rain Rate (Z-R)Relationships for Improved Precipitation Estimates, EWRI-ASCE World Environmental and Water Congress, 2010
2. Infilling Missing Precipitation Data using NEXRAD Data: Use of Optimal Spatial Interpolation and Data-Driven Methods, EWRI-ASCE World Environmental and Water Congress, 2010
3. Extreme Precipitation and Climate Change, IFI, Book Series Meeting, UNESCO, Paris, April 29, 2010.
4. Spatial Precipitation Analysis for Continuous Estimation: Issues, Approaches and Applications, Seoul National University, Seoul, BK21 Seminar Series, April 22, 2010.
5. Uncertainties in Z-R Relationships for Radar based Precipitation Estimates, SWFWMD, Tampa, March11, 2010.
6. Improvement of NEXRAD Data using new methods of Bias Corrections, SWFWMD, Tampa, March 11, 2010.
7. Spatial Precipitation Analysis for Continuous Estimation (SPACE): Patterns, Organization and Processes (POP), ASEC-EWRI 2010, India Conference, Chennai, India, January 5, 2010.
8. Evaluation of Improvised Spatial Interpolation Methods for Infilling Missing Precipitation Records, ASCE/EWRI International Conference, Kansas City, May 2009.
9. Evaluation of Spatial Weighting Methods for Transformation of Multi-Sensor Precipitation Estimates, ASCE/EWRI International Conference, Kansas City, May 2009

WRRC 104B Project Annual Report

(Activities during the period March 1, 2009 through February 28, 2010)

Project Title:

In-filling Missing Daily Rain Gauge Data Using NEXRAD Rainfall Data

Submitted to:

Water Resources Research Center (WRRC)

University of Florida

P.O. Box 116580, Gainesville, Florida

Submitted by

Dr. Ramesh S.V. Teegavarapu, P.E., P. Eng.
Assistant Professor
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May 26, 2010

EXECUTIVE SUMMARY

This report summarizes the work completed for the first phase of the project, “In-filling Missing Daily Rain Gauge Data Using NEXRAD Rainfall Data Study” supported by supported by USGS 104B Grant administered by Water Resources Research Center (WRRC), University of Florida, and matching funds from South Florida Water Management District (SFWMD). The report also discusses the methodologies, application of models and results based on the work completed under this project. The study investigated the use of optimal spatial interpolation and data driven models for infilling of rain gage data using NEXRAD based precipitation estimates. A total of 12 optimization model formulations were developed and implemented in this study. Two additional interpolation models and a model utilizing artificial neural networks (ANN) concepts were also developed. These models were assessed using data from pre-selected 27 rain gages in the SFWMD region. Results from these models were evaluated using four different performance measures and appropriate weight functions. The best model based on performance evaluations was selected for infilling the missing rain gage data at 286 rain gages in the South Florida Water Management District (SFWMD).

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INTRODUCTION AND BACKGROUND

The use of NEXRAD rainfall data for providing information about the extreme rainfall amounts resulting from storms, hurricanes and tropical depressions is common today. Often corrections are applied to this rainfall data-based on what was actually measured on the ground by rain gages (generally referred to as "ground truth"). Understanding and modeling the relationships between NEXRAD and rain gage data are essential tasks to confirm the accuracy and reliability of the former surrogate method of rainfall measurement. Traditional non-linear regression models in many situations are found to be incapable of capturing these highly variant non-linear spatial and temporal relationships. This study proposes to investigate the use of emerging computational data modeling techniques and assess these functional approximation methods for this purpose.

The project's objective is to develop a method that would be used to in-fill the historical daily missing rain gauge data. The proposed method would use NEXRAD rainfall data, for this purpose, and it will be applied to the existing available data and its performance would be evaluated and assessed. Upon successful development and verification of the model, the model will be used in filling the missing daily rain data for rain gauge stations. This project involves developing methodology for filling of the missing historical daily rain data from rain gauge stations. The daily rain gage data from 368 Districts' rain gages are also available for spatial and temporal analysis. For SFWMD, the rainfall data are available in DBHYDRO for downloading. The period-of-record (POR) for these stations varies. The POR for this study will be from January 1, 2002 to December 31, 2007.

In addition, the daily radar rainfall (NEXRAD rainfall) data coverage for each of the District rain gauge stations are also available and include radar rainfall amounts for 2 km by 2 km cells. Each cell has a specific time series of rainfall data. The SFWMD has database that contains values from January 1, 2002 to the present. The mean monthly precipitation data for all the NOAA rain gages that included the in-filling of the missing data were made available from Dr. Christopher Daly of the Spatial Climate Analysis Services at the Oregon State University. Theses datasets are known as Parameter-elevation Regression on Independent Slopes Model (PRISM) datasets. It is believed that these datasets may not be of reasonable data quality for the central and south Florida due to relatively flat topography of the region. In addition, Dr. Jennifer Adam of Department of Civil and Environmental Engineering from University of Washington reported that they have developed daily rainfall data for the continental USA from 1950 to 1999 at 1/8 th degree grid (from NCDC station data) that were scaled to match PRISM datasets. These available data sets are currently being evaluated for their suitability to the project.

PROJECT STATUS

The phase I of the project is now completed. The second phase of the project is currently supported by 104B Grant for the period (March 2010 – February 2011). Mr. Andre Ferreira, graduate student in the department of civil engineering, Florida Atlantic University, has graduated in December 2009. Two other graduate students, Mr. Kandarp Pattani and Mr. Ricardo Brown have helped in the successful completion of the project.

Publications

Journal publications have submitted and several papers have been published in prestigious international conferences. Two journals papers have been accepted for publication. The following is the list of papers presented and published.

Oral Presentations

1) Utility of Optimal Reflectivity-Rain Rate (Z-R) Relationships for Improved Precipitation Estimates, EWRI-ASCE World Environmental and Water Congress, 2010

2) Infilling Missing Precipitation Data using NEXRAD Data: Use of Optimal Spatial Interpolation and Data-Driven Methods, EWRI-ASCE World Environmental and Water Congress, 2010

3) Extreme Precipitation and Climate Change, IFI, Book Series Meeting, UNESCO, Paris, April 29, 2010.

4) Spatial Precipitation Analysis for Continuous Estimation: Issues, Approaches and Applications, Seoul National University, Seoul, BK21 Seminar Series, April 22, 2010.

5) Uncertainties in Z-R Relationships for Radar based Precipitation Estimates, SWFWMD, Tampa, March11, 2010

6) Improvement of NEXRAD Data using new methods of Bias Corrections, SWFWMD, Tampa, March 11, 2010.

7) Spatial Precipitation Analysis for Continuous Estimation (SPACE): Patterns, Organization and Processes (POP), ASEC-EWRI 2010, India Conference, Chennai, India, January 5, 2010.

8) Evaluation of Improvised Spatial Interpolation Methods for Infilling Missing Precipitation Records, ASCE/EWRI International Conference, Kansas City, May 2009

9) Evaluation of Spatial Weighting Methods for Transformation of Multi-Sensor Precipitation Estimates, ASCE/EWRI International Conference, Kansas City, May 2009.

List of students supported by 104B funding last year (March 2009 – February 2010)

1. Mr. Andre Ferreira, Graduate Student, graduated December, 2009
2. Mr. Ricardo Brown, Graduate student, expected graduation, Fall 2010
3. Mr. Kandarp Pattani, Graduate student, expected graduation, Fall 2010

DESCRIPTION OF PROJECT WORK

The following sections describe the completed work along with methodologies and results. The work described is already published in ASCE international conference proceedings. The work has been submitted for peer-reviewed international journals.

LITERATURE REVIEW: ESTIMATION OF MISSING PRECIPITATION DATA

Rainfall amounts vary geographically within central and south Florida. For example, rainfall characteristics and patterns on land surrounding Lake Okeechobee and ocean are different from that of central overland mass. In addition, spatial variation in rainfall amounts for shorter durations, such as one-, three-, and five- day, is significantly greater than monthly, seasonal and annual rainfall. Therefore, in this study, spatially varying rainfall should be considered based on varying meteorologically/climatological conditions during dry and wet periods. Rainfall is a multi-dimensional process occurring in space and time. For a selected rainfall event, various possible realizations could be formulated that are occurring along the time scale. Mean rainfall value over an area of all possible realizations of that event could be considered for the analysis.

The availability of precipitation data and its length are vital for hydrologic analysis and design of water resources systems. Often hydrologists encounter the problem of missing data due to a variety of reasons. Measurement of hydrologic variables (e.g., rainfall, streamflows, etc) is prone to systematic and random errors (ASCE, 1996; Larson and Peck, 1974; Vieux, 2001). Systematic errors (Vieux, 2001) in rain gage measurements can be of various types: water loss during measurement, adhesion loss on the surface of the gage, raindrop splash from the collector. Complete lack of data is also possible in many situations wherein the rainfall gage malfunctions for a specific period of time. Errors in recording of rainfall data are possible due to tree growth, instrumentation problems or techniques used in measuring the rainfall amounts. These errors are critical as they affect the continuity of rainfall data and ultimately influence the results of hydrologic models that use rainfall as input. Estimation of missing data is one of the most important tasks required in many hydrological modeling studies. In the current study missing rainfall data and its estimation techniques are of interest.

Traditional weighting and data-driven methods are generally used for estimating missing precipitation. Weighting methods belong to a class of spatial interpolation techniques such as inverse-distance (Simanton and Osborn, 1980; Wei and McGuinness, 1973), non-linear deterministic and stochastic interpolation methods (e.g. kriging). Regression and time series analysis methods belong to data-driven approaches. The handbook of hydrology (ASCE, 1996) recommends two methods for estimation of missing data. These methods are normal-ratio and inverse distance weighting methods. Singh and Chowdhury (1986) compared 13 rainfall estimation methods and found isohyetal method yielded higher estimates of mean daily, monthly areal rainfall than other methods in the area of their study. Tung (1983) compared 5 methods used for estimating point rainfall and indicated that arithmetic average and inverse-distance methods did not yield desirable results for mountainous regions. Ashraf et al. (1997) compared interpolation methods (kriging, inverse distance and co-kriging) to estimate missing values of precipitation. They indicate that kriging interpolation method provided the lowest root mean square error (RMSE).

Co-kriging of radar and rain gage data was performed by Krajewski (1987) to estimate mean areal precipitation. Seo, et al.(1990a, 1990b) and Seo (1996) discussed comprehensive studies using co-kriging and indicator kriging for interpolation of rainfall data. Seo and Smith (1993) discussed short-term rainfall prediction using radar and also the use of radar data in conjunction with rain gage data for rainfall estimation by using a Bayesian approach. Seo (1998) studied real-time estimation of rainfall fields using radar and rain gage data. Alternative methods such as regression (conventional least-squares) and time series analysis are also used for estimating missing precipitation values (Salas, 1993, Dingman, 2002). Daly et al. (1994) developed a regression model that uses spatial variables for estimation of precipitation. They have used climate data, elevation, topography and proximity to coastal area and distances as independent variables in their regression model to develop estimates of precipitation.

McCuen (1998) recommended a simple average method of estimating missing values of precipitation when the annual precipitation value at each of the gages differs by less than 10% from that of the gage with the missing data. When the mean annual precipitation of one or more of the adjacent stations exceeds the station with missing data by more than 10% normal-ratio method was recommended. Dingman (2002) and McCuen (1998) point out one major limitation of the normal-ratio method. They indicate that by including all the gages in computing the missing data, the method could fail to take into account redundant information if some of the gages are clustered together and also bias the estimate of missing data. McCuen (1998) discussed the coordinate system method in which only the gage that is closest to the origin in each quadrant is used for calculation of weights. In this context, Dingman (2002) points out that the selection of “nearby” precipitation gages for estimation of missing data must be based on meteorological judgment.

Inverse distance weighting method (IDWM) is most commonly used approach for estimation of missing data in hydrology and geographical sciences. In the U.S., especially in operational hydrology literature, IDWM is often referred to as national weather service (NWS) method and is routinely used for estimation of missing rainfall data (ASCE, 1996). In the field of quantitative geography IDWM is used for the purpose of spatial interpolation (Sullivan and Unwin, 2003). Several variants of IDWM were derived and adopted by researchers with a focus mainly on the weighting schemes. Hodgson (1989) modified IDWM to adopt a learned search approach that reduces the number of distance calculations. To incorporate topographical aspects, Shepard (1968) proposed a modified IDWM that is referred to as a barrier method.

The main motivating factors to re-visit the inverse distance weighting method and develop variants of this method are described in the arguments here. The success of inverse distance weighting method depends primarily on the existence of positive spatial autocorrelation (Griffith, 1987; Vasiliev, 1996), which is summarized by the following statement. Data from locations near one another in space are more likely to be similar than data from location remote from one another (Sullivan and Unwin, 2003). However, it can be easily argued that distance alone is not the measure of spatial autocorrelation, and also the existence of negative autocorrelation may be become a major limitation in the application of IDWM for estimation of missing data. Another important issue relevant to IDWM is the selection of neighborhood points of observations for estimation of missing data at a point of interest. Selection of locations in space for use of observations in arriving at the distances is arbitrary. Many researchers recommend the use of three or four closest stations for application of IDWM. The arbitrariness in the choice of weighting parameter and the definition of the neighborhood are two obvious limitations of IDWM.

Regression and time series models (Salas, 1993) were used in the past for estimation of missing rainfall data. One of the major limitations of such methods is the necessity to define the functional form of the relationships a priori. Application of artificial neural networks (ANN) as universal function approximators has gained enormous interest in the hydrology and water resources research community for application to a number of hydrological prediction problems (ASCE, 2001a; 2001b). ANNs are data-driven approaches that rely on learning relationships between dependent and independent variables to predict variables of interest. French et al. (1992) used a feed forward neural network with back propagation training algorithm for forecasting rainfall intensity fields at a lead-time of 1 hour with the current rainfall field as input. Navone and Ceccatto (1994) used an ANN model to predict summer monsoon rainfall over India.
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Teegavarapu and Chandramouli (2005) compared eight methods for estimating missing rainfall data. They recommended three methods, namely, coefficient of correlation weighing methods, artificial neural network estimation method, and kriging estimation method for estimation of missing rainfall data. They found these three methods to be conceptually superior to other approaches. Teegavarapu (2006) used universal function approximator (such as artificial neural network (ANN)) for fitting a semivariogram model using the raw data in ordinary kriging to estimate missing data.

The optimal estimation theory for a dynamic system (Bras, 1985) may begin with formulation of system equations for the rainfall process, which combines a model of the state (rainfall amount) of the system with a model of observations (measurement of rainfall) of those states. The observations of the state can be specified in terms of the nature, number, locations and frequency of observations (15-minutes, hourly, weekly or monthly). Both the state and observation models may be uncertain and can be combined with an error of estimation that is a function of the observation network attributes. Hence, a monitoring network evaluation may consist of varying the attributes until specified accuracy criteria in the knowledge of the state are achieved. Kalman filter is an algorithm for optimal estimation of a variable where the optimality is based on the principle of minimum variance.

PROJECT TASKS

The following three major tasks and related sub-tasks were completed as a part of this study. Initially a technical approach that would be used to in-fill the historical daily missing rainfall data for rain gauges was developed. The data collection effort was taken u. NEXRAD and rain gage data was collected from SFWMD and was analyzed. The time series data sets included daily District rain gage and NEXRAD rainfall data. These data sets have a period-of-record from January 1, 2002 to December 31, 2007. Methodologies to fill the daily missing rainfall data to obtain the best quality rainfall estimates was investigated and several optimization and data-driven models were formulated and developed for evaluation on a pre-selected set of rain gage stations. Several performance measures were evaluated before selecting the best model for infilling the missing rainfall data. The best model from the set of models investigated in the current study will be finally used for infilling missing rain gage data at 268 rain gage stations in the District.

INFILLING OF RAIN GAGE RECORDS USING RADAR (NEXRAD) DATA

Deterministic and stochastic weighting methods are the most frequently used methods for infilling rainfall values at a gage based on values recorded at all other available recording gages or other sources. Radar (NEXRAD) data is also commonly used for infilling of rainfall data. Several issues that affect the infilling methods include: the historical rain gage and radar data, spatial and temporal variability of rainfall, radar-rain gage relationships, selection of spatial extent of radar data. The current study evaluates the influence of spatial and temporal variability of rainfall processes on the performance of spatial interpolation algorithms. Seasonal variation of rainfall, rainfall areas that are delineated based on physical processes affecting the genesis and morphology of rainfall processes, and other factors may affect the performance of infilling methods. All these issues are important for south Florida which experiences wide variability in rainfall in space and time. In the current study, data from five rain gages and radar (NEXRAD) data in the south Florida region are used to evaluate the influence of spatial and temporal variability of rainfall processes on the performance of methods used for infilling rain gage data.

NEXRAD DATA

Next Generation Radar (NEXRAD) or Weather Surveillance Radar 88 Doppler (WSR-88D) data provide complete spatial coverage of rainfall amounts using a predetermined grid resolution (usually 2 km by 2 km or 4 km by 4 km). 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 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.

Weather data acquired from radar (NEXRAD) is generally used by the water management agencies in making decisions for operational purposes. However, the use has been largely limited to visual interpretation of data as opposed to quantitative analysis. Data derived from radar based precipitation estimates (i.e. NEXRAD data) can be used to estimate the missing precipitation values. However, the reliability of radar-based precipitation measurements is a contentious issue (Young et. al, 1999; Adler et al., 2001). Radar rainfall estimates derived from conversion of reflectivity measurements are known to contain systematic errors, or bias, and other random errors or artifacts that limit the utility of radar rainfall. Quality control and enhancement of radar rainfall estimates may be accomplished through gauge-adjustment procedures.

DATA COLLECTION EFFORT

Precipitation data sets for rain gage and NEXRAD (2km x 2km grid) were collected and analyzed. Data from a total of 268 rain gages depending on the type of recorder were collected from DBHYDRO database. The NEXRAD data developed by OneRain Corporation was also obtained from SFWMD. The rain gages are classified depending on four recording types and they are: 1) manual; 2) operational maintenance with multiple sources; 3) telemetry (radio network) and 4) CR10 (Campbell Scientific). Details of these rain gages are provided in Tables 1 – 8.

Table 1 List of stations based on recorder type 1

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
S20_R	05817	5/24/1968	3/17/2008	Belfort Rain Gage	25.36713319250	-80.37650645290
CLEW.FS_R	06220	11/13/1968	6/30/2008	Unknown (Manual)	26.73506462710	-80.89533872850
LWD.E1.3_R	06290	9/1/1955	6/30/2008	Unknown (Manual)	26.61228952610	-80.20504346010
LWD.E2.2_R	06321	8/31/1955	6/30/2008	Unknown (Manual)	26.45451731600	-80.17115411390
LWD.E2_R	06299	8/31/1955	6/30/2008	Unknown (Manual)	26.52840351420	-80.17032044000
LWD.GA_R	06276	8/31/1955	6/30/2008	Unknown (Manual)	26.61895580360	-80.12643009120
LWD.HQ_R	06306	8/31/1955	6/30/2008	Unknown (Manual)	26.48312720700	-80.12309703790
LWD.L28_R	06302	8/31/1955	6/30/2008	Unknown (Manual)	26.49562700240	-80.20282144950
LWD.L32_R	06322	8/31/1955	6/30/2008	Unknown (Manual)	26.47062794220	-80.20504387860
LWD.L38M_R	05892	9/30/1974	6/30/2008	Unknown (Manual)	26.42396271900	-80.12226398170
LWD.L39R_R	05893	9/30/1974	6/30/2008	Unknown (Manual)	26.41674105870	-80.20393304930
LWD.MIL_R	06298	8/31/1955	6/30/2008	Unknown (Manual)	26.52090364120	-80.12393025800
LWD.POWE_R	05793	8/31/1955	6/30/2008	Unknown (Manual)	26.36896486970	-80.15393185950
LWD.RANG_R	05792	8/31/1955	6/30/2008	Unknown (Manual)	26.38757548200	-80.20476657570
PRATT AN_R	06122	4/17/1957	6/30/2008	Unknown (Manual)	26.90450120580	-80.30393445760
S133_R	05845	6/23/1970	6/30/2008	Unknown (Manual)	27.20615719420	-80.80089003390
S4_R	05879	7/31/1974	6/30/2008	Unknown (Manual)	26.78984374420	-80.96171320990
BCBNAPLE_R	LX271	1/1/1995	6/27/2008	Unknown (Manual)	26.22536622760	-81.80813990820
EAST BEA_R	05962	5/31/1980	5/31/2008	Unknown (Manual)	26.79811626870	-80.69505581240
EAST SHO_R	05835	12/31/1969	5/31/2008	Unknown (Manual)	26.74895131520	-80.68366680650
PAHOKEE1_R	05838	3/4/1957	5/31/2008	Unknown (Manual)	26.81311461900	-80.56366393060
PAHOKEE2_R	05839	3/1/1957	5/31/2008	Unknown (Manual)	26.78394849770	-80.52532984090
PEL LAK1_R	05837	3/4/1957	5/31/2008	Unknown (Manual)	26.85172484670	-80.61338714730
PEL LAK2_R	06125	3/4/1957	5/31/2008	Unknown (Manual)	26.84200287330	-80.60227581550
S65C_R	06024	5/31/1966	5/31/2008	Unknown (Manual)	27.40101995520	-81.11511274760
SFCD_R	05965	5/31/1980	5/31/2008	Unknown (Manual)	26.72812018080	-80.85339321730
FT. LAUD_R	05850	9/30/1971	5/30/2008	Unknown (Manual)	26.06369922170	-80.25949193900
S61_R	05868	2/20/1965	5/7/2008	Unknown (Manual)	28.14033177710	-81.35205653780
S65A_R	05981	6/17/1965	5/7/2008	Unknown (Manual)	27.65805333240	-81.13421222380
DEVILS_R	05953	3/31/1980	4/30/2008	Unknown (Manual)	26.60284840610	-81.12839985080
LABELLE_R	05952	4/1/1980	4/30/2008	Unknown (Manual)	26.75312137980	-81.43868324770
S65_R	05940	3/5/1965	4/30/2008	Unknown (Manual)	27.80305527700	-81.19827915820
GILL REA_R	05807	3/31/1957	1/31/2008	Unknown (Manual)	26.06036587640	-80.23171337540
CORK.HQ_R	05916	11/1/1959	3/31/2007	Unknown (Manual)	26.38369256900	-81.58313292100
CHAPMAN_R	05902	11/7/1968	2/1/2007	Unknown (Manual)	28.00168484850	-81.19367405160

Table 2 List of stations based on recorder type 2

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
ARCHBO 2_R	16604	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.18171543690	-81.43395921230
BELLE GL_R	16595	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.65701023360	-80.62977679680
C18W_R	16603	1/9/1992	7/29/2008	Operational/Maintanence with Multiple Sources	26.87200259590	-80.24504400220
CANAL PT_R	16702	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.86700212790	-80.61644272350
CLEW.FS_R	16696	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.73506462710	-80.89533872850
CORK.HQ_E	16597	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.38369256900	-81.58313292100
CV5_R	16668	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.91951116130	-81.12177060320
FT. LAUD_R	16698	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.06369922170	-80.25949193900
G136_R	16598	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.66767299440	-80.94929719470
G56_R	16611	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.32785518660	-80.13087583980
HOLLYWOOD	16614	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.04842121550	-80.12754354350
HOMES.FS_R	16700	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.47761090670	-80.44838992620
IMMOKA 3_R	16602	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.46146625970	-81.43729565500
KISS.FS2_R	16617	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	28.29056448340	-81.44840001330
L005	16694	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.95673552340	-80.97238091610
L006	16695	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.82175691440	-80.78341609010
LZ40	16631	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.90174235290	-80.78924581950
MC COY	16634	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	28.45166974010	-81.31117586730
MIAMI 2_R	16632	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	25.78370841210	-80.13310014790
MIAMI.AP_R	16615	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.81704171550	-80.28310513320
MIAMI.FS_R	16609	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.82704166310	-80.34421775230
NNRC.SFS	DJ194	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.48479540320	-80.65311091750
OKEE F 2_R	16697	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.25393424370	-80.78727725720
PERRINE_R	16596	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	25.60038324170	-80.34977549610
POF-13	16590	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.94307539510	-81.35478842700
RACOON PT	16708	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	25.96704105610	-81.31646270150
S123	16577	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.61038253610	-80.30782996690
S124_R	16578	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.12925845240	-80.36569899830
S127_R	16573	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.12220559120	-80.89597346510
S129_R	16574	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.02977494840	-81.00145085910
S131_R	16575	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.97922185420	-81.09006411970
S133_R	16576	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.20615719420	-80.80089003390
S135_R	16580	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.08663792270	-80.66134976970
S13_R	16579	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.06612697290	-80.20884162700
S140_R	16581	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.17203010210	-80.82728352480
S153_R	16582	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.98894245310	-80.60449761730
S155_R	16583	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.64478812140	-80.05503909450
S174_R	16584	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.48372268290	-80.56339249030
S177_R	16585	3/18/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.40276844940	-80.55836621430
S18C_R	16659	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.33067259440	-80.52505968200

Table 3 List of stations based on recorder type 2

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
S191_R	16669	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.19193140100	-80.76244819580
S20F_R	16692	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.46288829260	-80.34755450890
S20G_R	16691	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.48947858110	-80.34689773060
S21A_R	16690	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.51935140640	-80.34633569430
S21_R	16689	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.54318716570	-80.33093596130
S26_R	16686	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.80743259430	-80.26049889760
S27_R	16628	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.85097909480	-80.18821674860
S28Z_R	16684	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.91342716010	-80.29310473710
S29Z_R	16685	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.96203641470	-80.26449256950
S29_R	16629	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.92905816090	-80.15147509110
S2_R	16647	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.70034251190	-80.71616761950
S308_R	16588	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.98467999800	-80.62115000130
S30_R	16608	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.95675937980	-80.43144128040
S331_R	16662	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.61093971470	-80.50977915970
S338_R	16661	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	25.66092660440	-80.48123240950
S33_R	16682	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.13584751210	-80.19449168390
S34_R	16683	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.15036304890	-80.44227385790
S352_R	16693	9/23/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.86394676820	-80.63199864290
S36_R	16681	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.17341676180	-80.17837797320
S37A_R	16680	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.20610898220	-80.13165307250
S37B_R	16612	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.22377325970	-80.17046897650
S38_R	16679	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.22980397370	-80.29838110870
S39_R	16677	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.35595086450	-80.29758714300
S3_R	16648	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.69895434790	-80.80728098650
S40_R	16676	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.42157807760	-80.07249941910
S41_R	16675	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.53118087710	-80.05920617790
S44_R	16674	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.81722044730	-80.08056784770
S46_R	16673	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	26.93422309810	-80.14170754690
S49_R	16589	4/25/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.26146340870	-80.35934580270
S5A_R	16645	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.68450861050	-80.36754787070
S65A_R	16572	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.65805333240	-81.13421222380
S65C_R	16657	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.40101995520	-81.11511274760
S65E_R	16621	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.22532322760	-80.96256031810
S65_R	16571	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.80305527700	-81.19827915820
S68_R	16654	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.32990717940	-81.25232899820
S6_R	16651	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.47229533120	-80.44560570210
S70_R	16664	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.11866113410	-81.15728707770
S71_R	16667	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.03386100600	-81.07089528330
S72_R	16666	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.09154318100	-81.00670841770
S77_R	16624	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.83931757220	-81.08534198390
S78_R	16625	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.78978607860	-81.30284709440
S79_R	16587	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.72242197930	-81.69305568760
S7_R	16652	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.33591180850	-80.53671975120
S80_R	16618	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.11116047130	-80.28476725620
S82_R	16655	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.27282194760	-81.20200942260
S83_R	16656	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.26687747970	-81.18100296280
S84	16599	10/21/1993	7/29/2008	Operational/Maintanence with Multiple Sources	27.21615690220	-80.97339393710
S8_R	16606	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.33230148990	-80.77422576490
S97_R	16627	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.20551102140	-80.34071111310
S99_R	16672	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	27.47059184340	-80.47171593760
TAMI AIR_R	16593	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	25.64121571430	-80.42672138340
WPB AIRP_R	16610	1/8/1991	7/29/2008	Operational/Maintanence with Multiple Sources	26.67812039630	-80.10976280090
S5AY_R	16643	1/8/1991	4/1/2008	Operational/Maintanence with Multiple Sources	26.76700429090	-80.49977377570
S65D_R	16658	1/8/1991	3/12/2008	Operational/Maintanence with Multiple Sources	27.31448693740	-81.02283905000
S75_R	16663	10/21/1993	3/12/2008	Operational/Maintanence with Multiple Sources	27.19183183350	-81.12719237920
FORTMYERWS	16594	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	26.58368622070	-81.86647136080
FTL	16613	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	26.09286445990	-80.20643469540
IMMOKALE_R	16601	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	26.39313535540	-81.40701773450
NAPLES_R	16633	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	26.16814625220	-81.78980644300
S332_R	16660	10/21/1993	3/1/2008	Operational/Maintanence with Multiple Sources	25.42178071880	-80.58978260900
S4_R	16650	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	26.78984374420	-80.96171320990
S61_R	16570	1/8/1991	3/1/2008	Operational/Maintanence with Multiple Sources	28.14033177710	-81.35205653780
S9_R	16607	1/8/1991	11/13/2007	Operational/Maintanence with Multiple Sources	26.06160206170	-80.44375240950
FTP FS_R	16591	1/8/1991	9/13/2007	Operational/Maintanence with Multiple Sources	27.36698472550	-80.51421704280

Table 4 List of stations based on recorder type 3

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
S190_R	15988	3/18/1997	7/28/2008	Telemetry (Radio Network)	26.28410586260	-80.96773573990
S21_R	K8670	3/18/1997	7/28/2008	Telemetry (Radio Network)	25.54318716570	-80.33093596130
CV5_R	K7776	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.91951116130	-81.12177060320
HGS5X_R	12737	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.86394676820	-80.63199864290
NNRC.SFS	UJ622	1/1/1999	7/27/2008	Telemetry (Radio Network)	26.48479540320	-80.65311091750
S127_R	K8632	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.12220559120	-80.89597346510
S129_R	K8633	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.02977494840	-81.00145085910
S131_R	K8635	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.97922185420	-81.09006411970
S135_R	K8637	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.08663792270	-80.66134976970
S140_R	K8640	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.17203010210	-80.82728352480
S169_R	K8653	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.76228693620	-80.92311706060
S2_R	K8665	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.70034251190	-80.71616761950
S334_R	K8651	3/18/1997	7/27/2008	Telemetry (Radio Network)	25.76176723770	-80.50227787720
S335_R	K8652	3/18/1997	7/27/2008	Telemetry (Radio Network)	25.77608375960	-80.48294263280
S34_R	K8658	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.15036304890	-80.44227385790
S38_R	K8669	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.22980397370	-80.29838110870
S39_R	K8674	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.35595086450	-80.29758714300
S3_R	K8622	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.69895434790	-80.80728098650
S5A_R	K8682	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.68450861050	-80.36754787070
S68_R	K8686	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.32990717940	-81.25232899820
S6_R	K8685	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.47229533120	-80.44560570210
S70_R	K8689	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.11866113410	-81.15728707770
S71_R	K8690	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.03386100600	-81.07089528330
S72_R	K8691	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.09154318100	-81.00670841770
S7_R	K8688	3/18/1997	7/27/2008	Telemetry (Radio Network)	26.33591180850	-80.53671975120
S82_R	K8694	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.27282194760	-81.20200942260
S83_R	K8695	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.26687747970	-81.18100296280
S97_R	K8698	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.20551102140	-80.34071111310
S99_R	K8699	3/18/1997	7/27/2008	Telemetry (Radio Network)	27.47059184340	-80.47171593760
S133_R	K8636	3/18/1997	7/24/2008	Telemetry (Radio Network)	27.20615719420	-80.80089003390
S177_R	K8656	3/18/1997	7/24/2008	Telemetry (Radio Network)	25.40276844940	-80.55836621430
G136_R	K8623	3/18/1997	7/23/2008	Telemetry (Radio Network)	26.66767299440	-80.94929719470
G57_R	K8628	3/18/1997	7/23/2008	Telemetry (Radio Network)	26.23119207380	-80.12420944350
S13_R	K8634	3/18/1997	7/23/2008	Telemetry (Radio Network)	26.06612697290	-80.20884162700
S167_R	K8647	3/18/1997	7/23/2008	Telemetry (Radio Network)	25.50284287930	-80.46505606120
S37B_R	K8667	3/18/1997	7/23/2008	Telemetry (Radio Network)	26.22377325970	-80.17046897650
S84_R	K8696	3/18/1997	7/23/2008	Telemetry (Radio Network)	27.21615690220	-80.97339393710
C18W_R	K7774	3/18/1997	7/22/2008	Telemetry (Radio Network)	26.87200259590	-80.24504400220
G56_R	K8627	3/19/1997	7/22/2008	Telemetry (Radio Network)	26.32785518660	-80.13087583980
S332_R	K8650	3/18/1997	7/22/2008	Telemetry (Radio Network)	25.42178071880	-80.58978260900
S338_R	K8654	3/18/1997	7/22/2008	Telemetry (Radio Network)	25.66092660440	-80.48123240950

Table 5 List of stations based on recorder type 3

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
S36_R	K8663	3/18/1997	7/22/2008	Telemetry (Radio Network)	26.17341676180	-80.17837797320
S37A_R	K8664	3/18/1997	7/22/2008	Telemetry (Radio Network)	26.20610898220	-80.13165307250
S44_R	K8678	3/18/1997	7/22/2008	Telemetry (Radio Network)	26.81722044730	-80.08056784770
S8_R	K8693	3/18/1997	7/22/2008	Telemetry (Radio Network)	26.33230148990	-80.77422576490
G200_R	K8701	3/18/1997	7/21/2008	Telemetry (Radio Network)	26.41702056990	-80.78311452430
S123	K8630	3/18/1997	7/21/2008	Telemetry (Radio Network)	25.61038253610	-80.30782996690
S27_R	K8673	3/18/1997	7/21/2008	Telemetry (Radio Network)	25.85097909480	-80.18821674860
S28Z_R	K8619	3/18/1997	7/21/2008	Telemetry (Radio Network)	25.91342716010	-80.29310473710
S40_R	K8675	3/18/1997	7/21/2008	Telemetry (Radio Network)	26.42157807760	-80.07249941910
S41_R	K8677	3/18/1997	7/21/2008	Telemetry (Radio Network)	26.53118087710	-80.05920617790
S47B_R	K8680	3/18/1997	7/21/2008	Telemetry (Radio Network)	26.85811606170	-81.13895464840
S153_R	K8643	3/18/1997	7/20/2008	Telemetry (Radio Network)	26.98894245310	-80.60449761730
S18C_R	K8660	3/18/1997	7/20/2008	Telemetry (Radio Network)	25.33067259440	-80.52505968200
S20F_R	K8666	3/18/1997	7/20/2008	Telemetry (Radio Network)	25.46288829260	-80.34755450890
S30_R	K8638	3/18/1997	7/20/2008	Telemetry (Radio Network)	25.95675937980	-80.43144128040
S331_R	P6930	3/7/2003	7/20/2008	Telemetry (Radio Network)	25.61093971470	-80.50977915970
S46_R	K8679	3/18/1997	7/20/2008	Telemetry (Radio Network)	26.93422309810	-80.14170754690
S49_R	K8681	3/18/1997	7/20/2008	Telemetry (Radio Network)	27.26146340870	-80.35934580270
S75_R	K8692	3/18/1997	7/20/2008	Telemetry (Radio Network)	27.19183183350	-81.12719237920
G331D_R	PT420	8/3/2005	7/17/2008	Telemetry (Radio Network)	26.42065363030	-80.51756069300
G54_R	K8626	3/18/1997	7/17/2008	Telemetry (Radio Network)	26.09488054070	-80.22984429440
S125_R	MJ469	1/1/1999	7/17/2008	Telemetry (Radio Network)	26.16425096980	-80.29754802710
S124_R	K8631	3/18/1997	7/16/2008	Telemetry (Radio Network)	26.12925845240	-80.36569899830
S179_R	K8657	3/18/1997	7/16/2008	Telemetry (Radio Network)	25.47372183880	-80.41450033290
S155_R	K8645	3/18/1997	7/15/2008	Telemetry (Radio Network)	26.64478812140	-80.05503909450
S174_R	V7571	7/24/2007	7/14/2008	Telemetry (Radio Network)	25.48372268290	-80.56339249030
S20G_R	K8668	3/18/1997	7/14/2008	Telemetry (Radio Network)	25.48947858110	-80.34689773060
S21A_R	K8671	3/18/1997	7/14/2008	Telemetry (Radio Network)	25.51935140640	-80.34633569430
S9_R	UJ621	5/8/2001	7/14/2008	Telemetry (Radio Network)	26.06160206170	-80.44375240950
S165_R	K8646	3/18/1997	7/13/2008	Telemetry (Radio Network)	25.54260809750	-80.40949962740
S26_R	K8672	3/18/1997	7/13/2008	Telemetry (Radio Network)	25.80743259430	-80.26049889760
S29Z_R	K8621	3/18/1997	7/13/2008	Telemetry (Radio Network)	25.96203641470	-80.26449256950
S29_R	K8620	3/18/1997	7/13/2008	Telemetry (Radio Network)	25.92905816090	-80.15147509110
S33_R	K8648	3/18/1997	7/13/2008	Telemetry (Radio Network)	26.13584751210	-80.19449168390
S154_R	K8644	3/18/1997	7/9/2008	Telemetry (Radio Network)	27.21060152810	-80.91839270130
S191_R	K8662	3/18/1997	7/8/2008	Telemetry (Radio Network)	27.19193140100	-80.76244819580
S174_R	K8655	3/18/1997	7/23/2007	Telemetry (Radio Network)	25.48372268290	-80.56339249030

Table 6 List of stations based on recorder type 4

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
ROTNWX	GE354	12/23/1997	7/29/2008	CR10 (Campbell Scientific Inc.)	26.33200839000	-80.87998992340
3AS3WX	LA375	3/5/2007	7/28/2008	CR10 (Campbell Scientific Inc.)	25.85172632830	-80.76626186310
FHCHSX	V2458	5/17/2007	7/28/2008	CR10 (Campbell Scientific Inc.)	26.65404504380	-80.06824918940
S12D_R	LS269	7/18/2000	7/28/2008	CR10 (Campbell Scientific Inc.)	25.76195478130	-80.68191499340
S59_R	16567	12/26/1995	7/28/2008	CR10 (Campbell Scientific Inc.)	28.26550006170	-81.31113514810
SEBRNG_R	TA405	11/30/2004	7/28/2008	CR10 (Campbell Scientific Inc.)	27.45831450680	-81.35429261520
ACRAWX	UA568	5/26/2006	7/27/2008	CR10 (Campbell Scientific Inc.)	27.12024402140	-80.43211364170
CFSW	15517	10/21/1992	7/27/2008	CR10 (Campbell Scientific Inc.)	26.73506462710	-80.89533872850
DANHP_R	DU537	5/7/1996	7/27/2008	CR10 (Campbell Scientific Inc.)	25.97870843360	-81.48091068880
MIAMI LO_R	16068	12/19/1994	7/27/2008	CR10 (Campbell Scientific Inc.)	26.68201054840	-80.80616988760
MIAMI.FS_R	DU524	4/23/1996	7/27/2008	CR10 (Campbell Scientific Inc.)	25.82704166310	-80.34421775230
S75WX	RQ467	12/29/2003	7/27/2008	CR10 (Campbell Scientific Inc.)	27.19187861030	-81.12800805840
AVEMARIA	VW740	5/21/2008	7/24/2008	CR10 (Campbell Scientific Inc.)	26.30169313440	-81.43136219060
JDWX	G0859	9/12/1997	7/24/2008	CR10 (Campbell Scientific Inc.)	27.02866361290	-80.16532114080
MAXCEY N_R	UA631	6/20/2006	7/24/2008	CR10 (Campbell Scientific Inc.)	27.68364077380	-81.02367105310
S65CW	15473	10/20/1992	7/24/2008	CR10 (Campbell Scientific Inc.)	27.40142848030	-81.11478499350
S65DWX	LJ290	2/23/2000	7/24/2008	CR10 (Campbell Scientific Inc.)	27.31425088980	-81.02215006610
SGGEWX	OR084	9/18/2002	7/24/2008	CR10 (Campbell Scientific Inc.)	26.14537083250	-81.57564333540
SVWX	FI273	5/14/1997	7/24/2008	CR10 (Campbell Scientific Inc.)	27.29031988730	-80.25365730040
3A-NE_R	LX283	8/2/2000	7/23/2008	CR10 (Campbell Scientific Inc.)	26.27876393400	-80.60501990560
ALL2R	HA469	2/19/1998	7/23/2008	CR10 (Campbell Scientific Inc.)	28.19863748040	-81.23990520050
BRYGR	OU142	10/11/2002	7/23/2008	CR10 (Campbell Scientific Inc.)	26.69709360880	-81.48511250160
COLGOV_R	DU536	4/30/1996	7/23/2008	CR10 (Campbell Scientific Inc.)	26.12981437350	-81.76258370660
COLLISEM	DU533	1/30/1996	7/23/2008	CR10 (Campbell Scientific Inc.)	25.99065284550	-81.59146894920
CREEK_R	P2035	12/12/2002	7/23/2008	CR10 (Campbell Scientific Inc.)	28.03882455540	-81.46506388860
ENR101_R	15851	2/11/1994	7/23/2008	CR10 (Campbell Scientific Inc.)	26.64228796930	-80.41754927240
ENR106_R	DU515	5/24/1995	7/23/2008	CR10 (Campbell Scientific Inc.)	26.64923559970	-80.41866081930
ENR203_R	15874	9/29/1993	7/23/2008	CR10 (Campbell Scientific Inc.)	26.64339897830	-80.43338303730
ENR301_R	15877	3/22/1994	7/23/2008	CR10 (Campbell Scientific Inc.)	26.62089997990	-80.43366082090
ENR401_R	15862	8/26/1993	7/23/2008	CR10 (Campbell Scientific Inc.)	26.63006622100	-80.43977210080
EXOTR	HA471	2/11/1998	7/23/2008	CR10 (Campbell Scientific Inc.)	28.15575779650	-81.11506802680
G600_R	G6530	10/20/1997	7/23/2008	CR10 (Campbell Scientific Inc.)	26.36059772120	-80.90566380100
GRIFFITH_R	SO643	7/8/2004	7/23/2008	CR10 (Campbell Scientific Inc.)	27.49475923010	-80.92950299180
IMMOKALE_R	DU523	7/30/1996	7/23/2008	CR10 (Campbell Scientific Inc.)	26.39313535540	-81.40701773450
INDIAN L_R	P6922	1/25/2003	7/23/2008	CR10 (Campbell Scientific Inc.)	27.78780280050	-81.32673259890
KISSFS_R	OU252	7/4/2002	7/23/2008	CR10 (Campbell Scientific Inc.)	28.29056448340	-81.44840001330
L2GW_R	SN311	6/24/2004	7/23/2008	CR10 (Campbell Scientific Inc.)	26.60800282500	-80.94937187600
PC61_R	OH522	4/17/2002	7/23/2008	CR10 (Campbell Scientific Inc.)	27.50484967680	-81.19614740640
S336_R	16713	10/12/1995	7/23/2008	CR10 (Campbell Scientific Inc.)	25.76148944540	-80.49672218270
S65_R	RQ463	2/4/2003	7/23/2008	CR10 (Campbell Scientific Inc.)	27.80305527700	-81.19827915820
S7WX	GG630	1/11/1998	7/23/2008	CR10 (Campbell Scientific Inc.)	26.33591180850	-80.53671975120
WSTWPB_R	UP592	7/28/2006	7/23/2008	CR10 (Campbell Scientific Inc.)	26.68861087370	-80.18805584490
WSTWPB_R	UP594	7/28/2006	7/23/2008	CR10 (Campbell Scientific Inc.)	26.68861087370	-80.18805584490
3A-NW_R	LA365	5/24/2000	7/22/2008	CR10 (Campbell Scientific Inc.)	26.26648313780	-80.77950022500
3A-S_R	HC941	4/8/1998	7/22/2008	CR10 (Campbell Scientific Inc.)	26.08209260090	-80.69154218030
AVON P_R	T0917	7/2/2004	7/22/2008	CR10 (Campbell Scientific Inc.)	27.63169738540	-81.26478729140
BCA17	PT542	6/11/2002	7/22/2008	CR10 (Campbell Scientific Inc.)	26.20494722240	-81.16846111140

Table 7 List of stations based on recorder type 4

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
KRBNR	FZ609	5/15/1997	7/22/2008	CR10 (Campbell Scientific Inc.)	27.46131020260	-81.17114896670
KREFR	FI286	5/16/1997	7/22/2008	CR10 (Campbell Scientific Inc.)	27.50253533050	-81.19533847400
L006	12524	1/27/1989	7/22/2008	CR10 (Campbell Scientific Inc.)	26.82175691440	-80.78341609010
LZ40	13081	4/25/1990	7/22/2008	CR10 (Campbell Scientific Inc.)	26.90174235290	-80.78924581950
OPAL_R	15580	10/23/1992	7/22/2008	CR10 (Campbell Scientific Inc.)	27.32198698100	-80.77533346850
S5AX_R	LS350	4/29/2000	7/22/2008	CR10 (Campbell Scientific Inc.)	26.67895293910	-80.53783021290
S6Z_R	JG018	5/4/1999	7/22/2008	CR10 (Campbell Scientific Inc.)	26.64284381930	-80.58088676830
WPBC_R	TS282	3/24/2006	7/22/2008	CR10 (Campbell Scientific Inc.)	26.76478214230	-80.49866264180
BCA10_R	V2489	6/19/2007	7/21/2008	CR10 (Campbell Scientific Inc.)	25.71399407870	-81.02173609220
BCA14_R	V2491	4/26/2007	7/21/2008	CR10 (Campbell Scientific Inc.)	26.04453762040	-81.29979518060
BCA15	PT536	6/13/2002	7/21/2008	CR10 (Campbell Scientific Inc.)	26.03959500080	-81.02711777630
BCA16	PT539	6/11/2002	7/21/2008	CR10 (Campbell Scientific Inc.)	26.05657500080	-81.15595000100
BCA18	PT545	6/11/2002	7/21/2008	CR10 (Campbell Scientific Inc.)	26.20656805490	-80.98360722140
BCA19	PT548	6/13/2002	7/21/2008	CR10 (Campbell Scientific Inc.)	25.79277777700	-81.20249999860
BCA20	PT551	6/13/2002	7/21/2008	CR10 (Campbell Scientific Inc.)	25.70611111160	-80.93499999980
BCNPA4_R	TA451	3/16/2005	7/21/2008	CR10 (Campbell Scientific Inc.)	25.95759563330	-81.10368020540
BCNPA9_R	TB034	9/27/2005	7/21/2008	CR10 (Campbell Scientific Inc.)	25.77871280920	-80.91201051970
BEELINE_R	TY244	4/12/2006	7/21/2008	CR10 (Campbell Scientific Inc.)	28.45278015240	-81.17811741850
BIG CY SIR	15685	10/21/1992	7/21/2008	CR10 (Campbell Scientific Inc.)	26.32146984830	-81.06784423780
C24SE	JI170	11/29/1998	7/21/2008	CR10 (Campbell Scientific Inc.)	27.33107876940	-80.46293761480
ENR308_R	15888	4/13/1994	7/21/2008	CR10 (Campbell Scientific Inc.)	26.62256656060	-80.43893874330
L001	16021	8/4/1994	7/21/2008	CR10 (Campbell Scientific Inc.)	27.13962310720	-80.78902942170
L005	12515	10/26/1988	7/21/2008	CR10 (Campbell Scientific Inc.)	26.95673552340	-80.97238091610
LOTELA_R	TA345	12/2/2004	7/21/2008	CR10 (Campbell Scientific Inc.)	27.59142168280	-81.43534645320
LOXWS	DU551	12/31/1995	7/21/2008	CR10 (Campbell Scientific Inc.)	26.49896027460	-80.22226642280
MCARTH_R	UA643	5/26/2006	7/21/2008	CR10 (Campbell Scientific Inc.)	27.43864928780	-81.20645336930
OKALN_R	RS692	12/18/2003	7/21/2008	CR10 (Campbell Scientific Inc.)	26.63355959910	-81.35678072390
OKALS_R	RS696	12/19/2003	7/21/2008	CR10 (Campbell Scientific Inc.)	26.52669097470	-81.32225125690
SIX L 3_R	16278	3/20/1995	7/21/2008	CR10 (Campbell Scientific Inc.)	26.23091792380	-81.13034598320
WCA1ME	DU517	2/12/1996	7/21/2008	CR10 (Campbell Scientific Inc.)	26.51062677460	-80.31032429240
BELLE GL	DO532	4/17/1996	7/20/2008	CR10 (Campbell Scientific Inc.)	26.65684143180	-80.63002468820
EAA2	15182	10/31/1991	7/20/2008	CR10 (Campbell Scientific Inc.)	26.55840372090	-80.70922327930
EAA5	15184	11/5/1991	7/20/2008	CR10 (Campbell Scientific Inc.)	26.43646379120	-80.61505461230
FKSTRN_R	SG918	6/10/2004	7/20/2008	CR10 (Campbell Scientific Inc.)	26.14338492680	-81.35041628810
KIRCOF_R	M1208	8/9/2000	7/20/2008	CR10 (Campbell Scientific Inc.)	28.15494443980	-81.42433333820
S140W	15506	10/21/1992	7/20/2008	CR10 (Campbell Scientific Inc.)	26.17129276450	-80.82598904860
S65AMW_R	V8859	6/26/2007	7/20/2008	CR10 (Campbell Scientific Inc.)	27.65937716250	-81.13295352620
SHING.RG	15323	3/12/1992	7/20/2008	CR10 (Campbell Scientific Inc.)	28.37750498870	-81.45034496380
SNIVELY_R	T0933	7/14/2004	7/20/2008	CR10 (Campbell Scientific Inc.)	27.97168553430	-81.41756730960
TICK ISL_R	MX236	1/16/2001	7/20/2008	CR10 (Campbell Scientific Inc.)	27.68586217170	-81.18645218360
WRWX	FF846	4/16/1997	7/20/2008	CR10 (Campbell Scientific Inc.)	28.04834922240	-81.39950674190
ACRA2_R	SX445	7/27/2004	7/19/2008	CR10 (Campbell Scientific Inc.)	27.16140610350	-80.43261225030

Table 8 List of stations based on recorder type 4

Station Name	DBKEY	Start Date	End Date	Recorder Type	Latitude	Longitude
ALICO_R	16224	3/20/1995	7/18/2008	CR10 (Campbell Scientific Inc.)	26.51285130910	-80.98200817380
ELMAX_R	UA602	8/8/2006	7/17/2008	CR10 (Campbell Scientific Inc.)	27.75280461660	-81.07728305050
FPWX	FZ598	9/3/1997	7/17/2008	CR10 (Campbell Scientific Inc.)	26.43258016290	-81.72340781170
GOLDFS2	DU525	7/9/1996	7/17/2008	CR10 (Campbell Scientific Inc.)	26.22842077180	-81.63202434990
ROCK K_R	QS268	11/23/2003	7/17/2008	CR10 (Campbell Scientific Inc.)	27.55788639030	-80.82736972340
SOUTH BA_R	15971	9/15/1994	7/17/2008	CR10 (Campbell Scientific Inc.)	26.66506602450	-80.70116734010
3A-SW_R	JA344	2/19/1999	7/16/2008	CR10 (Campbell Scientific Inc.)	25.98981505800	-80.83617370160
BLUEGOOS_R	HD301	5/3/1998	7/16/2008	CR10 (Campbell Scientific Inc.)	27.21979509420	-80.46506032500
S61W	15484	10/20/1992	7/16/2008	CR10 (Campbell Scientific Inc.)	28.14033177710	-81.35205653780
S78W	15495	10/21/1992	7/16/2008	CR10 (Campbell Scientific Inc.)	26.78978607860	-81.30284709440
SIRG	15730	10/28/1993	7/16/2008	CR10 (Campbell Scientific Inc.)	26.90727933530	-80.19170904610
FTP FS_R	HD299	5/1/1998	7/15/2008	CR10 (Campbell Scientific Inc.)	27.36698472550	-80.51421704280
KENANS1_R	T0958	12/14/2004	7/15/2008	CR10 (Campbell Scientific Inc.)	27.88891159950	-81.01811486110
MAXCEY S_R	UA598	8/4/2006	7/15/2008	CR10 (Campbell Scientific Inc.)	27.54142356860	-81.10033975750
OKEE F 2_R	16285	2/24/1995	7/15/2008	CR10 (Campbell Scientific Inc.)	27.25393424370	-80.78727725720
STA5WX	RQ470	11/30/2003	7/15/2008	CR10 (Campbell Scientific Inc.)	26.44752083220	-80.89019389010
TOHO10_R	JW234	6/24/1999	7/15/2008	CR10 (Campbell Scientific Inc.)	28.20249071900	-81.35043850240
3AS3W3_R	M6888	5/9/2000	7/14/2008	CR10 (Campbell Scientific Inc.)	25.85324262410	-80.76910772670
TMCWX	VM872	2/5/2008	7/14/2008	CR10 (Campbell Scientific Inc.)	27.39694441140	-80.42510915530
BASING_R	QS264	11/20/2003	7/13/2008	CR10 (Campbell Scientific Inc.)	27.40365070900	-81.01144957990
PEAVINE_R	T0919	7/5/2004	7/13/2008	CR10 (Campbell Scientific Inc.)	27.54947906850	-81.02339371530
MARCO_R	PT097	5/14/2003	7/10/2008	CR10 (Campbell Scientific Inc.)	25.93194372470	-81.71197818580
ROOK_R	PT099	5/3/2003	7/10/2008	CR10 (Campbell Scientific Inc.)	26.05083432310	-81.70045998040
ARS B0_R	15582	10/6/1992	7/9/2008	CR10 (Campbell Scientific Inc.)	27.32032027310	-80.84144608330
NAPCON_R	OU145	2/4/2002	7/9/2008	CR10 (Campbell Scientific Inc.)	26.16718701850	-81.78777343220
S331W	16261	7/20/1994	7/9/2008	CR10 (Campbell Scientific Inc.)	25.61093971470	-80.50977915970
BASSETT_R	15577	6/30/1992	7/8/2008	CR10 (Campbell Scientific Inc.)	27.41142848690	-80.92116978350
COCO1_R	DO535	4/19/1996	7/8/2008	CR10 (Campbell Scientific Inc.)	26.27286429930	-81.77980544530
COCO3_R	PT615	4/8/2003	7/8/2008	CR10 (Campbell Scientific Inc.)	26.27320632730	-81.71724567280
CORK_R	DO541	5/30/1996	7/8/2008	CR10 (Campbell Scientific Inc.)	26.42230208320	-81.57868797810
DAVIE2_R	16192	10/31/1991	7/8/2008	CR10 (Campbell Scientific Inc.)	27.26976621510	-80.70533214380
DUP3_R	DO542	8/15/1996	7/8/2008	CR10 (Campbell Scientific Inc.)	26.85894620190	-80.48421744080
INRCTY_R	PS983	3/5/2003	7/8/2008	CR10 (Campbell Scientific Inc.)	28.25593444360	-81.50379305440
VENUS_R	TF254	11/8/2005	7/8/2008	CR10 (Campbell Scientific Inc.)	27.08058777730	-81.33631100360
951EXT_R	DO534	6/19/1996	7/7/2008	CR10 (Campbell Scientific Inc.)	26.30258498560	-81.68841396600
S5A_R	16176	1/26/1995	7/7/2008	CR10 (Campbell Scientific Inc.)	26.68450861050	-80.36754787070
WPBFS_R	GA832	5/21/1997	7/7/2008	CR10 (Campbell Scientific Inc.)	26.68962009050	-80.18482048580
DCRK_R	PT427	8/3/2003	7/2/2008	CR10 (Campbell Scientific Inc.)	26.81622220180	-81.84472222330
GTRSLU_R	PT429	4/20/2004	7/2/2008	CR10 (Campbell Scientific Inc.)	26.80772999610	-81.88323001260
LEHIGH W_R	15464	11/10/1992	7/2/2008	CR10 (Campbell Scientific Inc.)	26.60729522980	-81.64979939860
MBTS	DO555	5/31/1996	7/2/2008	CR10 (Campbell Scientific Inc.)	25.25734134420	-80.42228006540
MDTS	15662	10/11/1991	7/2/2008	CR10 (Campbell Scientific Inc.)	25.27872923380	-80.39505700870
PALMDALE_R	15786	4/16/1992	7/2/2008	CR10 (Campbell Scientific Inc.)	26.92450289550	-81.31395792750
POPASH_R	PT425	9/10/2003	7/2/2008	CR10 (Campbell Scientific Inc.)	26.81457997720	-81.80601076410
TPTS	15658	10/11/1991	7/2/2008	CR10 (Campbell Scientific Inc.)	25.20650998550	-80.37477901510
WHIDDEN3_R	15465	11/9/1992	7/2/2008	CR10 (Campbell Scientific Inc.)	26.94672517380	-81.56618515210
COW CREE_R	JG320	11/21/1998	7/1/2008	CR10 (Campbell Scientific Inc.)	27.35781887530	-80.62977487590
FLYING G_R	7507	3/13/1988	7/1/2008	CR10 (Campbell Scientific Inc.)	27.31393144090	-80.94700406180
JBTS	15083	5/23/1991	7/1/2008	CR10 (Campbell Scientific Inc.)	25.22456572800	-80.54006104190
PEL 23_R	16191	1/30/1995	7/1/2008	CR10 (Campbell Scientific Inc.)	26.81228169810	-80.61005386460
S65E_R	16280	2/23/1995	7/1/2008	CR10 (Campbell Scientific Inc.)	27.22532322760	-80.96256031810
S70_R	16279	3/20/1995	7/1/2008	CR10 (Campbell Scientific Inc.)	27.11866113410	-81.15728707770
MOBLEY_R	15583	9/3/1992	6/3/2008	CR10 (Campbell Scientific Inc.)	27.35337491530	-80.81616762630
PINE ISL_R	T0929	7/21/2004	5/27/2008	CR10 (Campbell Scientific Inc.)	28.11612579730	-81.12645026820
SILVER	MX237	12/6/2000	5/20/2008	CR10 (Campbell Scientific Inc.)	26.30169313440	-81.43136219060
PAIGE_R	16204	1/30/1995	5/5/2008	CR10 (Campbell Scientific Inc.)	26.60562541680	-80.94950710870
SCOTTO	HD784	5/2/1998	4/14/2008	CR10 (Campbell Scientific Inc.)	27.37431852710	-80.45085698010
MICCO_R	LX296	9/1/2000	1/4/2008	CR10 (Campbell Scientific Inc.)	27.47253708580	-81.14395198500
SLT09_R	VG437	12/3/2004	12/31/2007	CR10 (Campbell Scientific Inc.)	27.18319137960	-80.30880305530
SLT26_R	VG446	11/13/2004	12/31/2007	CR10 (Campbell Scientific Inc.)	27.30399969960	-80.30700027630
SLT36_R	VG451	12/3/2004	12/31/2007	CR10 (Campbell Scientific Inc.)	27.14099971740	-80.18800029080
SLT40_R	VG456	11/12/2004	12/31/2007	CR10 (Campbell Scientific Inc.)	27.13800527200	-80.24838639290

RAIN AREAS

Rainfall areas (or rain areas) are defined to represent the physical processes responsible for, or affecting, the genesis and morphology of rainfall processes near the coast and inland. The delineation of these areas in south Florida is recently discussed in a study by Vieux (2006). The rainfall patterns are complex because they are influenced by local convergence zones and sea breeze effects near the coast that enhance precipitation, by inland gradients, and large water bodies such as Lake Okeechobee (in south Florida) that tends to suppress rainfall processes. Another factor affecting the rainfall patterns come from both frontal boundaries and hurricanes, which can produce rainfall gradients that vary in a north-south direction depending on path and location of stalled fronts and storms (Vieux, 2006). It would be interesting to investigate how the rain areas will affect the in-filling processes, both spatially and temporally. The main objective of the study is to in-fill rainfall records based on NEXRAD data using a mathematical programming model to identify clusters of NEXRAD grids surrounding a rain gage. Investigation of spatial and temporal variability of clusters (identified by weights) is also carried out as a part of this study.

OPTIMIZATION, SPATIAL INTERPOLATION AND DATA DRIVEN MODELS

Optimization, spatial interpolation and data driven models were developed for infilling of missing rain gage data. Details of these models are provided in next few sections.

Superstructure of Optimization Formulations

Several optimum weighting method formulations proposed and developed in the current study adopt a general structure of mixed-integer nonlinear programming (minlp) formulation. The structure is given by the set of equations 1-5. The superstructure form is adopted from Floudas (1995) and Teegavarapu and Simonovic (2000) is given by

$$\text{Minimize} \quad f(x,y) \tag{1}$$

Subject to

$$h(x,y) = 0 \tag{2}$$

$$g(x,y) \leq 0 \tag{3}$$

$$x \in X \subseteq \Re^n \tag{4}$$

$$y \in Y \ = \{0,1\}^{\tau} \quad (5)$$

where x is a vector of n continuous variables, y is a vector of r 0-1 (integer) variables, $h(x,y)=0$ are m equality constraints, $g(x,y)\leq 0$ are p inequality constraints, and $f(x,y)$ is the objective function which is a performance evaluation function that needs to minimized. If the integer variables are 0-1variables (i.e., binary variables), then the formulation is referred to mixed-integer nonlinear programming (minlp) model with binary variables. In case of general mathematical programming formulations, the constraints are functional relationships which relate variables in the formulation. However, in case of problem formulations defined in the current study, historical data need to be used simultaneously along with evaluation of objection function. Optimization solvers such as DICOPT (Discrete Continuous OPTimizer) under GAMS (general algebraic modeling system) or generalized reduced gradient (GRG) algorithm with branch and bound method available under Excel environment can be used for can be used for solution of these formulations. In GAMS environment, the constraints and objective function can be specified in algebraic form and the formulation can be solved with nonlinear and mixed integer linear solvers. In the current study a total of 12 optimization and 3 data-driven models were developed. The model variants are qualified based on different objective function and constraints. Details of these models are provided in the Table 9.

Table 9 Models investigated for in-filling of precipitation data

Model	Objective Function	Constraints	Approach
1	Sum of Squarred Error	Weights	NLP
2	Sum of Absolute Error	Weights	NLP
3	Sum of Squarred Error	Weights	MINLP
4	Sum of Squarred Error	Weights	NLP
5	None	None	Interpolation
6	None	None	Interpolation
7	Root Mean Squarred Error	Weights	NLP
8	Mean Absolute Error	Weights	NLP
9	Sum of Squarred Error	Weights	NLP
10	Sum of Squarred Error	Weights, Number of pixels	MINLP
11	Sum of Squarred Error	Weights	NLP
12	Sum of Squarred Error	Weights, Number of pixels	MINLP
13	Mean Squarred Error	Connection Weights, Ranges	Function Approximation - ANN
14	Sum of Squarred Error	Exponents	NLP
15	Sum of Squarred Error	Weights	NLP

NLP Nonlinear Programming
MINLP Mixed Integer Non Linear Programming
ANN Artificial Neural Network

DESCRIPTIONS AND FORMULATIONS OF MODELS

The following section describe the formulations developed for the optimization models and other data driven models adopted in the current study for infilling of rain gage data using NEXRAD based rainfall estimates. All the formulations use the grid structure of 9 NEXRAD grids shown in Figure 1. The grid is selected for each rain gage station in such a way that the rain gage is always located in the central grid cell (j=5 or cell "E"). The size of each cell (grid) has a spatial resolution of 2km x 2km. The words gird, pixel and cell are used interchangeably in the report. However they all mean the NEXRAD 2k x 2km grid with radar based precipitation estimate available.

A j=1	B j=2	C j=3
D j=4	E j=5	F j=6
G j=7	H j=8	I j=9

Figure 1. Grid structure used for development of mathematical programming formulations

Model 1:

Minimize

$$\sum_{i=1}^{no} (\hat{\phi}_i^m - \phi_i^m)^2 \qquad (6)$$

Subject to:

$$\phi_i^m = \frac{\sum_{j=1}^{ns} w_{mj}^k \theta_i^j}{\sum_{j=1}^{ns} w_{mj}^k} \qquad \forall i \qquad (7)$$

$$0 \leq w_{mj}^k \leq 1 \qquad \forall m, j \qquad (8)$$

The ϕ_i^m is the estimated observation at the rain gage station m; ns is the number of NEXRAD grids surrounding the rain gage which is equal to 9; θ_i^j is the NEXRAD based observation for grid, j, w^k_{mj} is the weight associated in relation to grid i to the grid m; and k is referred to as friction distance (Vieux, 2001) that usually ranges from 1.0 to 6.0 in distance based weighting methods.

Model 2:

The formulation for model 2 is same as model 1 excepting the objective function is different and is given by the equation 9.

Minimize

$$\sum_{i=1}^{no} \left| \hat{\phi}_i^m - \phi_i^m \right| \qquad (9)$$

Model 3:

In this formulation for model 3, one additional constraint is added as given by equation 12.

Minimize

$$\sum_{i=1}^{no} (\hat{\phi}_i^m - \phi_i^m)^2 \qquad (10)$$

Subject to:

$$\phi_i^m = \frac{\sum_{j=1}^{ns} w_{mj}^k \theta_i^j}{\sum_{j=1}^{ns} w_{mj}^k} \qquad \forall i \qquad (11)$$

$$\sum_{1}^{ns} w_{mj}^k = 1 \qquad \forall m, j, k \qquad (12)$$

Model 4:

In this formulation, binary variables are introduced to aid in selecting the appropriate stations in the optimal weighting of NEXRAD based precipitation estimates**.**

$$\phi_i^m = \frac{\sum_{j=1}^{ns} \lambda_j (\theta_i^j w_{mj}^k)}{\sum_{j=1}^{ns} \lambda_j w_{mj}^k} \qquad \forall i, j \qquad (13)$$

The variable λ_j is a binary variable associated each grid j.

Model 5:

Model 5 is a simple interpolation scheme in which the missing value for rain gage is estimated by average of all the NEXRAD based observations available in all the surround grids including the grid in which the rain gage is located.

$$\phi_i^m = \frac{\sum_{j=1}^{ns} \theta_i^j}{ns} \qquad \forall i, j \qquad (14)$$

Model 6:

Model 6 is again simple interpolation scheme in which the missing value for rain gage is estimated by equating it to the NEXRAD based observation for the grid in which the rain gage is located.

$$\phi_i^m = \theta_i^j \qquad \forall i, j \qquad (15)$$

$$j \in j' \qquad (16)$$

Model 7:

The formulation for model 7 is same as model 1 excepting the objective function, RMSE, is different is given by the equation 17.

Minimize

$$\left(\frac{\sum_{i=1}^{no} (\hat{\phi}_i^m - \phi_i^m)^2}{no} \right)^{0.5} \qquad (17)$$

Subject to:

$$\phi_i^m = \frac{\sum_{j=1}^{ns} w_{mj}^k \theta_i^j}{\sum_{j=1}^{ns} w_{mj}^k} \qquad \forall i \qquad (18)$$

Subject to:

$$0 \le w_{mj}^k \le 1 \qquad \forall m, j \qquad (19)$$

Model 8:

The formulation for model 8 is same as model 1 excepting the objective function, MAE, is different is given by the equation 20.

Minimize

$$\frac{\sum_{i=1}^{no}\left|\hat{\phi}_i^m - \phi_i^m\right|}{no} \qquad (20)$$

Model 9:

The model formulation described here is a traditional inverse distance weighting approach.

Minimize

$$\sum_{i=1}^{no}(\hat{\phi}_i^m - \phi_i^m)^2 \qquad (21)$$

Subject to:

$$\phi_i^m = \frac{\sum_{i=1}^{ns}\theta_i d_{m,i}^{-k}}{\sum_{i=1}^{ns} d_{m,i}^{-k}} \qquad (22)$$

Model 10:

In this formulation, binary variables are introduced to aid in selecting the appropriate number of NEXRAD grid values in the optimal weighting of NEXRAD based precipitation estimates. An upper limit on the number of the NEXRAD grid based values is established using the variable, np.

Minimize

$$\sum_{i=1}^{no}(\hat{\phi}_i^m - \phi_i^m)^2 \qquad (23)$$

Subject to:

$$\phi_i^m = \frac{\sum_{j=1}^{ns} \lambda_j (\theta_i^j w_{mj}^k)}{\sum_{j=1}^{ns} \lambda_j w_{mj}^k} \qquad \forall i,\, j \tag{24}$$

$$\sum_{1}^{ns} w_{mj}^k = 1 \qquad \forall m, j, k \tag{25}$$

$$\sum_{j=1}^{n} \lambda_j = np \tag{26}$$

In this formulation, the np value is set to 3.

Model 11:

This formulation uses the tradition inverse distance weighting method with optimal exponent values obtained through optimization. The variable *dr* is distance of the rain gage located in grid j=5 and any nearby rain gage and *nsr* is number of rain gages used in this formulation. The formulation is given by equations 27 and 28.

Minimize

$$\sum_{i=1}^{no} (\hat{\phi}_i^m - \phi_i^m)^2 \tag{27}$$

Subject to:

$$\phi_i^m = \frac{\sum_{i=1}^{nsr} \theta_i dr_{m,i}^{-k}}{\sum_{i=1}^{nsr} dr_{m,i}^{-k}} \tag{28}$$

Model 12

In this formulation, binary variables are introduced to aid in selecting the appropriate number of NEXRAD grid values in the optimal weighting of NEXRAD based precipitation estimates. An upper limit on the number of the NEXRAD grid based values is established using the variable, np and is equal to 6.

$$\sum_{j=1}^{n} \lambda_j = np \qquad (29)$$

Model 13:

A data-driven universal functional approximation model using artificial neural networks (ANN) is developed and is referred to as model 13. The description of the model is provided below.

Artificial Neural Network (ANN)

The ANN architecture used in the current study is shown in the Figure 2. The structure uses on hidden layer with 9 neurons (9 NEXRAD based precipitation values from the 9 pixels (grids) surrounding the rain gage along with the grid in which the rain gage is located) and 1 output neuron. A back-propagation feed-forward network was used to train the network using a best net search method. A post processor for correcting the negative precipitation estimates was also used in case the ANN provides a negative output.

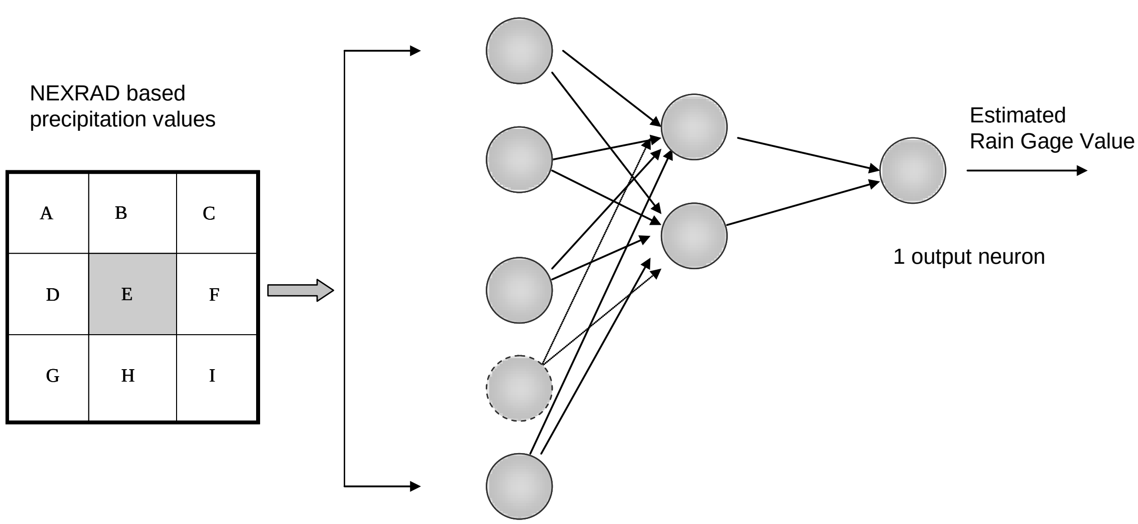

Figure 2. Architecture of Artificial Neural Network used in the current study

Model 14:

Model 14 is a variation of a traditional inverse distance weighting methods in which the weights are now replaced by correlation coefficients with exponents. The correlation coefficients are calculated based on historical (calibration) data.

$$\phi_i^m = \sum_{j=1}^{ns} (\theta_i^j \rho_{mj}^k) \qquad \forall i, j \qquad (30)$$

Model 15

In this formulation, grid based NEXRAD precipitation estimates and rain gage observations in the vicinity of the rain gage with missing observations are used in an optimal weighting scheme.

$$\phi_i^m = \sum_{j=1}^{ns} (w_{mj} \theta_i^j) + \sum_{jr=1}^{nr} (w_{jr} \theta_i^{jr}) \qquad \forall i \qquad (31)$$

The variable, nr is the number of rain gages used in the optimal weighting scheme, jr is the index for rain gage, θ_i^{jr} is the rain gage observation.

Model 16

Cluster based approaches for infilling missing precipitation records are also being investigated in the current study. A general mathematical programming formulation based on one such method is provided below.

$$\text{Minimize } \sum_{i=1}^{no} (\hat{\phi}_i^m - \phi_i^m)^2 \qquad (32)$$

$$\theta_i^m = \sum_{j=1}^{nc} \sum_{i=1}^{N} \lambda_{ij} \phi_i^j w_{mj}^k \qquad (33)$$

$$\sum_{i=1}^{N-1} \lambda_{ij} \leq (N-1)\, nc^{-1} \quad \forall j \qquad (34)$$

$$\sum_{j=1}^{nc} \sum_{i=1}^{N} \lambda_{ij} \leq N \qquad (35)$$

or

$$\sum_{j=1}^{nc} \sum_{i=1}^{N} \lambda_{ij} \leq np \qquad (36)$$

where θ_m is the observation at the rain gage station m; ns is the number of ; θ_i is the observation at rain gage station i, w_{mj} is the weight associated in relation to NEXRAD grid i to the station m, $\lambda_{ij:}$ binary variable, N is the number of grids, nc: cluster size, and np is the upper bound on the number of cells used. A schematic showing the location of the rain gage and location of surrounding NEXRAD grids is shown in Figure 1. The objective is to investigate the changes in the clusters over different time periods or seasons as illustrated in Figure 3.

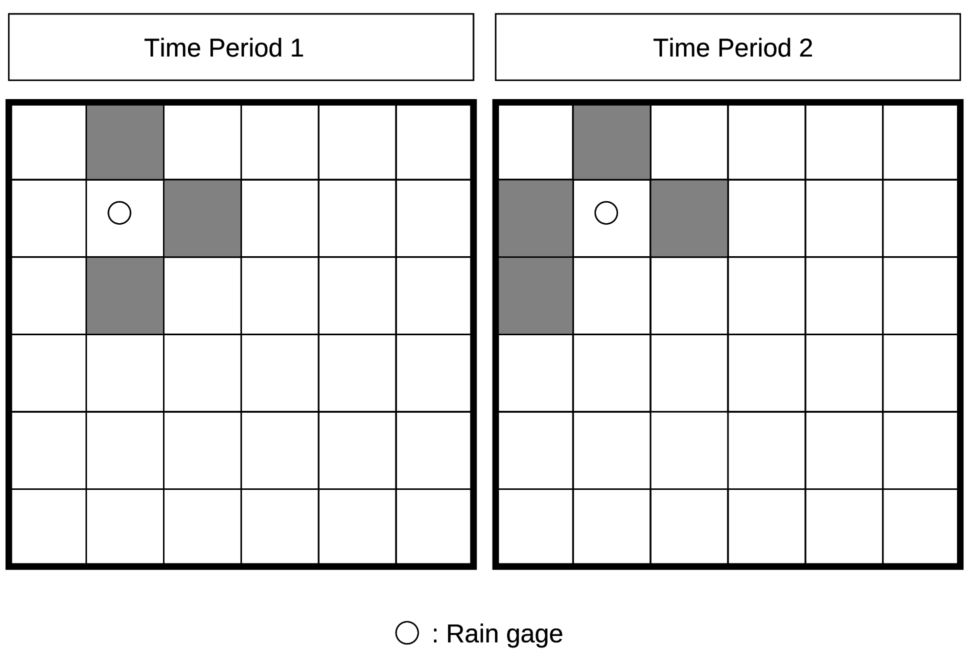

Figure 3. Schematic of location of a rain gage and NEXRAD grids for two time periods.

APPLICATION OF MODELS

The mathematical programming models for in-filling rainfall data are tested for application in SFWMD where the radar-based (NEXRAD) rainfall data is available (refer to Figure 4). To evaluate the models developed in the study, 27 rain gage stations are selected from the SFWMD region. The station identification numbers and their locations are provided in Table 14. The locations of these stations in space are shown in Figure 5. To evaluate the spatial variation of optimal weights 5 rain areas in the study area along with rainfall data from 5 rain gages are used Data from years 2002 -2004 was selected for testing. The following sections describe the application of the models and results.

Table 10. Locations of selected stations

STATION	Latitude	Longitude
BLUEGOOS_R	27.220	-80.465
CHAPMAN_R	28.002	-81.194
COLGOV_R	26.130	-81.763
CORK_R	26.422	-81.579
EAA2	26.558	-80.709
FKSTRN_R	26.144	-81.350
FTP FS_R	27.367	-80.514
G54_R	26.095	-80.230
G56_R	26.328	-80.131
IMMOKA 3_R	26.461	-81.437
IMMOKALE_R	26.393	-81.407
KISSFS_R	28.291	-81.448
L006	26.822	-80.783
LZ40	26.902	-80.789
S123	25.610	-80.308
S124_R	26.129	-80.366
S18C_R	25.331	-80.525
S2_R	26.700	-80.716
S20F_R	25.463	-80.348
S36_R	26.173	-80.178
S38_R	26.230	-80.298
S49_R	27.262	-80.359
S59_R	28.266	-81.311
S6Z_R	26.643	-80.581
S97_R	27.205	-80.341
S99_R	27.471	-80.472
TOHO10_R	28.202	-81.350

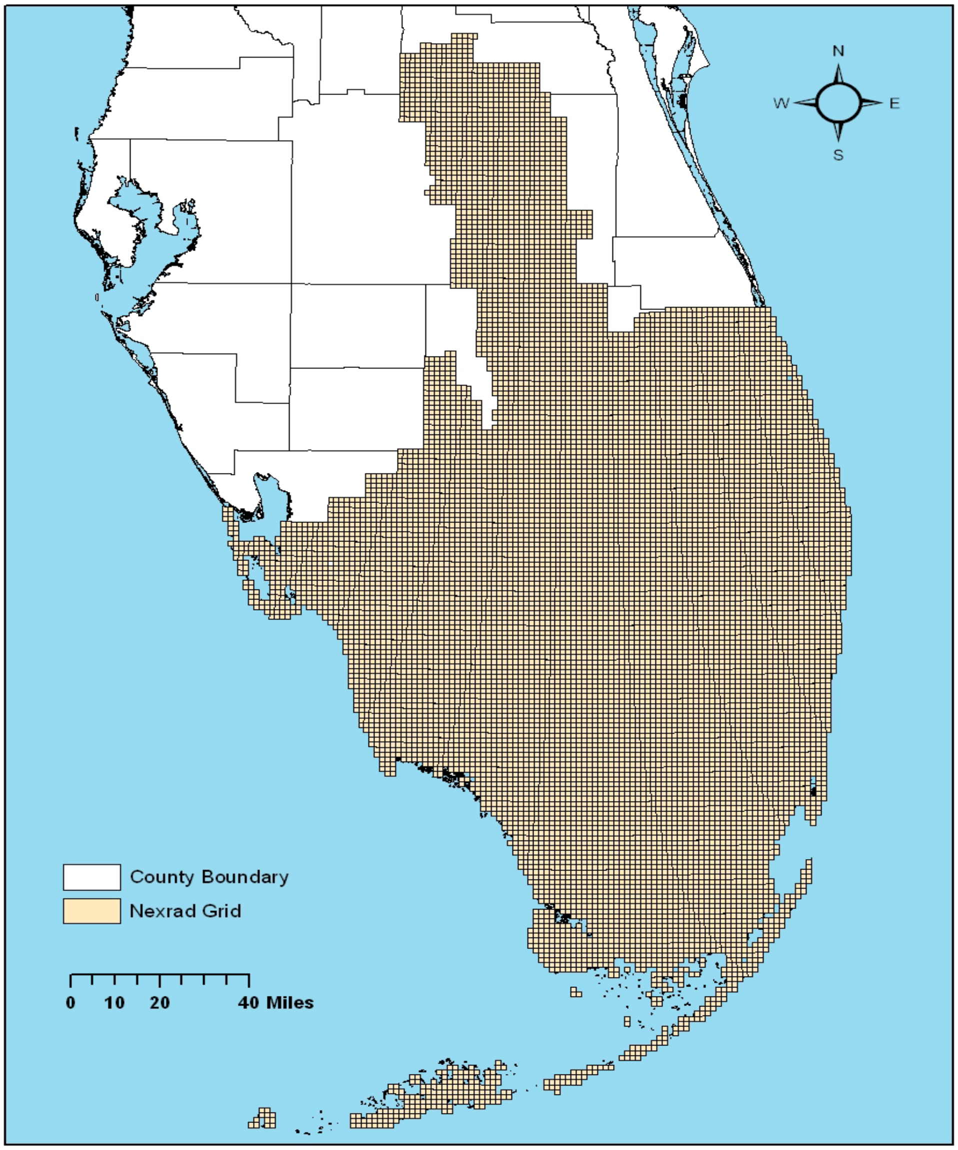

Figure 4: NEXRAD (2km x 2 km) grid overlaid in the SFWMD region

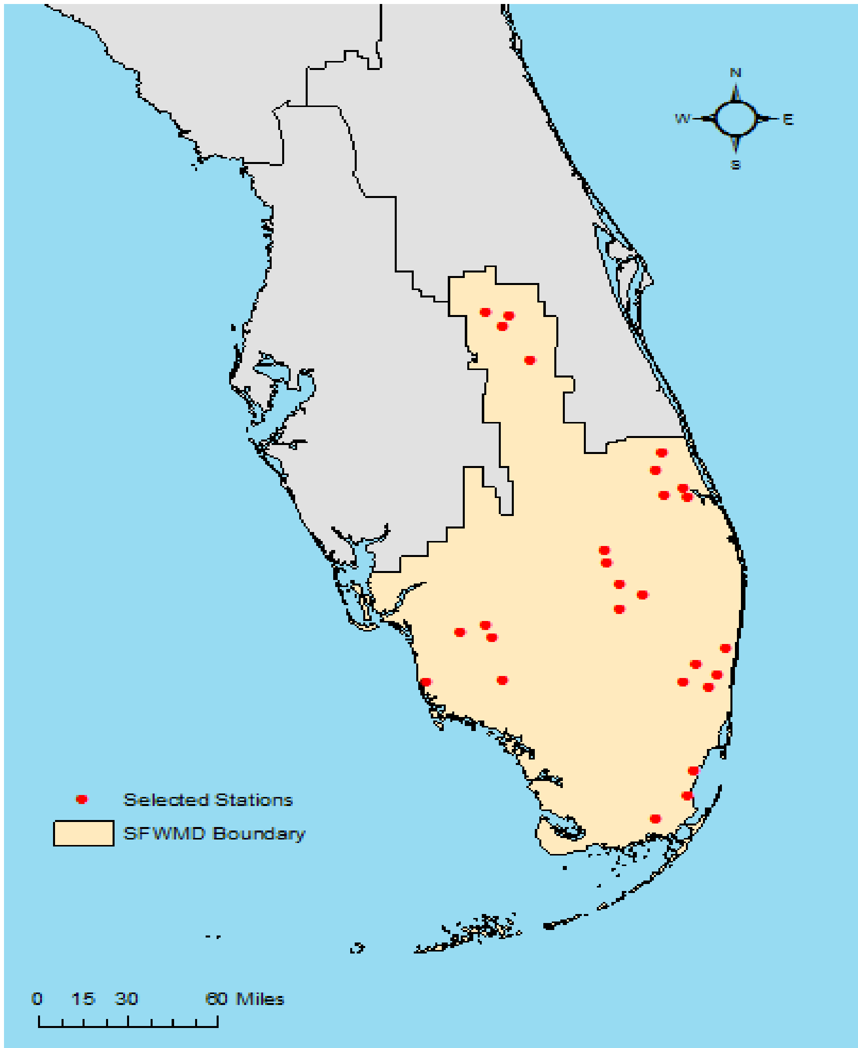

Figure 5. Location of selected stations in SFWMD region

Distances from the rain gage to the centroids of the surrounding NEXRAD cells are calculated for all the 27 rain gage stations and also for all the 268 rain gage stations in the SFWMD region. Average distances in miles for these two sets of stations are shown in Figures 6 and 7. It is interesting to note that the average distances for these two sets of rain gage stations are similar in magnitude.

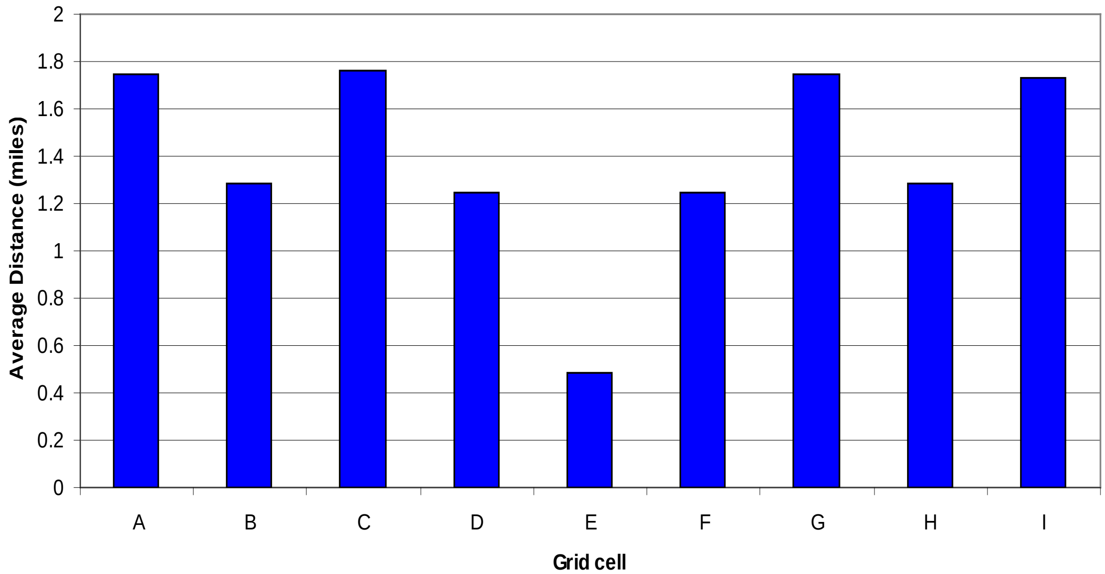

Figure 6. Average distance of the rain gage to the centroid of different grid cells for 27 stations

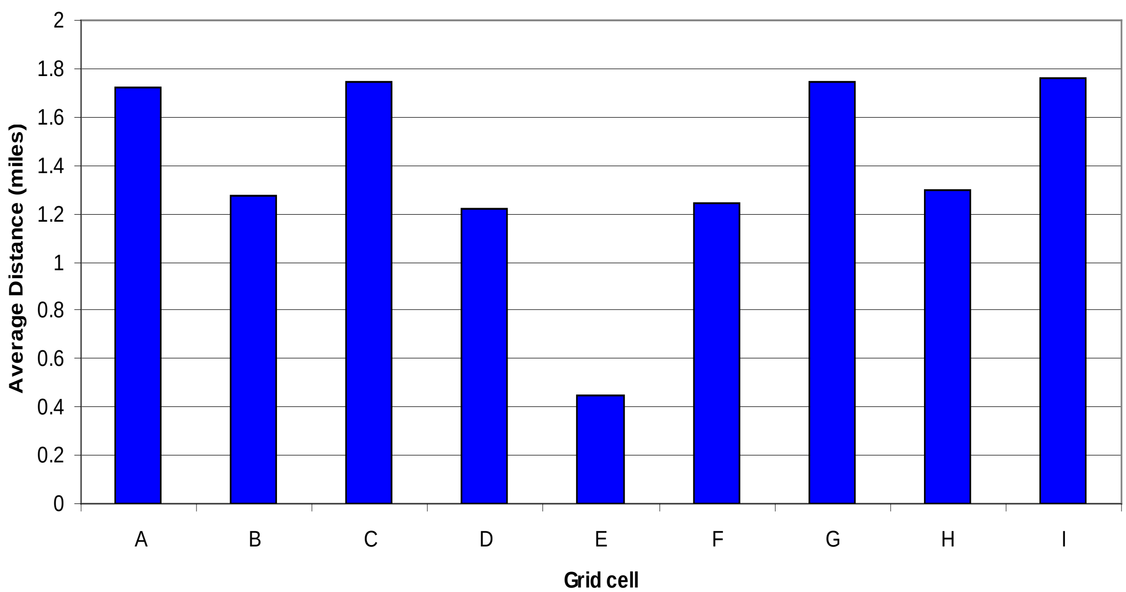

Figure 7. Average distance of the rain gage to the centroid of different grid cells for 286 stations

Distribution of distances from grid cells: A to I to the rain gage locations are shown in Figures 8, 9 and 10. These distances are essential for interpolation and optimization models used for infilling missing precipitation data.

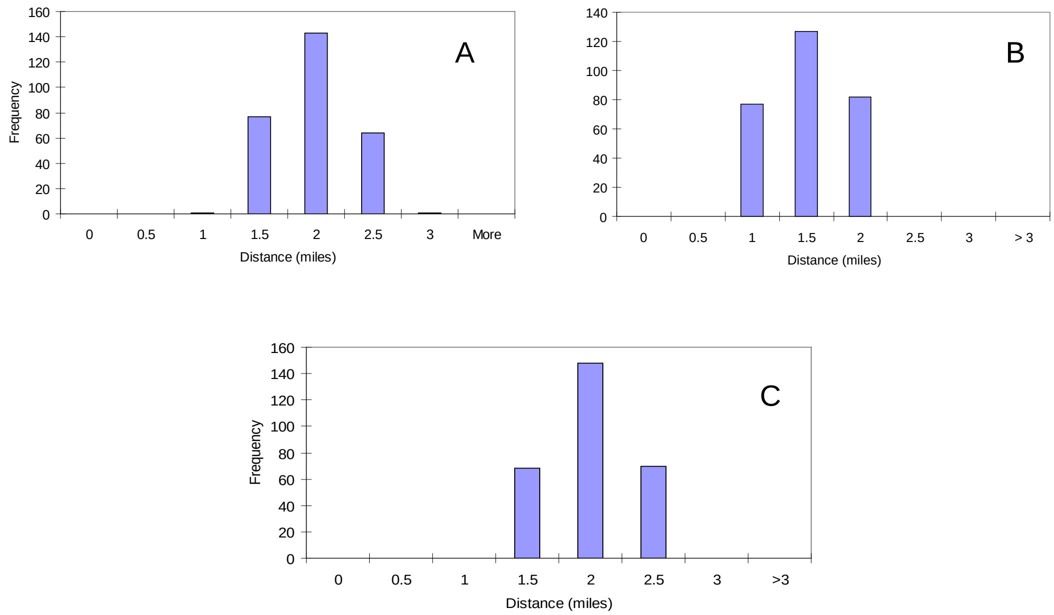

Figure 8. Distribution of distances of the rain gage to the centroid for different grid cells based on 286 rain gage stations

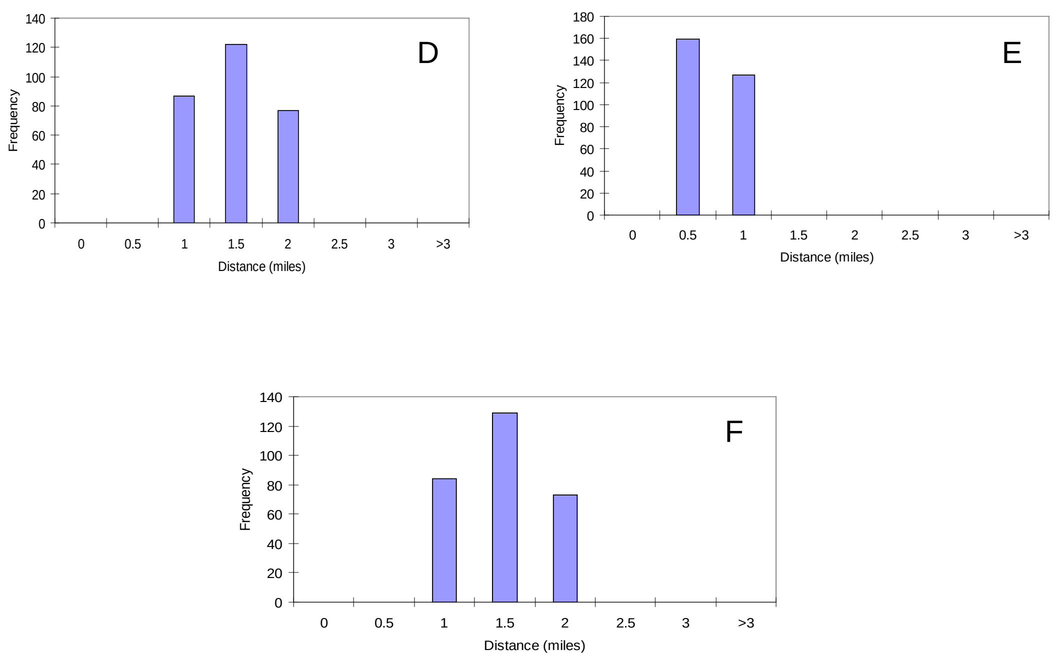

Figure 9. Distribution of distances of the rain gage to the centroid of different grid cells based on 286 rain gage stations

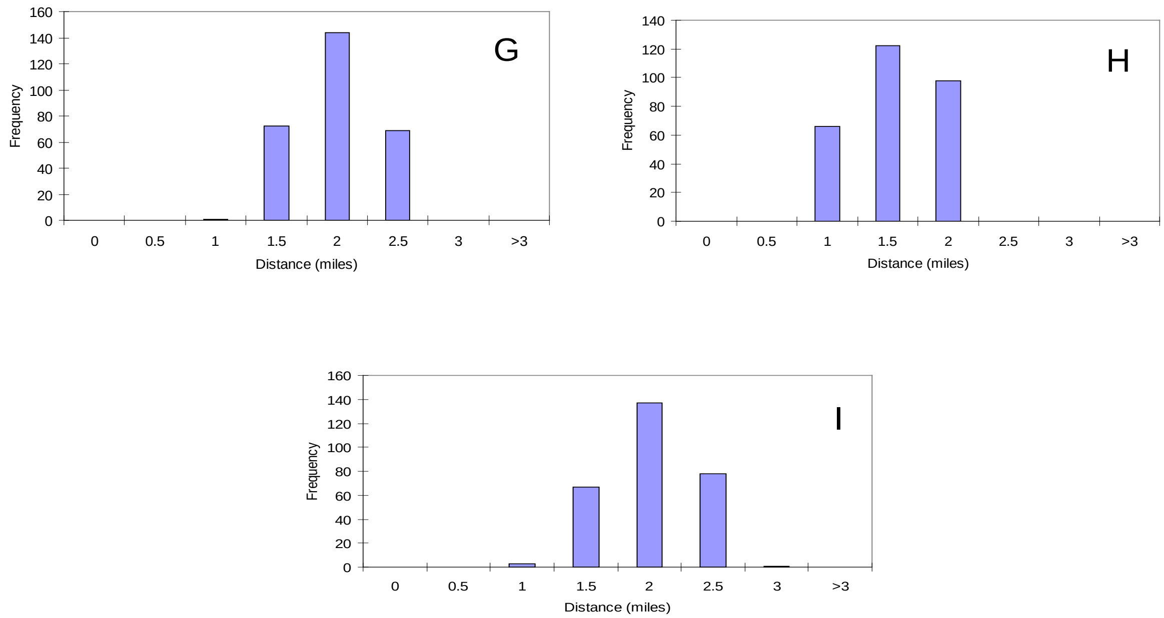

Figure 10. Distribution of distances of the rain gage to the centroid of different grid cells based on 286 rain gage stations

Depending on the data availability, the number of rain gage stations in the vicinity of a gage missing rainfall data used for optimal weighting schemes change for different stations. These numbers are provided in Table 16.

Table 11. Number of rain gage stations used in Model 15

Station Name	Number of stations
BLUEGOOS_R	2
CHAPMAN_R	2
COLGOV_R	3
CORK_R	4
EAA2_COMP	2
FKSTRN_R	2
FTP FS_R	2
G54_R	4
G56_R	2
IMMOKA 3_R	2
IMMOKALE_R	2
KISSFS_R	4
L006	2
LZ40	4
S123	4
S124_R	2
S18C_R	3
S2_R	4
S20F_R	3
S36_R	2
S38_R	3
S49_R	4
S59_R	3
S6Z_R	4
S97_R	2
S99_R	4
TOHO10_R	4

RESULTS AND ANALYSIS

The optimization models are formulated and solved using nonlinear mathematical programming solver. The solver uses a generalized reduced gradient search method and has the capability of including real and binary variables in the formulations. Approximately 67% data are used to obtain optimal weights, cluster size and station selection and 33% of the data are used for testing the methods.

PERFORMANCE EVALUATIONS OF DIFFERENT MODELS

The performance of the methods are compared using widely recognized and commonly used error measures (Kanevski and Maignan, 2004; Chang, 2004; Ahrens, 2006), root mean squared error (RMSE), mean absolute error (AE) and goodness-of-fit measure criterion, coefficient of correlation (ρ), based on actual and estimated rainfall values at the base station. The error measures are given by the equations 37- 40.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{\phi}_i - \phi_i)^2} \quad (37)$$

$$AE = \sum_{i=1}^{n}\left|\hat{\phi}_i - \phi_i\right| \quad (38)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{\phi}_i - \phi_i\right| \quad (39)$$

$$\rho = \frac{\sum(\hat{\phi}_i - \mu_g)(\phi_i - \mu_n)}{(n-1)\sigma_g \sigma_n} \quad (40)$$

The average, minimum and maximum values of performance measures from application of models are provided in Tables 12, 13 and 14 respectively. These four measures provide an overall assessment of the models for estimating missing precipitation data.

Table 12. Average values of performance measures for different models

	Performance Measure			
Model	**ρ**	**AE**	**RMSE**	**MAE**
1	0.813	38.855	0.215	0.080
2	0.815	38.337	0.216	0.080
3	0.815	38.289	0.218	0.080
4	0.814	38.860	0.219	0.081
5	0.810	41.490	0.225	0.086
6	0.809	47.850	0.234	0.100
7	0.813	39.512	0.217	0.083
8	0.815	38.338	0.210	0.084
9	0.810	41.103	0.218	0.085
10	0.810	42.070	0.221	0.081
11	0.517	66.029	0.339	0.139
12	0.813	39.358	0.219	0.083
13	0.791	40.280	0.211	0.081
14	0.815	38.236	0.220	0.080
15	0.806	43.696	0.244	0.088

Table 13. Minimum values of performance measures for different models

	Performance Measure			
Model	**ρ**	**AE**	**RMSE**	**MAE**
1	0.235	18.626	0.131	0.050
2	0.235	20.630	0.121	0.039
3	0.238	20.630	0.030	0.039
4	0.228	23.332	0.129	0.046
5	0.233	24.461	0.131	0.048
6	0.230	23.655	0.119	0.046
7	0.237	21.344	0.031	0.041
8	0.230	20.604	0.023	0.039
9	0.233	24.128	0.136	0.047
10	0.230	23.423	0.129	0.046
11	0.051	32.177	0.176	0.061
12	0.238	23.480	0.097	0.046
13	0.220	21.907	0.123	0.032
14	0.235	20.219	0.118	0.038
15	0.099	20.429	0.119	0.029

Table 14. Maximum values of performance measures for different models

	Performance Measure			
Model	**ρ**	**AE**	**RMSE**	**MAE**
1	0.931	89.951	0.550	0.173
2	0.934	93.846	0.570	0.180
3	0.935	93.836	0.569	0.180
4	0.936	95.448	0.585	0.183
5	0.921	105.350	0.572	0.199
6	0.998	185.492	0.611	0.399
7	0.928	89.664	0.549	0.172
8	0.935	93.490	0.571	0.186
9	0.923	105.521	0.567	0.199
10	0.936	122.349	0.581	0.181
11	0.832	122.695	0.633	0.283
12	0.933	95.333	0.587	0.183
13	0.928	91.940	0.540	0.174
14	0.935	92.448	0.568	0.177
15	0.937	133.119	0.743	0.270

WEIGHTING FUNCTIONS

The error measures are used to select the best method out of the 15 methods discussed. The use of several error measures provides several advantages as well few disadvantages in the selection process. The advantages include 1) accurate assessment of performance of methods using different indices, 2) evaluation of error structure and correlation between observed and estimated values. The main disadvantage is that no absolute way of selecting the best method. Therefore, a method by which the error measures are transformed to a common dimensionless parameter that can be used for selection process is required. In the current study weighting functions are proposed as a way of generating non-dimensional weights from each of the error/performance measures.

The functions are designed in such as way, which the maximum value is always attached to the best performance based on a specific error measure. Linear and weighting functions are developed considering the upper and lower bounds of each performance measure. The weighting functions for correlation coefficient, absolute error (AE), root mean squared error (RMSE) and mean absolute error (MAE) are shown in the figures 11, 12, 13 and 14 respectively.

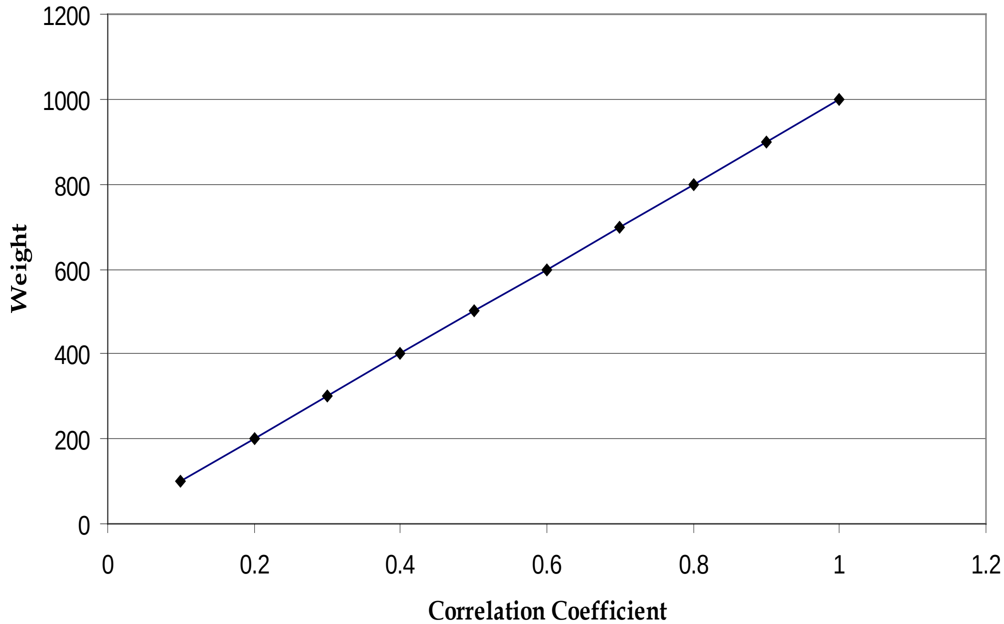

Figure 11. Weight function for correlation coefficient

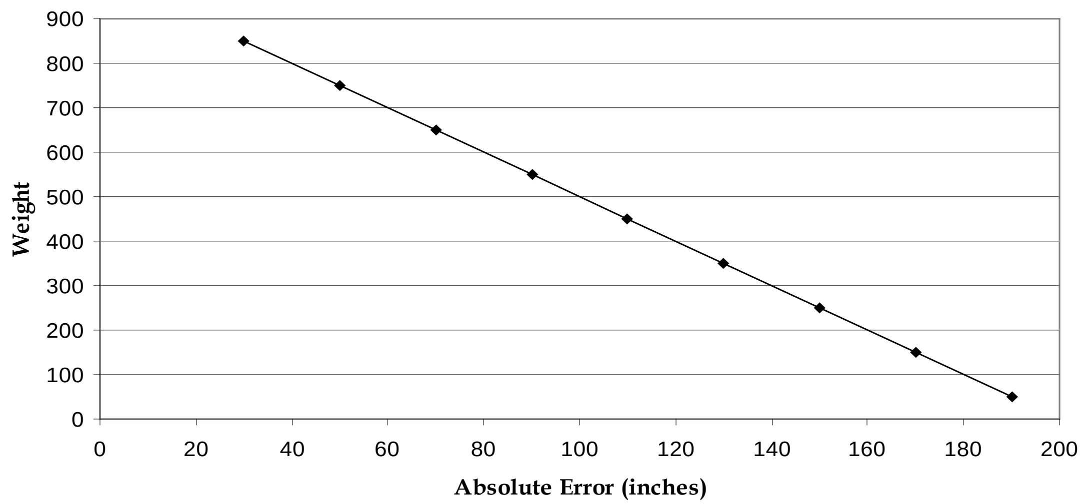

Figure 12. Weight function for absolute error

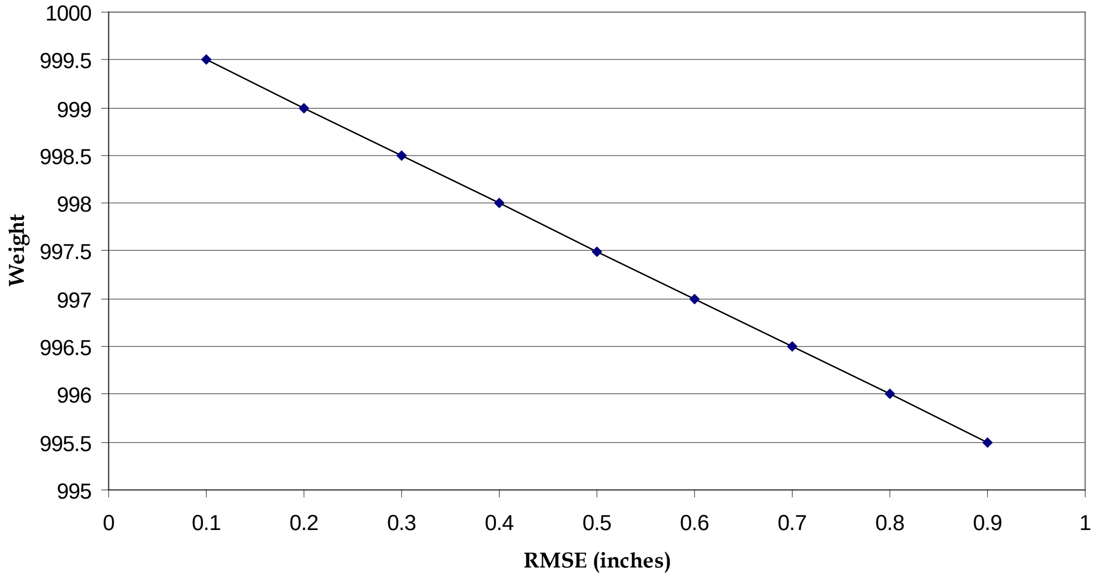

Figure 13. Weight function for root mean squared error (RMSE)

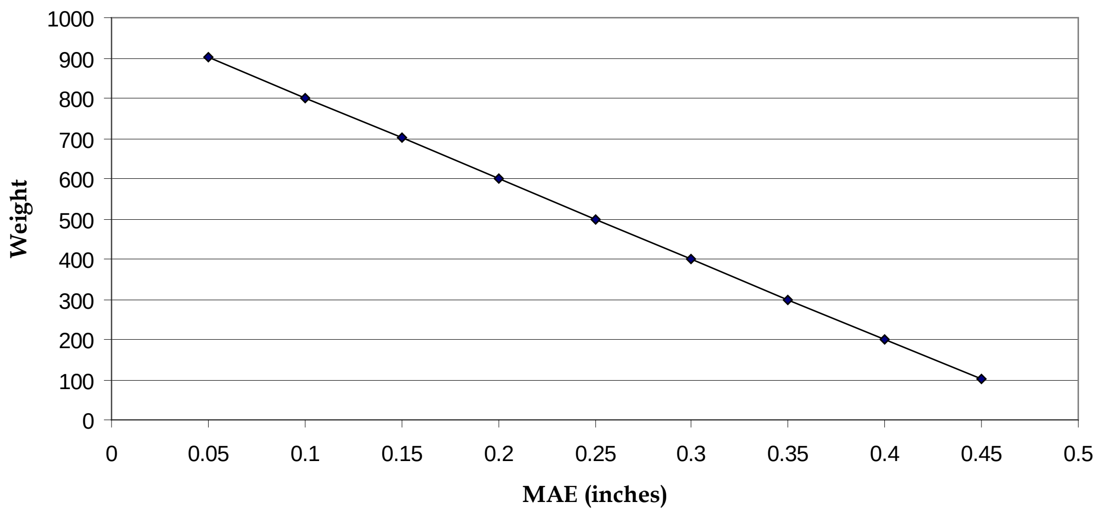

Figure 14. Weight function for mean absolute error (MAE)

The final performance measure values after application of weighting functions for different models are provided in Table 15. Based on the final values, Model 8 provided the highest performance measure and was selected as the best model for infilling missing precipitation data.

Table 15. Final performance measure (weight) values for different models

Model	Performance Measure
Model 8	86214.972
Model 2	86207.342
Model 3	86137.179
Model 1	86118.362
Model 14	86112.324
Model 4	85970.066
Model 7	85969.511
Model 12	85793.397
Model 13	85425.992
Model 10	85398.812
Model 9	85377.818
Model 5	85037.915
Model 15	84700.120
Model 6	83085.254
Model 11	68906.670

Assignment of weights to grids is assessed based on Model 8 application to 27 rain gage stations. It is interested to note that highest value of weight is assigned to cell "E" (i.e., the cell in which the rain gage is located) only for 33% of the number of rain gage stations. It is expected that this cell would receive the highest weight in the optimal weighting method.

Table 16. Assigned maximum and minimum weights for pixels based on Model 8

Station	Pixel with maximum Weight	Pixels with lowest weights
BLUEGOOS_R	F	D,G,H
CHAPMAN_R	E	B
COLGOV_R	D	B,G
CORK_R	E	A,D,G,I
EAA2	F	A,B,G,H
FKSTRN_R	E	A,B,C,F
FTP FS_R	D	H,I
G54_R	C	A,G,I
G56_R	B	D,G,H,I
IMMOKA 3_R	F	B,E,H,I
IMMOKALE_R	E	F,G,I
KISSFS_R	E	G
L006	B	G,I
LZ40	F	G
S123	F	A,D,G,H
S124_R	B	A,D,G,H
S18C_R	A	C,F,I
S2_R	B	D,G,H,I
S20F_R	F	A,B,D,E,G,H,I
S36_R	C	A,B,G,H
S38_R	B	A,D,G
S49_R	C	A,B,D,G
S59_R	E	A,B,G
S6Z_R	E	A,D,G,H,I
S97_R	E	A,B,G
S99_R	E	B,F,G,H,I
TOHO10_R	B	A,D,G,H,I

The application of Model 8 to 27 rain gage stations was also evaluated for any bias in estimation process. Three different stations were selected and predicted and observed values are evaluated. Results from these evaluations are shown in Figures 15-20 for calibration and validation periods. Calibrations periods were used for estimation of weights. Results suggest that estimations are un-biased and the Model 8 has no limitations associated with structure that influences estimations over time.

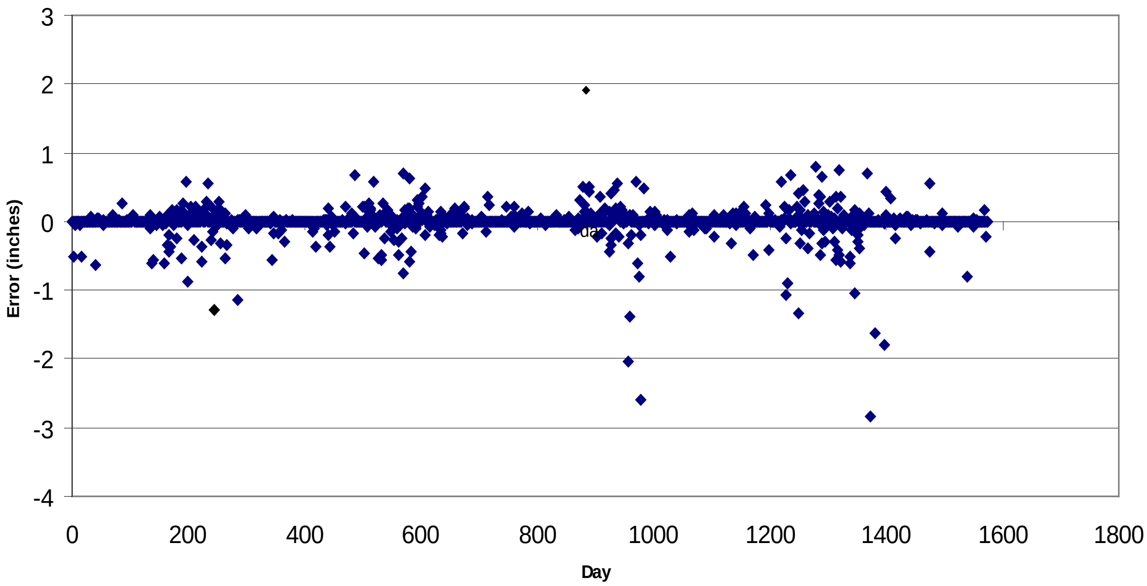

Figure 15 Error (estimated-observed) values based on application of Model 8 for calibration period for station Bluegoos

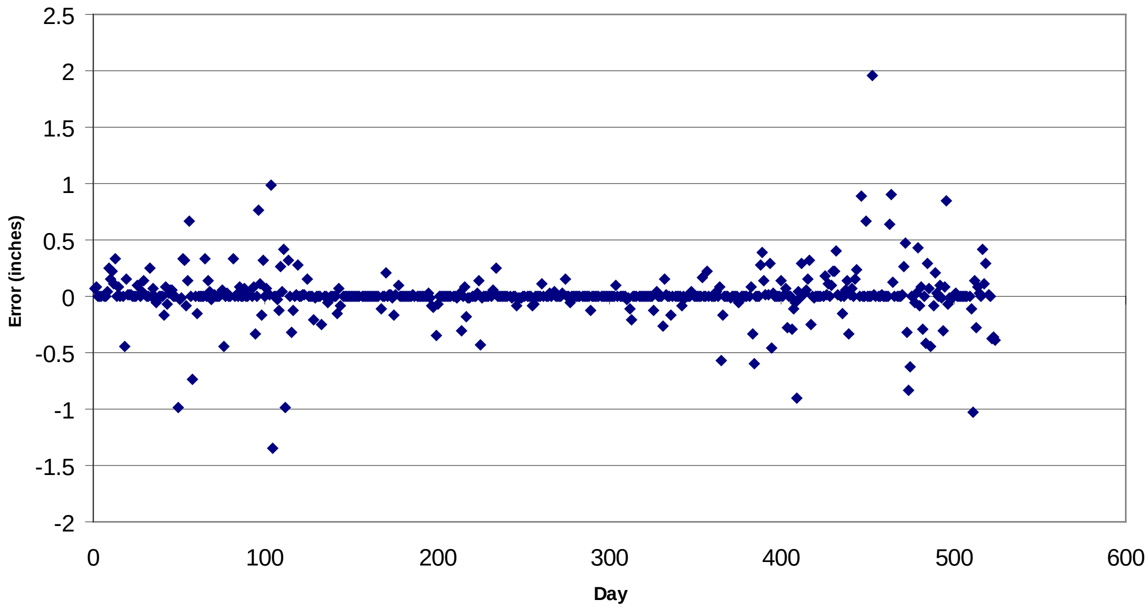

Figure 16 Error (estimated-observed) values based on application of Model 8 for validation period for station Bluegoos

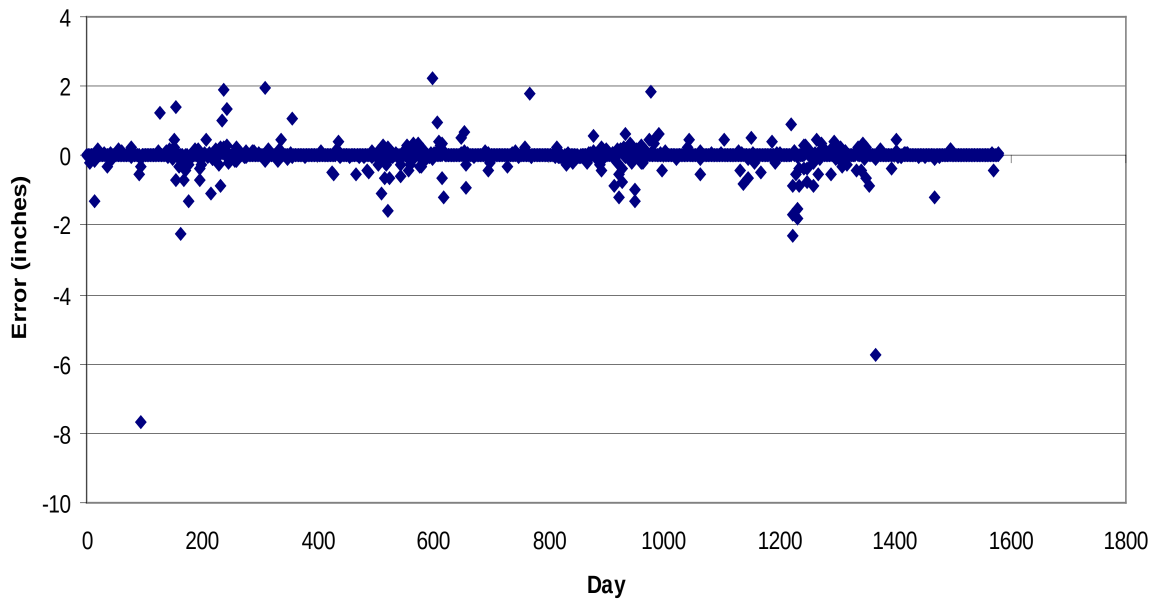

Figure 17 Error (estimated-observed) values based on application of Model 8 for calibration period for station Colgov

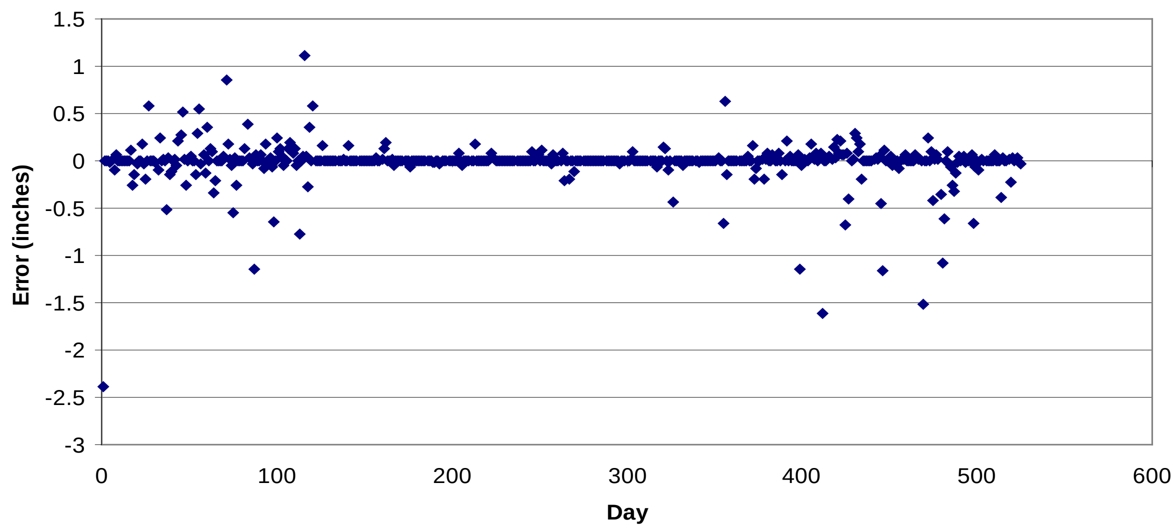

Figure 18 Error (estimated-observed) values based on application of Model 8 for validation period for station Colgov

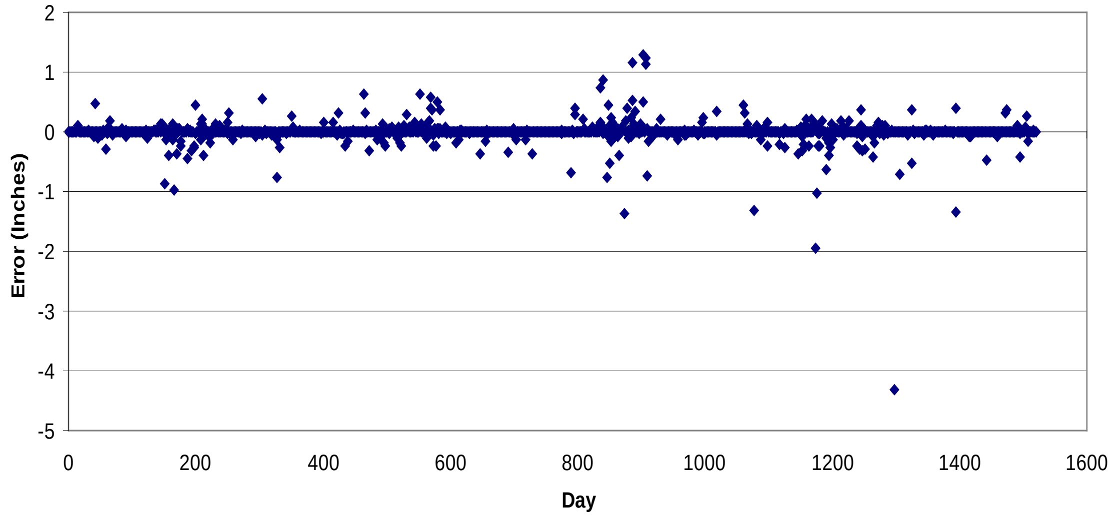

Figure 19 Error (estimated-observed) values based on application of Model 8 for calibration period for station L006

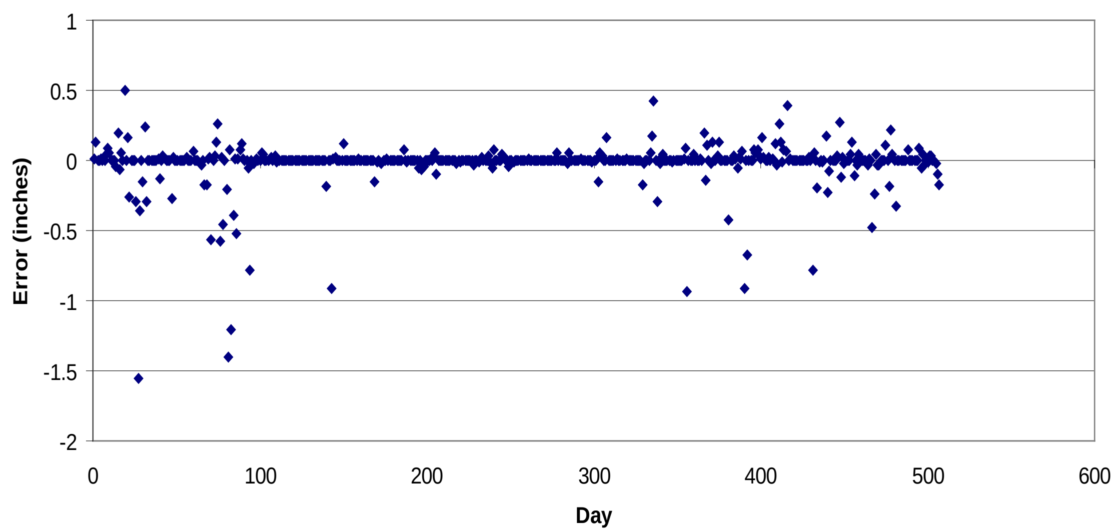

Figure 20 Error (estimated-observed) values based on application of Model 8 for validation period for station L006

INFILLING OF MISSING DATA: WEIGHT VARIATIONS IN RAIN AREAS

The mathematical programming model, Model 16 was applied for in-filling rain gage values. Data at the rain gage station are assumed to be missing for the purpose of testing the cluster based in-filling method proposed in this study. In order to understand the distribution of weights in the NEXRAD grid surrounding a gage, the cluster of nine cells are designated in alphabetical order as shown in Figure 21.

A	B	C
D	E	F
G	H	I

Figure 21 Designation of NEXRAD grids surround a rain gage.

It is important to note that all the NEXRAD data used in the current study are gage adjusted. In addition to Model 16, another model, referred to as Model 6 is defined for evaluation of results. In case of Model 6, the missing rain gage values are in-filled using the values of NEXRAD grid (i.e. cell E shown in Figure 21) in which the rain gage is located.

The weights obtained by solution of Model 16 for different clusters are shown in Table 17. It is evident from the results, that the weights assigned to the cell (i.e. grid) in which the rain gage is located either zero or not necessarily highest as generally expected. The number of cells participating in the optimal weighting scheme ranges from 1 to 8. The upper bound on the number of cells is fixed at nine. Five stations (referred to as station #1, 2, 3, 4 and 5) are used for the current study and these are: 1) station # 1(station: Avon Park, location: latitude:27 35 28; longitude: 81 31 07); 2) station # 2 (station: Palmdale, location: latitude: 26 55 28; longitude: 81 18 50); 3) station # 3 (station: S99, location: latitude:27 28 14; longitude: 80 28 18), station # 4 (location: WPB Airport, latitude:26 40 41; longitude: 80 06 35) and station # 5 (location: CV5 latitude:26 55 10; longitude: 81 07 18). The location of these five stations along with surrounding cluster of 9 cells (pixels) and rain areas are shown in Figure 22.

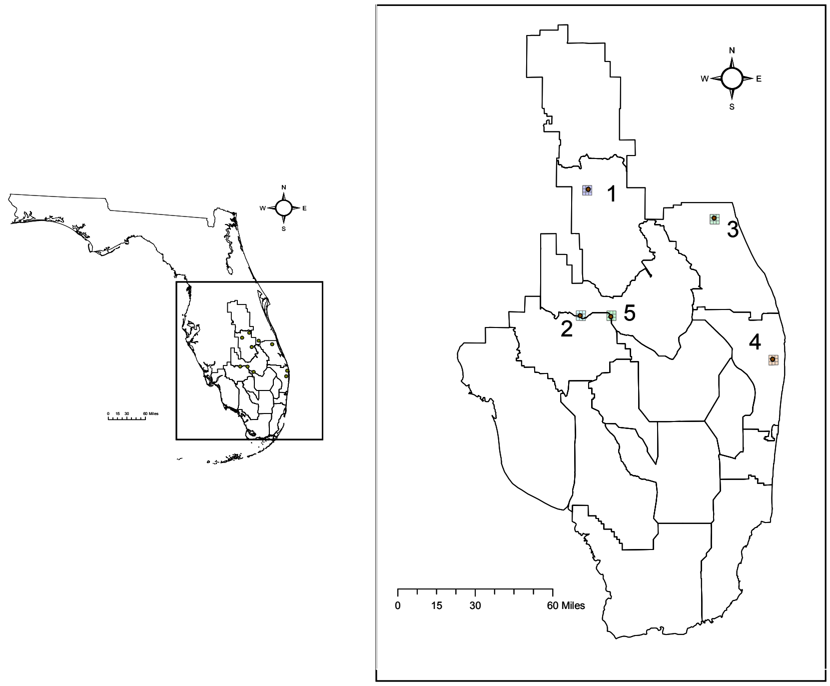

Figure 22 Location of selected NEXRAD grids (of 9 pixels each) and the rain areas in different locations of South Florida.

Table 17 Weights obtained from mathematical programming formulations for different clusters

Cells Cluster	A	B	C	D	E	F	G	H	I
1	0.020	0.253	**0.727**	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.020	**0.489**	0.020	0.391	0.020	0.020	0.020	0.020
3	0.000	0.081	**0.572**	0.000	0.347	0.000	0.000	0.000	0.000
4	**0.878**	0.000	0.000	0.020	0.000	0.000	0.000	0.102	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	**1.000**	0.000	0.000

Models 16 and 6 were applied for in-filling precipitation data. Results related to the performance of these models are shown in the Table 18. Two performance measures, namely, mean absolute error (MAE) and correlation coefficient (ρ) are used for evaluation of the models.

Table 18 Performance of models for in-filling of precipitation data

Cluster		Performance Measure MAE	(ρ)
1	Model 16	17.520	0.910
	Model 6	20.510	0.885
2	Model 16	19.500	0.885
	Model 6	19.300	0.875
3	Model 16	52.080	0.528
	Model 6	61.948	0.488
4	Model 16	18.546	0.939
	Model 6	20.710	0.932
5	Model 16	16.060	0.415
	Model 6	25.630	0.379

Evaluation of the two performance measures from Table 18 suggests that Model 16 is consistently performing better than Model 6. The mean absolute error values in case of cluster 2 are almost equal.

In order to evaluate the temporal variability of weights, only wet season (i.e., May – October) data are used to train and test the models. In case of cluster #1, for wet season, the weights for A, B, C,….I are 0.023, 0.299, 0.678, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000 respectively. These weights are marginally different from those reported for station # 1 for the wet and dry seasons combined (shown in Table 9).When only dry season data is used for station #1, the weights were different. The weights for A, B, C,… I., are 0.141, 0.000, 0.839, 0.000, 0.020, 0.000, 0.000, 0.000, 0.000 respectively. Further studies need to be conducted to assess the temporal variability. The limited number of experiments completed in the study may not completely reveal the spatial and temporal patterns and the variations of weights for in-filling purposes in rain areas.

CONCLUSIONS

The study reports development, implementation and evaluation of several optimization formulations, interpolation and data-driven models for estimating missing precipitation records at 268 rain gage stations in SFWMD region. The infilling of missing data was based on NEXRAD data and also data from rain gages. Of all the methods developed, the best method based on the evaluation of several performance measures was selected to obtain NEXRAD grid based data for infilling missing rain gage records. Data available at 27 pre-selected rain gages located in the SFWMD were used in the assessment of the methods. The selected method is recommended to infill missing precipitation estimates based on NEXRAD data in the SFWMD region. Two methods were also evaluated for five different rain areas in the District. Improvements in the estimates of missing data may be obtained if conceptually superior methods that combine rain gage and NEXRAD based data are adopted. However, lack of data at rain gages has posed conceptual limitations in adopting methods that combine data from two sources. Recommendations for further work on improvement of precipitation estimates are provided in the next section.

RECOMMENDATIONS

1. Stochastic interpolation methods based on the concepts of geo-statistics may be used for the estimation of missing precipitation data using NEXRAD data sets if the spatial correlation structure of NEXRAD data permits such use.
2. The missing rain gage data estimates obtained using more advanced interpolation schemes need to be evaluated.
3. A total of 9 surrounding cells (NEXRAD grids) are used in the current study. Evaluation of the models developed in the current study with cells higher than 9 should be carried out in future studies.
4. Optimization methods based on seasons (i.e., dry and wet) and for extreme events need to be developed and evaluated.
5. Detailed analysis of estimates from different methods for different rain areas in SFWMD region needs to be assessed.
6. The results from the nonlinear mathematical programming solver used for optimization formulations in the current study can be improved if conceptually superior global optimization approaches such as genetic algorithms are used.

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Sensitivity Analysis of South Florida Regional Modeling

Basic Information

Title:	Sensitivity Analysis of South Florida Regional Modeling
Project Number:	2008FL213B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Models, Ecology
Descriptors:	
Principal Investigators:	Rafael Munoz-Carpena, Wendy D Graham, Gregory Alan Kiker

Publications

1. Muller, S. Testing a new water quality model for the southern Everglades: University of Florida, Gainesville, FL. Poster Presentation: 2010 University of Florida Water Institute Symposium, February 24-25, Gainesville, FL.
2. Muller, S. Southern Everglades Water-Quality Modeling in an Uncertain Future. 2009 Annual Meeting of the Florida Section for the American Society of Agricultural and Biological Engineers, June10-13, Daytona Beach, FL.
3. Muller, S. Everglades Water Quality in an Uncertain Future: 2009 American Water Resources Association Spring Specialty Conference - Managing Water Resources Development in a Changing Climate, May 4-6, 2009, Anchorage, AK.
4. Muñoz-Carpena, R, and S. Muller (2009) Formal Exploration of the Complexity and Relevance of Biogeochemical Models through Global Sensitivity and Uncertainty Analysis: Opportunities and Challenges. Invited article in (Eds.) O. Rojas, and J. Ramirez: Estudios de la Zona no Saturada del Suelo, Vol.IX. Barcelona, Spain.
5. Zajac, Z. Global Uncertainty and Sensitivity Analysis of Spatially Distributed Hydrological Model, Regional Simulation Model (RSM), to spatially distributed factors. AGU Fall Meeting. San Francisco, CA. December 17 2009.
6. Zajac, Z. Uncertainty Analysis of Spatially Distributed Hydrological Model, Regional Simulation Model (RSM), as a Tool for Optimization of Spatial Data Collection. Florida Section Agricultural and Biological Engineers Annual Conference and Trade Show. Daytona Beach, FL. June 12 2009.
7. Perez-Ovilla, O. Thinking and Modeling Out of the (black) Box: An Example Using Vegetative Filter Strips for Runoff, Florida - Georgia Sections American Society of Agricultural and Biological Engineers 2009 Annual Conference and Trade Show, June 2009.
8. Perez-Ovilla, O. Flexible Simulation of Surface Runoff Pollutants: Analytical and Lab Scale Testing. The second University of Florida Water Institute Symposium, Gainesville, Fl. February 2010.

Status Report
104B student assistantship
Project: Development and Sensitivity and Uncertainty Analysis of Spatially Distributed Hydrological and Water Quality Models in South Florida

PIs: R. Muñoz-Carpena and Greg A. Kiker, Agricultural and Biological Engineering.
Ph.D. Student(s): Stuart Muller, Zuzanna Zajac, Oscar Perez-Ovilla

Subproject 1 (Student PhD Dissertation): Spatially-distributed modeling of surface water phosphorus in the southern Everglades under variable-density hydrodynamics

Ph.D. Student: Stuart Muller, Agricultural and Biological Engineering

Recent publications, proceedings, or presentations.

Presentations

Testing a new water quality model for the southern Everglades: Stuart Muller, University of Florida, Gainesville, FL. Poster Presentation: 2010 University of Florida Water Institute Symposium, February 24-25, Gainesville, FL.

Southern Everglades Water-Quality Modeling in an Uncertain Future: Stuart Muller, University of Florida, Gainesville, FL. Presentation: 2009 Annual Meeting of the Florida Section for the American Society of Agricultural and Biological Engineers, June10-13, Daytona Beach, FL.

Everglades Water Quality in an Uncertain Future: Stuart Muller, University of Florida, Gainesville, FL. Presentation: 2009 American Water Resources Association Spring Specialty Conference - Managing Water Resources Development in a Changing Climate, May 4-6, 2009, Anchorage, AK.

Conference Proceedings

Muñoz-Carpena, R, and S. Muller (2009) *Formal Exploration of the Complexity and Relevance of Biogeochemical Models through Global Sensitivity and Uncertainty Analysis: Opportunities and Challenges*. Invited article in (Eds.) O. Rojas, and J. Ramirez: Estudios de la Zona no Saturada del Suelo, Vol.IX. Barcelona, Spain.

Academic Status

All course work requirements for graduation have been met with a final GPA of 3.92. In addition, all requirements have been met for two specializations; the Hydrologic Sciences Academic Cluster, and the Wetlands Certificate. Doctoral candidacy has also been attained with the successful completion of written and oral qualifying exams.

Project status report

Objectives

Development of a water quality model, to be integrated with the FTLOADDS hydrologic model for the southern Everglades, and applied to evaluate water quality in the region and assess changes in nutrient loading to Florida Bay resulting from possible CERP flow scenarios

Status

The Reaction Simulation Engine (RSE) was successfully integrated with the Surface-Water Integrated Flow and Transport in 2-D (SWIFT2D) model component of the USGS hydrologic model, Flow and Transport in a Linked Overland-Aquifer Density Dependent System (FTLOADDS). This required extensive new coding, including:

- Additional code to the RSE wrapper to overcome a major initialization obstacle (a remnant of TaRSE, the version of RSE that previously contained unnecessary transport functionality that has since been excised), and the re-introduction of spatial distribution to RSE (previously lost after the removal of transport).
- Additional coding added to RSE to facilitate exchange of data with an external source, in this case SWIFT2D, including the identification of "active grid" cells within an irregular SWIFT2D model domain and the translation of these values from 3D arrays in SWIFT2D to 2D arrays required by RSE.
- Extensive further coding added to SWIFT2D to prepare data for exchange with RSE, and to receive and reintegrate updated values for transport and hydraulics.
- Ancillary code additions to smooth the integration of the two tools for user-friendliness, including changes to output printing and input reading, and user-definable options controlling the time interval at which RSE is called on to perform reactions.
- Functionality has also been built in for possible future exchange of stabile (i.e. non mobile) state variables in RSE, such as rooted macrophytes, that are currently unused by FTLOADDS but may prove valuable in the future.

Comparative testing of results obtained using the surface water reactions functionality of SWIFT2D and the same kinetics reproduced using the reactions functionality within RSE were conducted to demonstrate that the code linking the two tools is correct and that the models are now a functional pairing. Comprehensive testing of both models has been conducted through comparison with analytical solutions. In order to compare results to known 1D analytical solutions it was necessary to establish a quasi-1D flow domain in FTLOADDS to approximate conditions necessary for the analytical solutions. A quasi-steady-state uni-directional flow field has been produced that reduces the 2D flow dynamics of SWIFT2D to quasi-1D. The following testing has been conducted:

- Corroboration of SWIFT2D transport and reactions results against analytical solutions for conservative, decaying, and interacting solutes. This was necessary to validate the SWIFT2D code within FTLOADDS, which has undergone many changes since it's integration with MODFLOW to create FTLOADDS.
- Reproduction of these results using FTLOADDSaRSE, the integrated pairing of FTLOADDS and RSE. Specifically, conservative solutes remain unaffected by the addition of RSE, as expected since RSE performs reaction calculations on solutes, and decaying solute concentrations calculated by both SWIFT2D and RSE have been shown to be equal, thereby demonstrating correct code linkage.
- Final testing against 2D analytical solutions is currently underway in conjunction with preparation for application of the linked models to the SICS application of FTLOADDS.

Initial work calibrating SWIFT2D to the hydrology of the Southern Inland and Coastal Systems (SICS) of the southern Everglades was reproduced/validated. Changes to the surface-water code since SWIFT2D was integrated into FTLOADDS introduced many changes to the model's performance in the SICS region. This necessitated an extensive recalibration and testing effort. The hydrology of SICS has now been successfully modeled with FTLOADDS.

Appropriate water-quality data for calibration to the SICS domain has been collected and processed for calibration and testing of the new water-quality functionality in FTLOADDS. An extensive literature review of local ecology and biogeochemistry was conducted and conceptual models of the water quality processes in SICS were produced. Conceptual models have been converted into XML and run successfully within FTLOADDS. Calibration of these the models is currently ongoing.

Subproject 2 (Student PhD Dissertation): Global sensitivity and uncertainty analysis of hydrologic, spatially distributed watershed models.

Ph.D. Student: Z. Zajac, Agricultural and Biological Engineering

Recent publications, proceedings, or presentations

Presentations (since March of 2009)

- Zajac, Z. Global Uncertainty and Sensitivity Analysis of Spatially Distributed Hydrological Model, Regional Simulation Model (RSM), to spatially distributed factors. AGU Fall Meeting. San Francisco, CA. December 17 2009
- Zajac, Z. Uncertainty Analysis of Spatially Distributed Hydrological Model, Regional Simulation Model (RSM), as a Tool for Optimization of Spatial Data Collection. Florida Section Agricultural and Biological Engineers Annual Conference and Trade Show. Daytona Beach, FL. June 12 2009

Academic Status

- All UF course requirements were fulfilled by the student with a cumulative UF GPA 3.93.
- Student has assembled a graduate committee that consists of five experts in the fields of hydrological modeling and geostatistics.
- Student has attended meetings with the South Florida Water Management District Hydrologic & Environmental Systems Modeling Department experts. During the meetings, the project progress, future steps and other related issues were discussed.

Project status report

Objectives

The main objective of this work is to incorporate the effect of spatially distributed numerical and categorical model inputs into Global Uncertainty and Sensitivity Analysis (GUA/SA) of spatially distributed hydrological models. Regional Simulation Model (RSM), applied to the Water Conservation Area-2A, is being used as a benchmark model for this study.

Satus

An evaluation framework for spatially distributed model inputs is applied, based on a combination of sequential simulation (SS) for estimation of spatial uncertainty of model inputs, and global, variance-based method of Sobol for incorporation of spatial uncertainty into GUA/SA. Sequential Gaussian Simulation (SGS) is used for estimation of spatial uncertainty for numerical inputs (like land elevation), while Sequential Indicator Simulation (SIS) is used for assessment of spatial uncertainty of categorical inputs (like land cover type).

The combination of SS and the method of Sobol allows for the spatial layer to be treated as random variable in the GUA/SA and it accounts for the spatial autocorrelation of distributed variables. Incorporation of variance-based method of Sobol for the GUA/SA makes the method independent of model assumptions (linearity or monotonicity), allows for exploration of the whole space of input parameters and provides measures of parameters' importance (first-order sensitivity indexes) and their interactions (difference between total and first-order effects). The proposed framework is model independent, it allows for evaluation of the model as a decision-support tool by estimation of model predictive quality, and for optimization of data collection (including spatial data) for the modeling purposes.

The initial sensitivity analysis results were obtained for Water Conservation Area-2A (WCA-2A) application based on uniform probability density function, with ranges ± 20% of base values. Level parameters were used for maintaining original spatial relations between factors.

Probability distributions of the uncertain model inputs, characteristic to the WCA-2A area, were estimated based on the literature review and SFWMD's expert's opinion. The further global sensitivity and uncertainty analysis (GS/UA) is going to be based on these probability distributions.

Geostatistical techniques suitable for Monte Carlo generation of spatially distributed input factors were examined based on literature review and discussions with experts. As a result several alternatives to incorporate spatial variability into global sensitivity and uncertainty analysis techniques are being evaluated with the WCA-2A application.

The GS/UA model evaluation framework has been moved to the University of Florida High Performance Computing Center (http://hpc.ufl.edu). Although the initial effort invested in moving to the HPC has been significant, the dramatic increases in running time obtained in the preliminary testing of the framework there indicate that it is now possible to perform a detailed evaluation of the complex and spatially distributed RSM..

Subproject 3 (Student PhD Dissertation): A TaRSE-based generic approach for simulating dynamics and removal of runoff pollutants in Vegetative Filter Strips

Ph.D. Student: Oscar Perez-Ovilla, Agricultural and Biological Engineering

Recent publications, proceedings, or presentations

Presentations

- Thinking and Modeling Out of the (black) Box: An Example Using Vegetative Filter Strips for Runoff, Florida – Georgia Sections American Society of Agricultural and Biological Engineers 2009 Annual Conference and Trade Show, June 2009.
- Poster: Flexible Simulation of Surface Runoff Pollutants: Analytical and Lab Scale Testing. The second University of Florida Water Institute Symposium, Gainesville, Fl. February 2010.

Academic Status

- Ph. D. course work finished in December 2007. Eighteen courses in total. Six courses related to modeling (Simulation of Agricultural Watershed Systems, Biological Systems Modeling, Evaluation of Groundwater Quality (using MODFLOW), Numerical Methods I, Groundwater Flow II and Numerical Partial Differential Equations).
- Officially accepted as Ph. D candidate. Qualifying Oral examination passed on April 28, 2007.
- Expected graduation date: Summer 2010.

Project status report.

Objectives

- Perform analytical and lab scale testing of the FEMADR-RSE model, which solves a steady state case of a soluble pollutant in runoff using a standard Bubnov-Galerkin cubic/quadratic Finite Elements Method (ADFEM) for solving the 1-D Advection-Dispersion Equation coupled with an adaptation of a module called RSE (Reaction Simulation Engine) for the reactive part of the Advection-Dispersion-Reaction Equation. The later based on the Transport and Reaction Simulation Engine (Tarse, James 2009).
- Coupling of the module RSE with VFSMOD to simulate transport and reaction of a pollutant in runoff under variable (non-steady state) conditions. VFSMOD is a physically based program to simulate the transport of water and sediments in runoff through vegetative filter strips.

Status

A new module to account for the transport and reaction of pollutants in surface runoff has been successfully developed and tested for lab scale conditions. This module combines a standard Bubnov-Galerkin cubic/quadratic Finite Elements Method (ADFEM) for solving the 1-D Advection-Dispersion Equation $\frac{\partial C}{\partial t} = Dx\frac{\partial^2 C}{\partial x} - Vx\frac{\partial C}{\partial x}$ with a flexible module that accounts for the reactive part of the full Advection-Dispersion-Reaction Equation (ADRE). The reactive flexible module called RSE (Reaction Simulation Engine) is program based on the flexibility of the Transport and Reaction Simulation Engine (TaRSE) generic algorithm (James et al., 2009). The new flexible module has been tested with various analytical solutions with a Nash-Sutcliffe model efficiency coefficient greater than 0.999.

A lab scale testing was also performed to test the flexible module. Test was based on Yu's (2009, unpublished) experimental work. In her experiment, a plug of bromide is released in the runoff that runs over a sand bed and receives additional water from a rainfall simulator. Thanks to the flexibility of the program, a couple of theories were used to fit the experimental data: 1) A "pumping" process, as that described by Packman et al. (2000), 2) A rainfall induced chemical transport from soil to runoff, based on Gao (2004) theory. The theory that explained better the experimental data was the rainfall induced chemical transport by Gao (2004). Nash-Sutcliffe model efficiency coefficient was greater than 0.98.

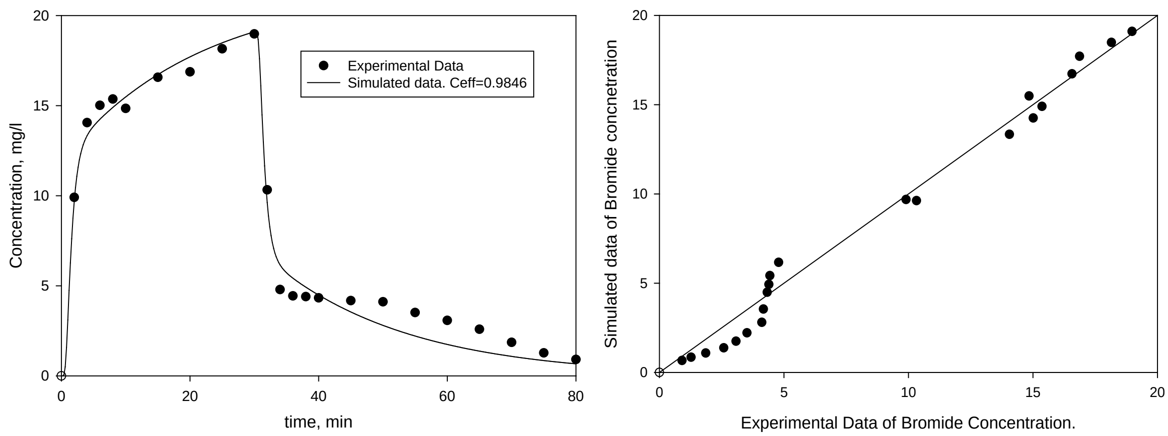

Figure 1. Concentration during the simulation of bromide in runoff at the end of the experimental sand box (x=1.52 m). Bromide was release as a plug during 0<time<30 mins with a constant concentration of 103 mg/l. The Nash-Sutcliffe model efficiency coefficient was 0.9846.

The development of this new flexible module is a powerful tool that let us to explore multiple theories and conditions for the transport and reaction of pollutants in runoff. Analytical and lab scale testing results are being processed to be published at the close of this report. A second stage involves testing the program under non-steady state conditions in vegetative filter strips using the program VFSMOD. Field scale testing is expected to be done by the end of the second quarter of 2010.

References:

GAO, B., WALTER, M. T., STEENHUIS, T. S., HOGARTH, W. L. & PARLANGE, J. Y. 2004. Rainfall induced chemical transport from soil to runoff: theory and experiments. *Journal of Hydrology,* 295**,** 291-304.

JAMES, A. I., JAWITZ, J. W. & MUÑOZ-CARPENA, R. 2009. Development and Implementation of a Transport Method for the Transport and Reaction Simulation Engine (TaRSE) based on the Godunov-Mixed Finite Element Method. U.S. Geological Survey Scientific Investigations: Report 2009-5034.

PACKMAN, A. I., BROOKS, N. H. & MORGAN, J. J. 2000. A physicochemical model for colloid exchange between a stream and a sand streambed with bed forms. *Water Resources Research,* 36**,** 2351-2361.

Addition of Ecological Algorithms into the RSM Model

Basic Information

Title:	Addition of Ecological Algorithms into the RSM Model
Project Number:	2008FL215B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Ecology, Models
Descriptors:	None
Principal Investigators:	Gregory Alan Kiker, Wendy D Graham, Rafael Munoz-Carpena

Publications

1. Lagerwell, G. An Introduction to Modeling Vegetation Dynamics in the Everglades; Annual Florida Section-American Society of Agricultural and Biological Engineers; Daytona, Fl; June 2009
2. Lagerwell, G. Methods to Predict Typha domingensis (cattail) Dynamics in the Everglades; Bi-Annual University of Florida Water Institute Symposium; Gainesville, Fl; February 2010.

Status Report
104B student assistantship
Project: Addition of Ecological Algorithms to the Regional Simulation Model (RSM)

PIs: Greg A. Kiker and R. Muñoz-Carpena, Agricultural and Biological Engineering.
Ph.D. Student: Gareth Lagerwall

Recent publications, proceedings, or presentations.

Presentations

- An Introduction to Modeling Vegetation Dynamics in the Everglades; Annual Florida Section-American Society of Agricultural and Biological Engineers; Daytona, Fl; June 2009
- Methods to Predict Typha domingensis (cattail) Dynamics in the Everglades; Bi-Annual University of Florida Water Institute Symposium; Gainesville, Fl; February 2010

Academic Status

All requirements have been met for two specializations; the Hydrologic Sciences Academic Cluster, and the Wetlands Certificate. Doctoral candidacy has also been attained with the successful completion of written and oral qualifying exams.

Project Status Report

Objectives

This research project aims to systematically review, design and develop selected ecological algorithms for the RSM model (TaRSE-ECO) using a similar methodology to the development of water quality algorithms (RSM-WQ) (Jawitz et al., 2008). To this end, the objectives of this research are:

- Review of relevant ecological models, design concepts and code implementation tools for development of TarSE-ECO ecological algorithms.
- Selection of ecological species (habitat, plant and/or animal) to be included in the initial development and testing of TarSE-ECO.
- Development of the conceptual model of TaRSE-ECO organisms
- Prototype model development and testing on the “10x4” mesh (Jawitz et al., 2008)
- Selection of a test site for model calibration and testing
- Systematic global sensitivity analysis

Status

The project began with a review of the RSM Model (SFWMD, 2005), RSM-WQ, and TaRSE (Jawitz et al., 2008) design, codes, and structure in C++. TaRSE is an extraction of the water quality section of code from the RSM-WQ model, creating a model-independent, highly flexible, spatially distributed, water quality module/library (Jawitz et al., 2008). Current, Everglades-system ecological models such as ATLSS (ATLSS, 1996) and ELM (Fitz and Trimble, 2006) were examined to determine any similarities or differences in modeling similar organisms to our effort. ATLSS is a collection of different models acting across various trophic levels, with process models for lower trophic levels, structured population models for primary consumers, and individual-based models for large consumers. As such, it provides a central location for detailed information about various tried and tested modeling techniques. One fundamental aspect that separates TaRSE:ECO from most other Everglades ecological models is that it runs in full integration with the water/water quality parts of the model, whereas other ecological models use time series and spatial output from hydrological and water quality models to create a separate ecological run in series (ATLSS, 1996).

As outcome of meeting with the South Florida Water Management District (SFWMD), it was decided to focus on modeling cattail (*Typha Domingensis*) migration through the Water Conservation Area 2A (WCA 2A). The word migration in this context being the spatial and temporal establishment of cattail populations throughout a habitat due to altered hydrology and water quality.

A literature review was conducted in order to determine the factors that affect cattail growth, to identify previous attempts to model cattail migration, and to source the availability of relevant ecosystem data. In reference to the Everglades ecosystem, there are five main factors affecting cattail growth; water depth, duration of flooding, frequency of flooding, porewater phosphorus concentration, and fire regime (Newman, *et al.*, 1998). Of these potential factors water depth and porewater phosphorus were selected for initial TaRSE:ECO model designs as they are already accounted for in the current RSM/TaRSE models. To date, the best source of data has been from the Everglades Nutrient Removal Project (ENRP) (Chimney; Date Unknown) and (Chimney and Goforth; 2006) and (Chimney and Pietro; Date Unknown) and (DBHYDRO; 2007). This is patchy data covering the two years of 1995 and 1996. However, the location is close enough to WCA 2A that any results or conclusions should be directly relevant.

From the literature review it became apparent that there are two main schools of thought when considering ecology, and hence an ecological model. One group tends to focus on the biology and physical processes of individual organisms, while the other group tends to focus on the landscape scale, and deals with the general trend and interactions of populations. A meeting with the South Florida Water Management District (SFWMD) resulted in the decision being taken to develop three cattail models of increasing complexity, starting with a more landscape-scale diffusionary front, as is currently under development, and progressing to a more physically-based model, with a Habitat Suitability Index (HSI) model as a mid-way complexity model.

Examining the design of the XML-based input files for TaRSE has led to the creation of a cattail "store" (The phosphorus in the water quality module is modeled as a "store" in the original file), and an understanding of the equations that drive the chemical processes in the water quality module. Semi-regular weekly meetings with the research team continue to expand current understanding and to explore design issues in creating XML-based input equations for simulating ecological components in the RSM structure.

Sufficient data has been collected, and a number of runs for the diffusionary-front algorithm have been conducted over the test site, WCA2A. The algorithm at present is a simple function of previous cattail densities and current water depth, with cells not containing cattails being "seeded"/initialized with a minute cattail density. Vegetation (specifically cattail) data has been collected for the years 1987, 1991, 1995, 1999, and 2004. The model runs have been time-consuming, and it has been proposed to move the operation to the High Performance Computing (HPC) lab on campus before conducting any analyses. A white paper is currently under development to discuss the modeling progress to date, and introduce the RSM and TARSE models.

During 2009, the research was further categorized into two phases. Phase 1 representing the spatially static growth of cattails, represented as stabile components in the input file. Phase 2 represents the spatially dynamic growth of cattails, using the newly developed Movement algorithm. This algorithm is a simple mass balance, with the distinguishing feature being that it is not tied to the hydrology as previous “mobile” components in TARSE were. Some initial model runs, along with a simple difference and RMSE analysis, were performed.

It was decided to model cattail densities rather than percent area covered. The levels of complexity were changed, and more closely follow the distinctions defined by (Jawitz et al., 2008). The first level of complexity sees cattail growth following a simple logistic curve. The second level builds on the first level, and includes a depth-dependent factor, which negatively influences the logistic curve when the depth lies outside the optimal range. The third level builds on the second level, and includes a phosphorous-dependent factor which negatively influences the logistic growth when levels drop below optimum. The fourth level includes a simple interaction with *Caldium jamaicense* (sawgrass), which itself is grown using a simple logistic curve. The interaction itself was relatively simple, with a negative-density-dependence factor added to the logistic growth, so that as sawgrass densities increase, they will negatively impact the cattail growth. As a result the model runs and analysis were required to be re-done. Also, there was an issue implementing Phase 2 (the Movement algorithm) with the model, which further delayed progress.

At current time, most of the issues previously encountered with running TARSE have been overcome. A proper set of statistical analyses were developed. This includes A goodness of fit graph (with R^2 statistic) – to determine overall similarity of model results and data; A semi-variance (or beta-diversity) graph – to determine the impact of distance on species density; And an abundance/area graph – to compare the “patchiness” of model results and data. These analyses have been conducted on Phase 1, Level of complexity 1 through 4. The results are currently under review, and model runs for Phase 2 are under way.

References

Jawitz, J W; Muñoz-Carpena, Rafael; Muller, Stuart; Grace, Kevin; James, Andrew I; 2008; Development, Testing, and Sensitivity and Uncertainty Analyses of a Transport and Reaction Simulation Engine (TaRSE) for Spatially Distributed Modeling of Phosphorus in South Florida Peat Marsh Wetlands; U.S. Geological Survey Scientific Investigations Report 2008-5029

Information Transfer Program Introduction

During the review period, the Florida WRRC actively supported the transfer of water resources research findings and results to the scientific and technical community that addresses Florida's water resource problems. The Center provided support for preparation and presentation of 12 peer reviewed publications, 19 proceedings and presentations and 2 PhD dissertations.

WRRC Website: The Center maintains a website (http://www.ce.ufl.edu/~wrrc/) which is used to provide timely information regarding applied water resources research within the state of Florida. The Center website provides information regarding ongoing research supported by the WRRC, lists research reports and publications that are available, and provides links to other water-resources organizations and agencies, including the five water management districts in Florida and the USGS.

WRRC Digital Library: The Center maintains a library of technical reports that have been published as a result of past research efforts (Dating back to 1966). Several of these publications are widely used resources for water policy and applied water resources research in the state of Florida and are frequently requested by others within the United States. Starting in 2005, as part of the information transfer program, copies of these reports were provided free of charge with the Center covering the cost of publication. Now, as part of the WRRC information and technology transfer mission, the library is being converted to digital form and will be provided free to the public through the WRRC Digital Library which is housed on the center website. Documents are being processed and added to the digital library based upon the number of prior requests for reproduction. All documents should be online by June 2010.

More information regarding the Digital Library is available on the WRRC website http://www.ce.ufl.edu/~wrrc/reports.html.

Florida Water Resources Information Transfer

Basic Information

Title:	Florida Water Resources Information Transfer
Project Number:	2009FL232B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	6
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Kirk Hatfield, Mark Newman

Publications

1. Hong, S-H, S. Wdowinski, S-W Kim. 2009. Evaluation of TerraSAR-X observations for Wetland InSAR application, IEEE Geosciences and Remote Sensing, in press.
2. DeSilva, M., M. H. Nachabe, J. Simunek, and R. Carnahan. 2008. Simulating Root Water Uptake from a Heterogeneous Vegetation Cover using Finite Element Modeling. J. Irrig. and Drain. Engrg. Volume 134, Issue 2, pp. 167-174. http://dx.doi.org/10.1061/(ASCE)0733-9437(2008)134:2(167).
3. Zhang, J., R.R. Murch, M.A. Ross, A.R. Ganguly, and M. Nachabe. 2008. Evaluation of Statistical Rainfall Disaggregation Methods Using Rain-Gauge Information for West-Central Florida. J. Hydrologic Engrg. Volume 13, Issue 12, pp. 1158-1169. http://dx.doi.org/10.1061/(ASCE)1084-0699(2008)13:12(1158).
4. Basu, N.B., P.S.C. Rao, I.C. Poyer, S. Nandy, M. Mallavarapu, R. Naidu, G.B. Davis, Bradley M. Patterson, M.D. Annable and K. Hatfield. 2009. Integration of traditional and innovative characterization techniques for flux-based assessment of dense non-aqueous phase liquid (DNAPL) sites. Contaminant Hydrology, 105(3-4), 161-172.
5. Klammler, H., and K. Hatfield. 2009. Analytical Solutions for the Flow Fields near Funnel-and-Gate Reactive Barriers with Hyraulic Losses. Water Resources Res., 25, W02423.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	9	9
Masters	0	0	0	8	8
Ph.D.	12	0	0	3	15
Post-Doc.	0	0	0	4	4
Total	12	0	0	24	36

Notable Awards and Achievements

The WRRC continues efforts to maximize the level graduate student funding available to the state of Florida under the provisions of section 104 of the Water Resources Research Act. Listed below are some of the Center's notable achievements for FY 2009:

UCOWR Best Dissertation Award: Heather Byrne, a Ph.D. graduate (2009) from University of Florida Department of Environmental Engineering Sciences has received the Universities Council on Water Resources (UCOWR) best dissertation award for 2010, for her dissertation, "Adsorption, Photocatalysis, and Photochemical Reactions of Trace Level Aqueous Mercury." Heather earned a Bachelors, Masters, and Ph.D. through the Department of Environmental Engineering Sciences in addition to her doctoral degree. Her research focused on aqueous mercury and sorbent development. Heather's supervisory committee chair was Dr. David Mazyck.

A prior 104B seed project has been extended to a multi-year project with cooperating state agencies (Southwest Florida Water Management District and Florida Geologic Survey) to investigate arsenic mobilization during aquifer storage recovery (ASR). With the topic of alternative water supply becoming a critical issue within the state and nation, this is a critical research area to pursue

NSF funded US-Brazil Collaboration: NSF project to develop collaborative water resources research between University of Florida and Brazil, with the objective of providing education and training through a graduate student exchange program and creation of a teaching laboratory in Brazil.

Florida Water Resources Digital Library: The WRRC maintains a library of technical reports that have been published as a result of past research efforts (Dating back to 1966). Several of these publications are widely used resources for water policy and applied water resources research in the state of Florida and are frequently requested by other states within the United States. As part of the WRRC information and technology transfer mission, the library is being converted to digital form and will be provided free to the public through the WRRC Digital Library.

Publications from Prior Years

1. 2004FL57B ("Sensitivity of the Hydroperiod of Forested Wetlands to Alterations in Topographic Attributes and Land Use") - Articles in Refereed Scientific Journals - Nachabe, M. H. 2006. Equivalence Between Topmodel and the NRCS Curve Number Method in Predicting Variable Runoff Source Areas. Journal of the American Water Resources Association. Volume 42, Number 1, February 2006, pages 225-235.
2. 2004FL57B ("Sensitivity of the Hydroperiod of Forested Wetlands to Alterations in Topographic Attributes and Land Use") - Articles in Refereed Scientific Journals - Nachabe, M. H., N. Shah, M. Ross, and J. Vomacka. 2005. Evapotranspiration of Two Vegetation Covers in Humid Shallow Water Table Environment. Soil Science Society of America Journal, 69:492-499.
3. 2004FL57B ("Sensitivity of the Hydroperiod of Forested Wetlands to Alterations in Topographic Attributes and Land Use") - Articles in Refereed Scientific Journals - Said, A., M. Nachabe, M. Ross, and J. Vomacka. 2005. Methodology for Estimating Specific Yield in Shallow Water Environment Using Continuous Soil Moisture Data. J. Irrig. and Drain. Engrg., Volume 131, Issue 6, pp. 533-538.