Florida Water Resources Research Center
Annual Technical Report
FY 2010

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 2010) 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 three state agencies (South Florida Water Management District, Southwest Florida Water Management District, and the Florida Geological Survey).

Recognizing the importance of STEM (Science, Technology, Engineering, and Mathematics) Education initiatives, the Florida Water Resources Research Center is very proud to have supported the research efforts of 13 Ph.D., 9 Masters, and 3 undergraduate students along with 3 post doctoral associates all focusing on water resources issues during the review period (March 2010 to February 2011).

During FY 2010, 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 19 peer-reviewed journal articles, 4 book chapters, 20 proceedings and presentations, 6 PhD dissertations and 4 MS Thesis. 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 2010 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 was 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: Four Ph.D. student assistantship projects were 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).

Center Affiliated Projects

Development of new tools for characterizing groundwater contaminant source zones. University of Florida flux meter research has received national recognition and as such, two research projects are ongoing to further the field of characterizing subsurface contaminant flux. The Department of Defense has funded a three-year $700,000 project to develop a fractured rock passive flux meter, and the Department of Energy has funded a three year 1.2 million dollar project for investigation of subsurface uranium flux.

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.

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:	3/1/2010
End Date:	2/28/2011
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. 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.
10. 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.

11. Shah, N., M.Ross. 2006. Variability in Specific Yield for Different Drying and Wetting Conditions. Vadose Zone Journal, In Review.
12. Shah, N., J.Zhang, and M.Ross. 2006. Long Term Air Entrapment Affecting Runoff and Water Table Observations. Water Resources Research, In Review.
13. 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, in press.
14. 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, In Review.
15. Shah, N., J.Zhang, and M. Ross, 2006. Long Term Air Entrapment Affecting Runoff and Water Table Observations, Water Resources Research, AGU Paper # 2006WR005602, In Review.
16. 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, In Review.
17. Zhang, Jing and Mark A. Ross. 2007. Two Layer Vadose Zone Model for Surface and Groundwater Interactions. ASCE Journal of Hydrologic Engineering, Vol 12, No. 6: 663-675.
18. Ross, M., J. Zhang, and J. Geurink. 2007. Modeling Vadose Zone Moisture Dynamics with the Integrated Hydrological Model (IHM) Part I: Theoretical Basis. ASCE Journal of Hydrologic Engineering, accepted with requested revisions, revised and resubmitted February 2008.
19. Zhang, J., M. Ross, and J. Geurink. 2007. Modeling Vadose Zone Moisture Dynamics with the Integrated Hydrological Model (IHM) Part II: Field Scale Testing and Application. ASCE Journal of Hydrologic Engineering, requested revisions, revised and resubmitted February 2008.
20. 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.
21. 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.
22. 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.
23. 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.
24. 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.
25. 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.
26. 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.
27. 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.
28. Zhang, Jing and Mark A. Ross An Innovative Approach at Calibrating Stage/Storage/discharge Behavior in Hydrologic Modeling , Proceedings of World Environmental and Water Resources Conference 2008, doi , pp., May 19th- 25th, 2008, Honolulu, Hawaii.
29. Shah, N., M. Ross, and G.S. Ladde. 2008. Dynamic Modeling of Root Water Uptake Using Soil Moisture Data. Neural, Parallel and Scientific Computations, Vol.16, No. 1, pgs 105-124, Dynamic Publishers.

30. Shah, N., M. Ross. 2008. Variability in Specific Yield for Different Drying and Wetting Conditions. Journal of Hydrologic Engineering, accepted, in press.
31. 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.
32. 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.
33. 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.
34. 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.
35. 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.
36. 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.
37. 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.
38. 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.
39. 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.
40. 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.
41. 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.
42. 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.
43. 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.
44. 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.
45. 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.
46. 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.
47. 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.
48. 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.

49. 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.
50. M. Ross, K. Trout, A. Rodriquez, J. Vomacka. Measurement of Evapotranspiration, Recharge, and Runoff in a Transitional Water Table Environment. AWRA Annual Conference, Philadelphia, PA, November 2010.

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

Final Report

Prepared by
Center for Modeling Hydrologic and Aquatic Systems
Department of Civil and Environmental Engineering
University of South Florida

Funding Agencies

Southwest Florida Water Management District
Brooksville, Florida

USGS Water Resources Research Center
University of Florida

February, 2011

Table of Contents

List of Figures

List of Tables

Executive Summary

This report summarizes data and study of recorded data from early 2007 through September 2010. A Microsoft Access® database containing all project data has been provided to the District as part of the deliverable.

The objective of this study was to instrument, measure and develop detailed water budgets including surface runoff, groundwater recharge, and evapotranspiration (ET) from a high slope ridge-type environment in west-central Florida. This setting exhibited water table depths ranging from deep (>20 feet) to shallow (0-6 feet) over a varied period of meteorological conditions. Data were collected at the site for approximately four years, from 2007 to 2010.

The site selected for the study is within the USF Eco Area in Temple Terrace, Florida near the intersection of 56th Street and Fletcher Avenue close to the USF campus. The site was chosen because it contained a significant range of topography over a relatively short distance and was undisturbed by development. The six sites selected for aquifer water level and soil moisture measurement were chosen by topography, accessibility and such that they would lie on a general down-slope flow path. The sites range from the top of a relic dune ridge, approximately 51 feet in elevation, to a low-lying area at the edge of the floodplain of the Hillsborough River at approximately 24 feet elevation. The vegetative cover transitions from a xeric pine and scrub oak forest at the top of the ridge to palmetto and slash pine/mixed forest down to floodplain hardwoods wetland cover. Soils are fine to very-fine sand (~ 0.1mm< D_{50} <0.5 mm), typical for west-central Florida.

The upper three sites are characteristic of a very deep water table for west-central Florida (>12'). The predominant vegetative cover in these upper stations is xeric pine and scrub oak forest. The two upper-most shallow (~25' casing depths) wells have rarely contained water. Both of those wells are in a relatively thin unit of very-fine sand overlying a thick clay lens. The sand unit at these locations is typically dry and unsaturated. All other down-slope wells have contained water since installation. The third well in the series (ECO - 3) has provided the most useful data for a deep water-table setting (average depth to the water table is approximately 13 feet). The lowest stations (ECO-5 and ECO-6) are typical of shallow water table settings in Florida but differ by being down-gradient of steep slope uplands.

A Florida aquifer monitoring 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. From these observations it is concluded that if a water table forms on the upper portion of the ridge, it is an ephemeral appearance, present only during the wet season and perched above the underlying discontinuous clay units.

The well at the lowest elevation (ECO-6) is approximately 1000' from the Hillsborough River and is in a high (shallow) water-table environment (average depth to the water table during this study was approximately 2 feet). 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 was 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 soil between the water table and the advancing wetting front can equilibrate to the atmospheric air pressure outside of the well. There have been many observed instances where the partially-screened well was more responsive to rainfall (false water-table response) than the fully-screened well which vented trapped air (precluded excess pressurization) during the study period.

Observations, made at the highest practical resolution and recorded at 10-minute time intervals, included: 1) surficial and Floridan aquifer water elevations at sites chosen along a transect ranging from deep to shallow water table; 2) vertically resolved soil moisture content at each well site; 3) open-pan evaporation and estimated reference evapotranspiration measured at high resolution; 4) continuously monitored atmospheric conditions and precipitation; and 5) field surveyed 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 each location.

Unfortunately, during much of the study period, the site experienced below average rainfall. However, there were a few wet periods which helped to provide insight into more typical west-central Florida meteorological conditions. 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. The rainfall deficit continued in 2009 with an annual total of 44.4 inches. Rainfall in 2010 was more normal for the eight month period with 45 inches recorded through September 1st. Typical annual rainfall for this area is approximately 52 inches. This lack of rainfall produced a cumulative three year deficit of 25 inches (following a undetermined previous deficit); however, the dry period provided an opportunity to examine recharge characteristics for drought conditions but may not be representative of recharge during normal weather conditions.

A number of important findings were gained through this study. These findings can be broadly classified as Recharge Processes, Rainfall Excess (contributing to downslope runoff) Processes, Detailed Point-Scale Water Budgets, Assessment of Recharge in Hydrologic Modeling and specific testing results for the HSPF-MODFLOW Integrated Hydrologic Model, IHM.

Four factors were identified and studied that control resulting recharge for the study site: 1) depth to the water table,2) pre-existing soil moisture conditions, 3) root ET uptake depth, and 3) post-event rainfall/ET deficit. These same factors influence rainfall excess contributing to recharge.

Depth to water table controls the timescale of recharge via the wetting front propagation. Deeper water table settings recharge more slowly as the water needs to move further through the soil column before reaching the water table. The time required to reach the water table is highly variable by soil condition but appears exponential in depth. This has also been supported by theoretical unsaturated zone modeling and laboratory experiments (not part of this study). Recharge to the water table in west-central Florida fine sands for depths less than 3 ft occurs over minutes to hours, for depths 3-6 ‘ occurs over hours to days, to reach depths 6’ -13’ days to weeks, and greater than 13’ was not measured but was theoretically determined to be on the order of months.

It was also observed that if the soil is dry before the event, infiltrating water (in excess of the rather large vadose zone storage) propagates more slowly. Because the soil water pressures are relatively higher in and behind the front this is the easiest water for the plant roots to take in and is thus preferentially absorbed. Thus, a significant recharge event is sensitive to the ET (and rainfall deficit) period following the event. Significant rainfall events potentially producing recharge may be completely taken up by the plant ET demand before reaching the water table according to the conditions of these four influences.

This study supports findings from other studies that suggest vegetated settings in west-central Florida can remove a significant amount of soil water through transpiration (in excess of ¼"/day). Thus, the root zone depth and post-event rainfall/ET deficit plays the most significant role in the uptake and resultant propagation of a wetting front for deeper water-table settings. The importance of vegetation cover to recharge has been well documented but it can be reduced to the simple relationship between timescale of propagation and post-rainfall/ET deficit. It is for these reasons a heavily forested area will provide less recharge than an area containing grass or pasture. For example, the loss of soil moisture is pronounced during the late spring when ET is high. With the exception of rare spring heavy rainfall events, almost all of the increase to the water table occurred during the wet summer months due to the prevalence of post-event wet antecedent conditions. At the deep water-table location, a significant rainfall event may produce no recharge during the dry season. But an event of the same intensity and duration occurring during the wet season when the soil moisture is sufficient to allow percolation can produce significant recharge.

In general, there is some rainfall threshold that exists for both shallow and deep water-table locations below which produces no recharge during any season. This threshold (similar to but larger than initial abstraction defined for runoff) is much higher for deep water tables and greatly increases for warmer conditions. Therefore, a seasonal rainfall infiltration threshold exists for any site before any recharge can occur dry or wet. In addition to this, the soil moisture conditions can be depressed which results in significant vadose zone recharge potential that must also be exceeded, in addition to this infiltration abstraction, before any water table recharge can occur.

At the shallow water-table locations (ECO-5 and ECO-6) most rainfall events produced some recharge. Much of that recharge, however, was quickly lost to ET. Plants in this environment were able to extract water directly from the water table in contrast to the deep water-table environment where plants extract water from the vadose zone storage. Thus, predicting water-table response in shallow water table (runoff rich) environments requires characterizing stresses on the order of minutes. The transition to saturation excess runoff and the observed water levels are highly dynamic compared to deeper settings.

In summary, for these reasons, there is little_to no correlation between rainfall and recharge (or similarly runoff) as a single dependent variable. Attempting to estimate recharge by multiplying rainfall by a factor will likely overestimate recharge during dry periods and underestimate recharge during wet periods and overall be highly inaccurate.

In shallow water table observations, during the wet season, the water table was near land surface. When the capillary fringe approaches the land surface, near-saturation soil moisture conditions exist and there is little fillable pore space available for infiltration. Small rainfall events can produce a large rise in the water table which is quickly offset by a large decline in the water table from ET. Much of the wet season is characterized by frequent large and rapid changes in the position of the water table. The specific yield (recharge required to raise the water table one unit height) was highly variable and rapidly decreasing non-linearly near land surface due to the presence of capillary suction, moisture held above the water table (for water table depths less than 6').

Last was the observation of the significance of surface slope on runoff, ET and recharge. All six observation stations where positioned in different but generally high slope settings for west-central Florida (many greater than 1%). From the observations compared for each site, there is a clear indication that higher surface slope affects (increases) runoff and this is well documented in the literature. Interestingly and previously not documented is the reduction in recharge (probably associated with decreased infiltration and associated reduced ET. One of the wells (ECO-2) and soil moisture probes was installed in a very high slope (~10%) setting and exhibited very high runoff, low ET and low recharge conditions despite having high infiltration fine sandy soil and a deep water table. Consequently and supporting these observations, the stations right down gradient (ECO-3) experienced infiltration rates greater than rainfall for many larger events and overall higher ET than could be supported by the annual rainfall only, likely caused by up-slope runoff. The implications for hydrologic modeling suggest that it may be required to subdiscretize flow plains with high slope variability to adequately reproduce runoff/recharge and ET processes.

Testing of the IHM on the conditions measured at the study site revealed that some model modifications may ultimately be warranted to better represent this timescale of recharge and ET recharge uptake behavior. The model testing was consistent with previous testing in shallow water-table settings indicating that, if sufficiently small time steps are used (ideally 15-min or less). The model adequately reproduces all of the major water budget processes including infiltration, runoff, ET and recharge fluxes as well as vadose zone and water table storage behavior throughout the seasonal and antecedent variable moisture conditions monitored. However, the model behavior for deeper water table conditions was only adequate on average as the model was seen to miss-represent the timing of recharge (model recharge occurs sooner than actual) and there are clear seasonal differences in ET. This may have implications for representing the ET uptake of the recharge wetting front in deep root zone settings. Further testing and/or possible model modifications are warranted.

Introduction

New instrumentation and field procedures have been developed at USF 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 was to test the methodologies developed at USF (Ross et al., 2005; Trout et al., 2005 and Rahgozar, 2005) to measure hydrologic processes in a small but variably vegetated ecological study area. The site is in west-central Florida, adjacent to and maintained by USF, lying within the Hillsborough River watershed.

Objectives of the study

There were multiple objectives for this study. Foremost was the direct measurement of runoff, recharge and evapotranspiration (ET) in a deep water table and transitional water table environment that represents a significant portion of the SWFWMD domain. A second objective was to determine causative processes and rates through dry and wet transitions. Other objectives were to test methods developed at USF to estimate ET for different plant communities, investigate recharge characteristics at high and low water-table environments and under various meteorological conditions 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 high-resolution hydrologic and meteorologic data were obtained over three and a half years. Groundwater monitoring was paired with soil moisture monitoring down through 2 m depths to provide data to determine detailed water balances at each station and to understand the time-scale, magnitude and uptake mechanisms of recharge. An evaporation pan, rainfall and full meteorological instrumentation were also included.

Mapping and GIS

Topographic maps, GPS and site inspection were used to delineate surface-water flow paths. Site data maps were imported into a Geographic Information System (GIS) for further analysis and presentation.

Rainfall and Evapotranspiration

The time scales of infiltration and Hortonian surface runoff in Coastal Plain environments are minutes to hours (Ross et al., 2005) which require the temporal resolution of rainfall to be similar. A tipping-bucket rainfall gauge, which samples every ten minutes, was used to measure rainfall at the site. A manually-read rain gauge was used as a backup and for 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 was estimated using three independent methods: soil moisture balance, the Penman-Montieth combination equation for reference ET (from meteorological data), 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 data collected at an on-site weather station. The weather station installed at the study site continuously measured air temperature, humidity, barometric pressure, solar radiation, atmospheric pressure, air temperature, wind speed and wind direction. An evaporation pan was 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, in Adelaide, Australia) were installed on a downhill flow transect. Each probe had 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, infiltration, ET, and percolation rates can be measured.

At close proximity to each probe was a continuously recording surficial well to provide water-table elevations at the same time interval as the soil moisture data. The wells were installed with 2 inch PVC pipe, with a slotted PVC screen extending below a bentonite clay seal. Silica sand was 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 recorded soil moisture measurements and water-table elevation data from pressure transducers.

Monitor Wells

Groundwater monitoring wells were associated with the soil moisture sensors to record changes in the elevation of the water table. This was 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 not necessary for the Floridan but made anyway.

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 hydrological research.

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 51 feet in elevation, to a low-lying area at edge of the floodplain of the Hillsborough River at approximately 24 feet elevation. The vegetative cover transitions from a xeric pine/live oak forest at the top of the ridge to palmetto scrub with scattered slash pine trees ending with riverine hardwood floodplain.

The upper site is characteristic of deep water table ridge environments ubiquitous in west-central Florida. It is covered by dry very-fine (0.1 mm < D_{50} < 0.5 mm) relic dune sand. The predominant vegetative cover is pine and scrub oak forest. The two upper-most shallow (<30') wells have not contained water since they were installed. Both of those wells are in a relatively thin unit of very-fine sand overlying a thick but discontinuous clay lens. The sand unit at these two wells 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 fine sand were primarily clay and sandy-clay lenses. Based on the installation and measurements at the site, 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, at the edge of a rather large hardwood floodplain 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 was 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. The hypothesis was that 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 trapped between an advancing wetting front and the saturated water table can more easily vent to the atmosphere.

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 were observed to be almost identical throughout the study. It is therefore believed that both wells reflect the Floridan aquifer water elevations the at ECO-4 location.

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. Xeric-type pine and live oak trees predominate on the ridge, giving way to scrub oaks and palmetto scrub moving toward the floodplain which transitions to hardwood wetland 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 xeric sandy areas with deep water tables to high slope loamy areas with mid-range water table depths and mesic plant communities to flat floodplain-type high water table settings with hydric plant communities.

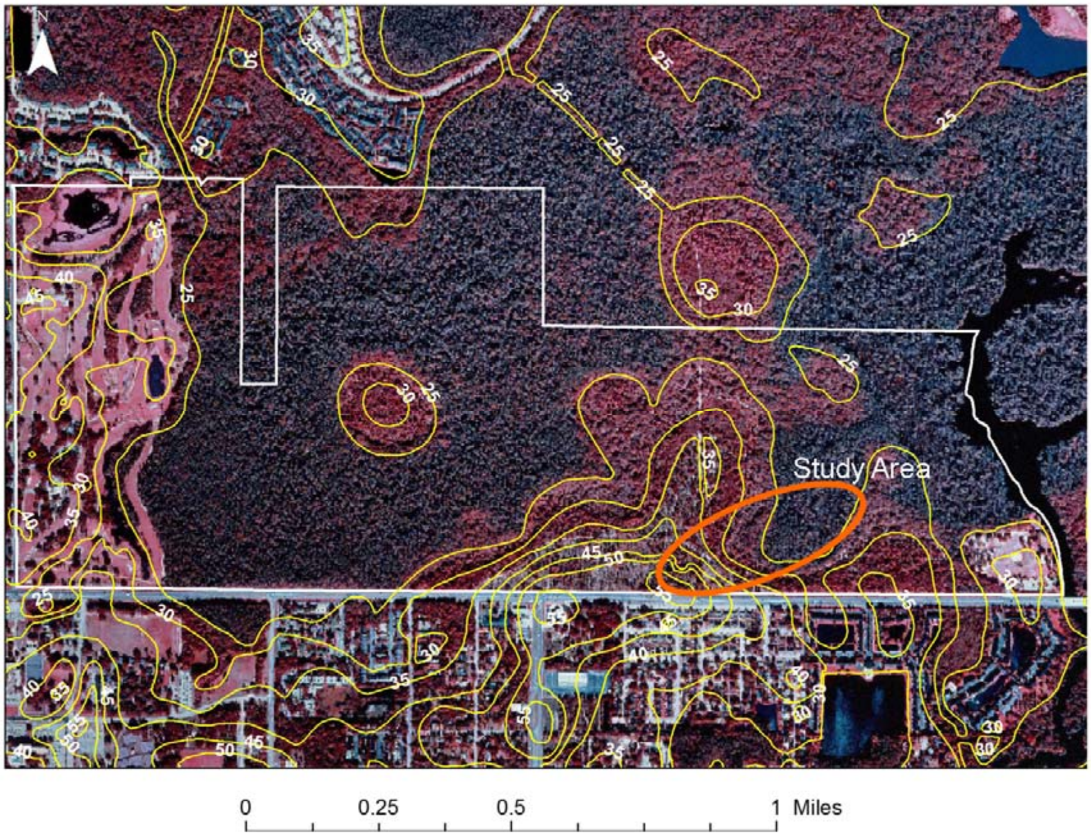

Figure 1. The Orange oval identifies the study area with white line showing the boundary of the USF Eco Area.

Data Collection

The data from all the equipment were collected at 10-minute intervals and stored in a Microsoft Access® database. Manual measurements were made biweekly for rainfall and water elevations in wells to ensure that the equipment was 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 Appendix A.

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

A Campbell ET-106 (Campbell Scientific Inc., Logan, Utah) weather station (Figure 3) collected meteorological data at the site for rainfall, wind velocity and direction, solar radiation, temperature and relative humidity. In addition, barometric pressure data was collected at ECO-1 initially via a Unidata Model 6522B barometric pressure instrument and later by a Solinst Barologger. Solar radiation 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.

The raw and cumulative open water evaporation rate data from the standard Class A evaporation pan (Figure 4). The blue line in the evaporation figures represents the water level from a fixed instrument reference. Thus, increases in this value 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 4. Class A ET pan with GeoKon water level monitoring device installed next to the weather station.

The following figures show the meteorological data collected for the years 2007 through August 2010.

Rainfall 2007-2010

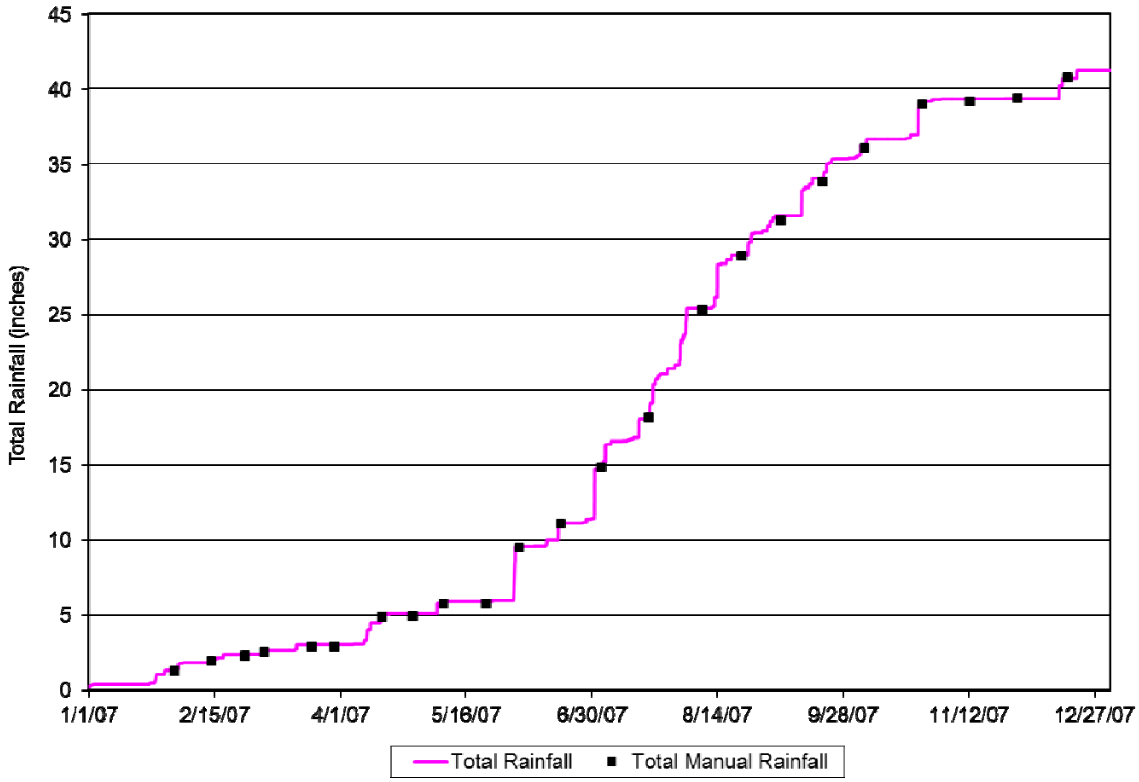

Figure 5. Cumulative and manual rainfall for 2007.

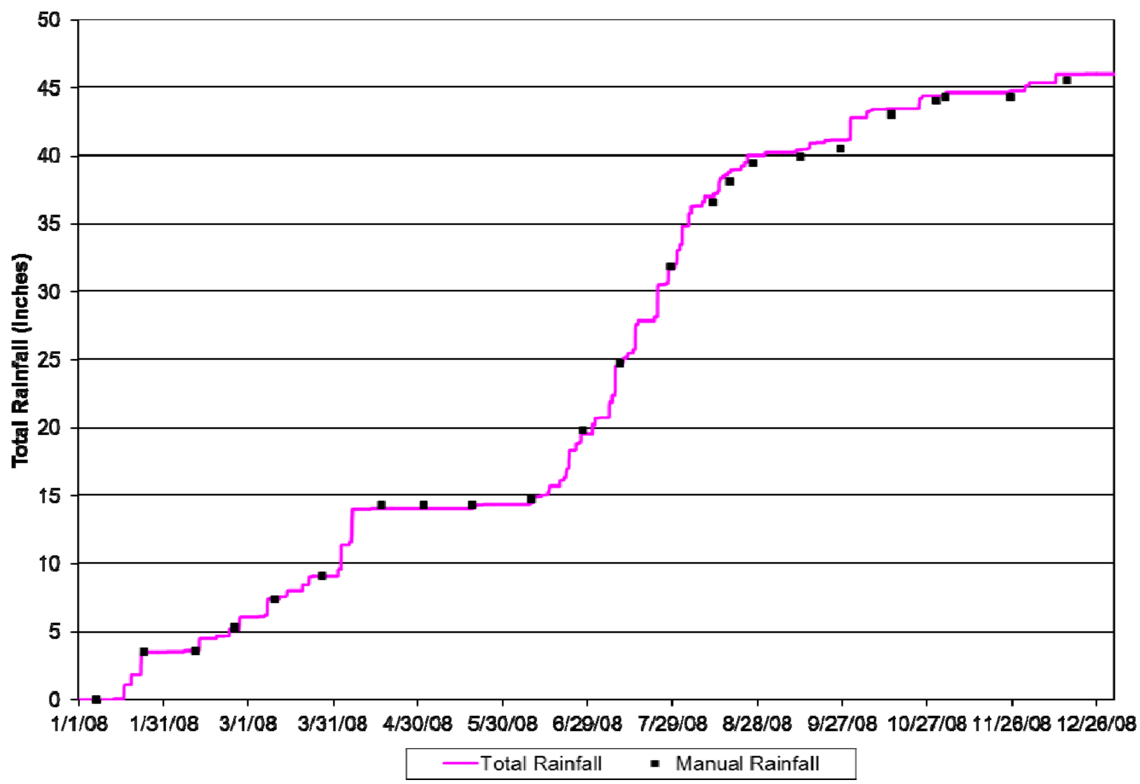

Figure 6. Cumulative and manual rainfall for 2008.

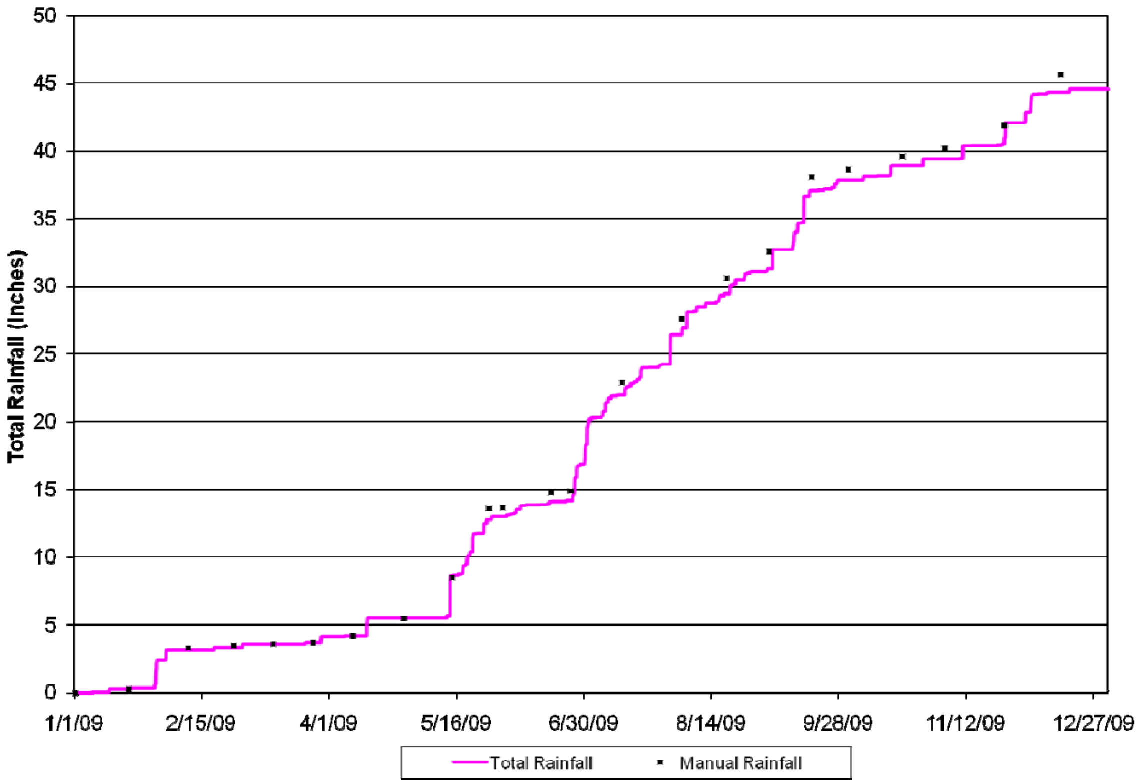

Figure 7. Cumulative and manual rainfall data for 2009.

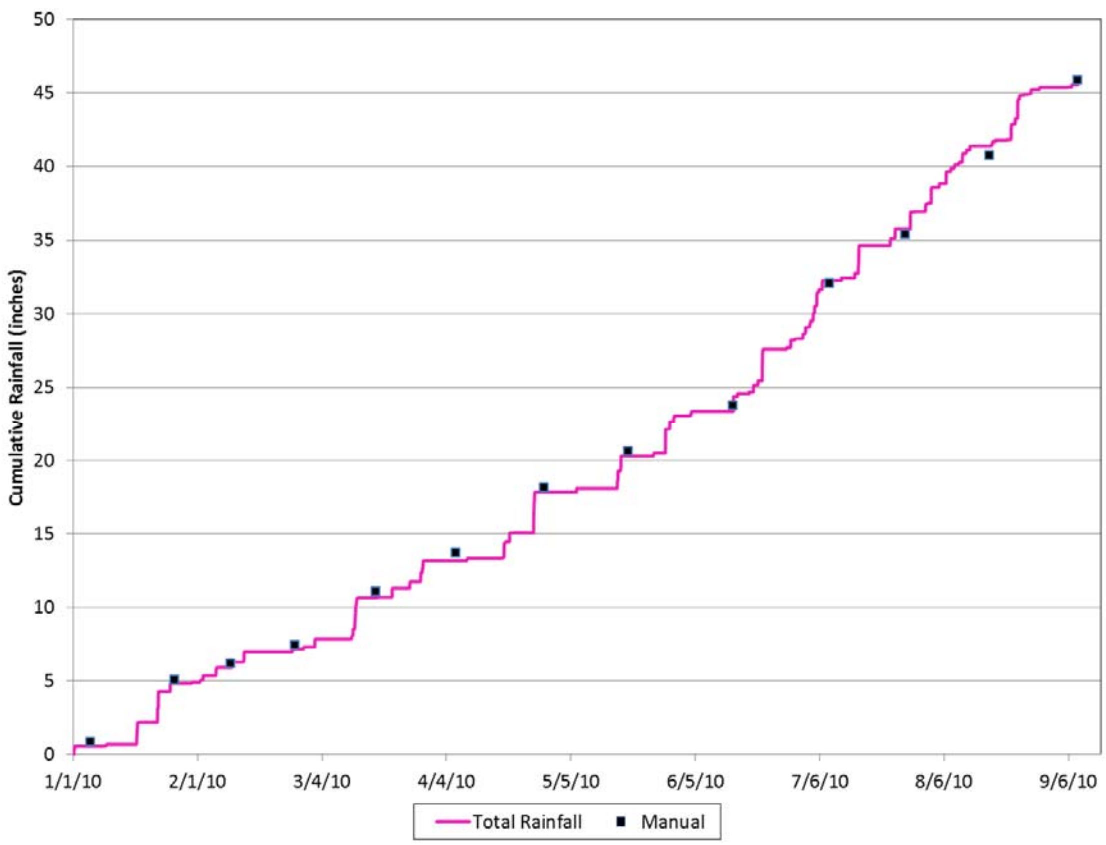

Figure 8. Cumulative and manual rainfall data for 2010.

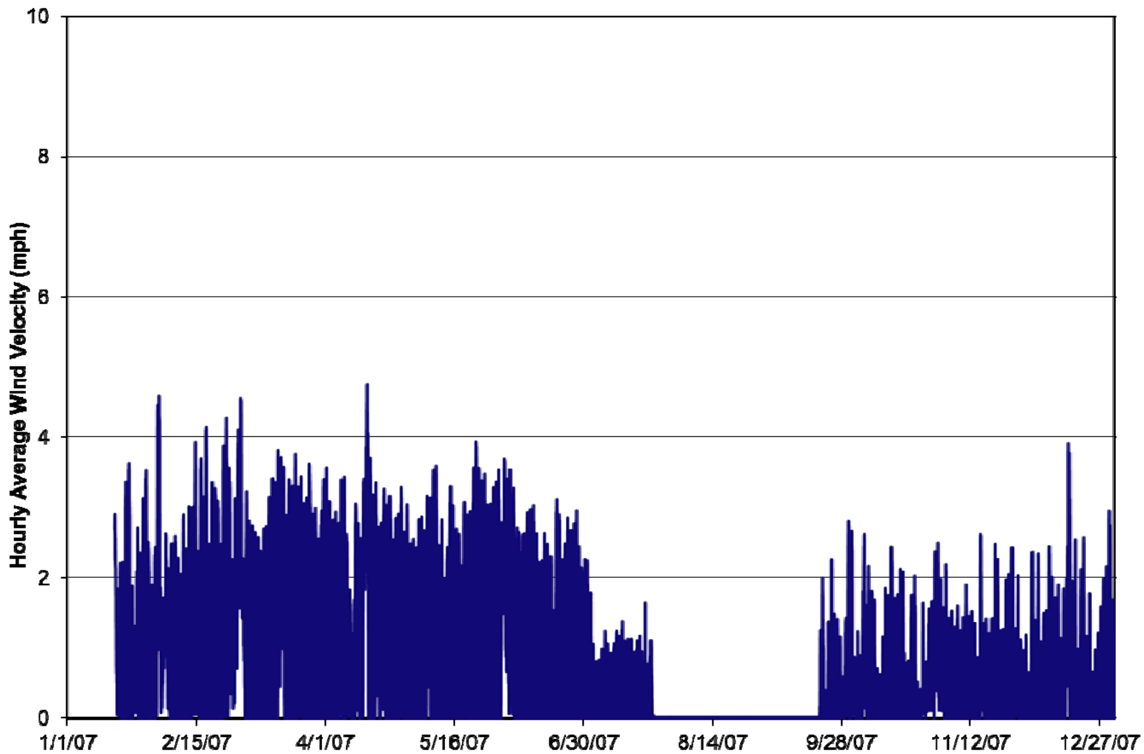

Figure 9. Average hourly wind velocity for 2007.

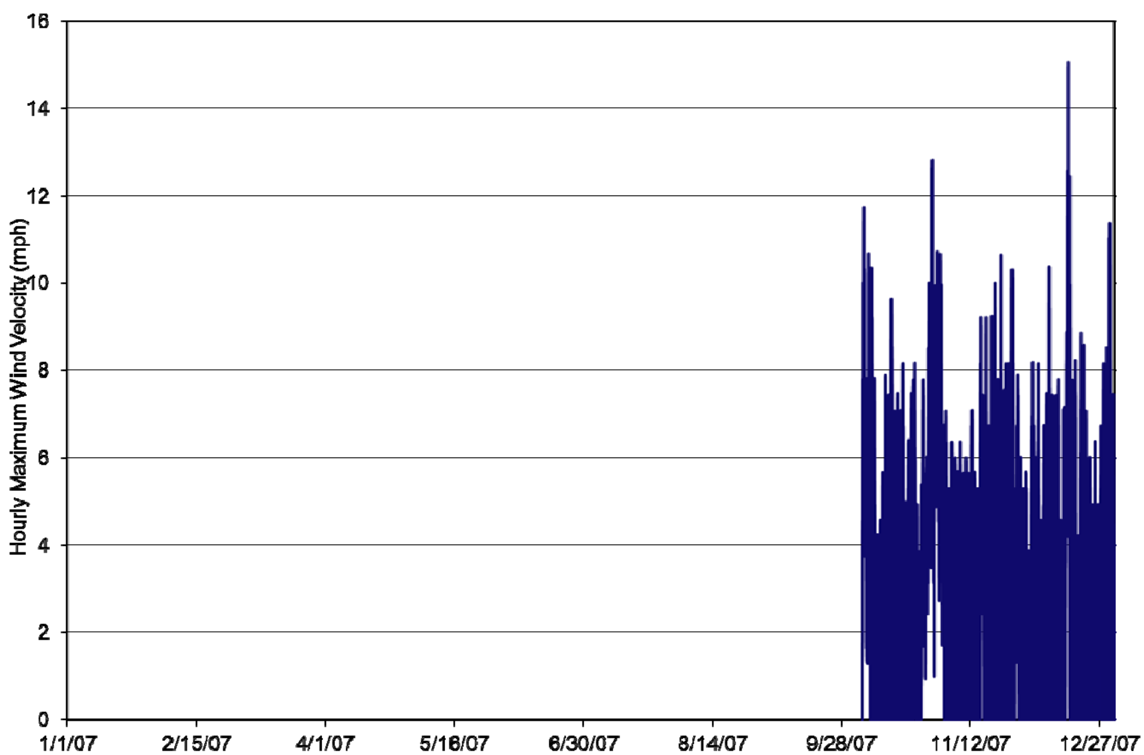

Figure 10. Hourly maximum wind velocity for 2007.

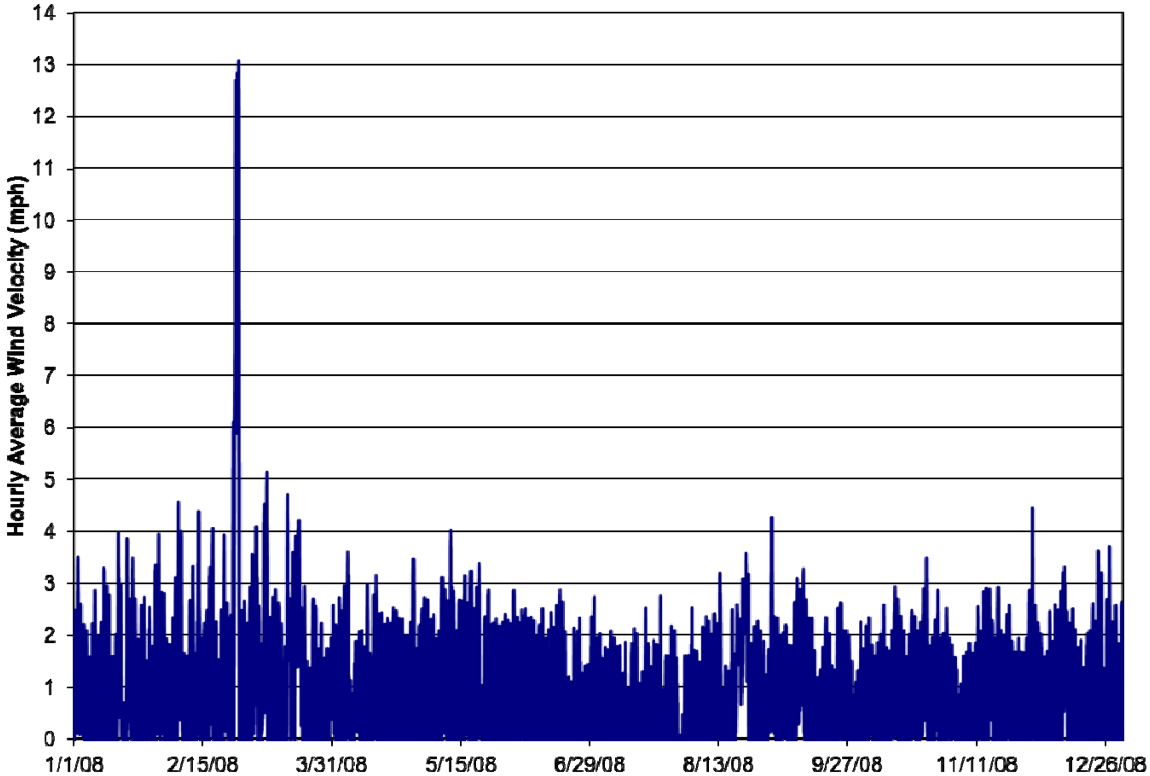

Figure 11. Average hourly wind velocity for 2008.

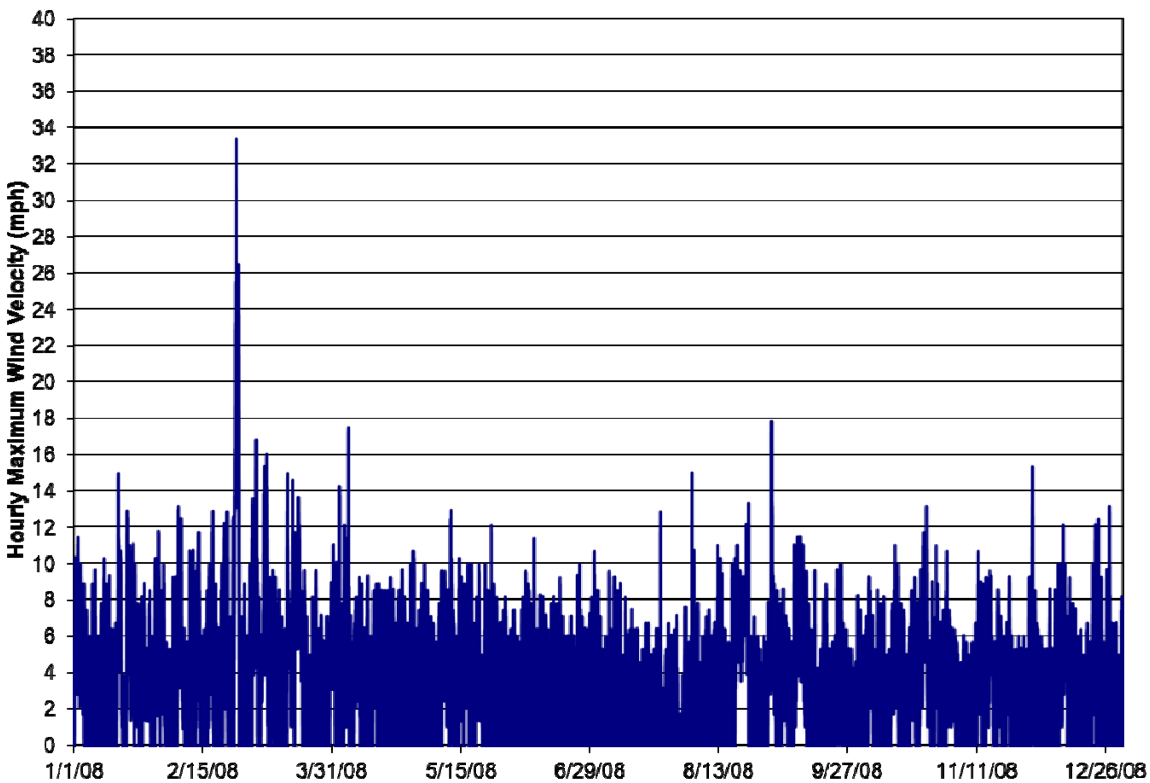

Figure 12. Hourly maximum wind velocity for 2008.

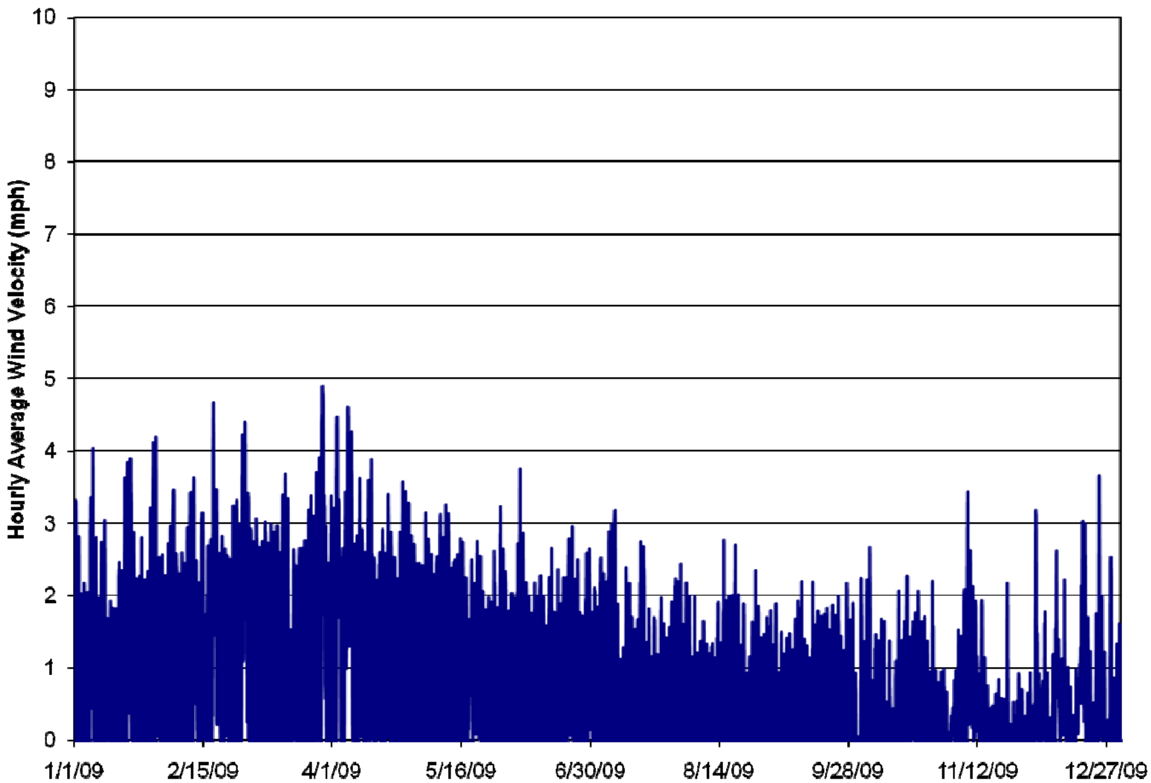

Figure 13. Average hourly wind velocity for 2009.

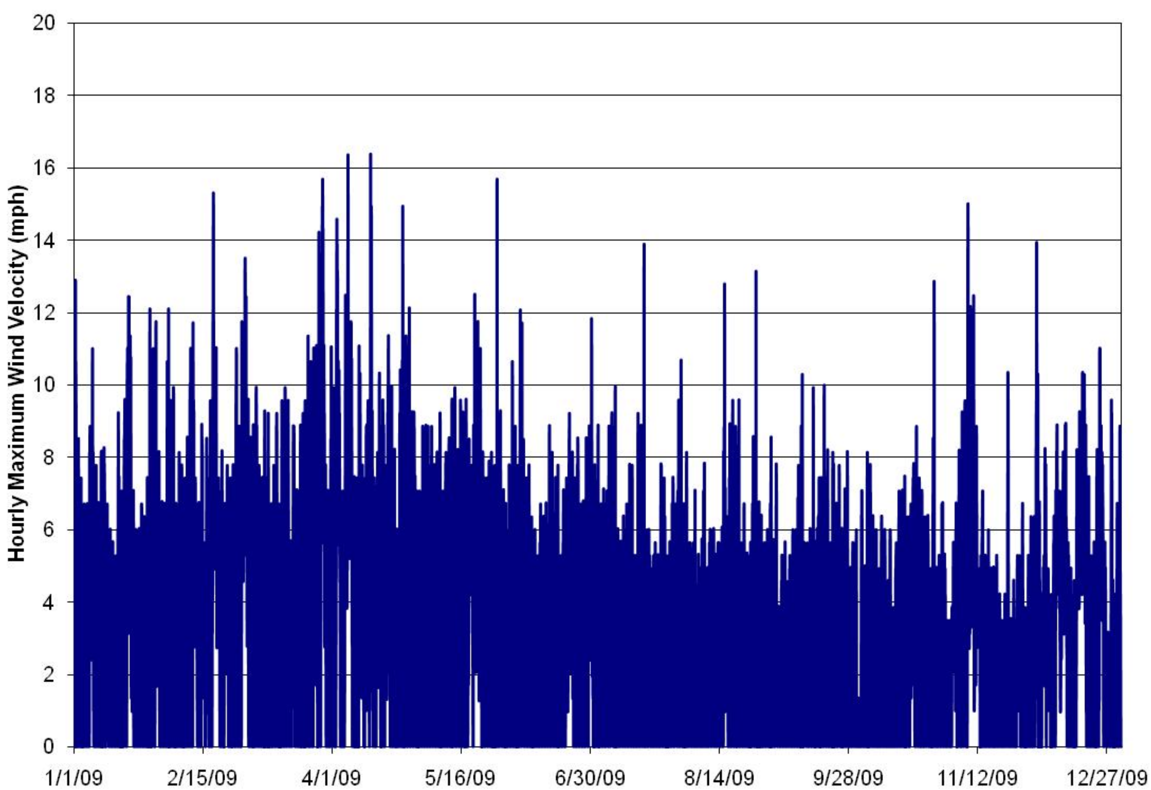

Figure 14. Hourly maximum wind velocity for 2009.

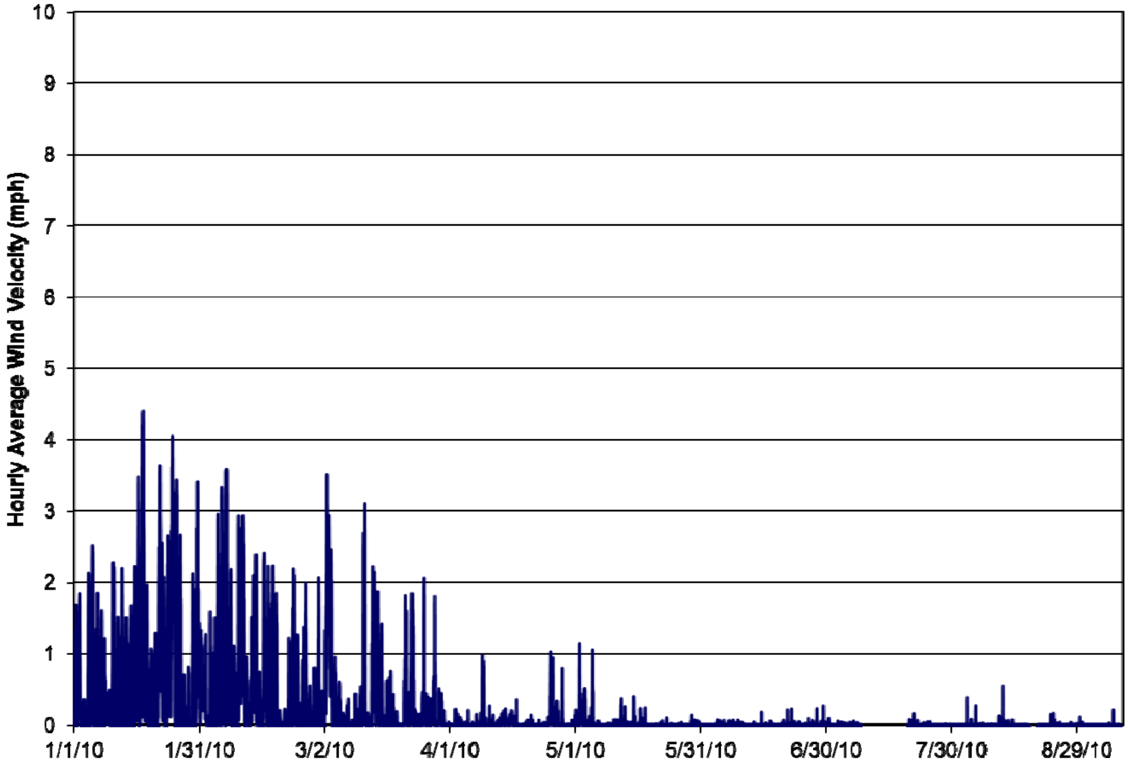

Figure 15. Average hourly wind velocity for 2010.

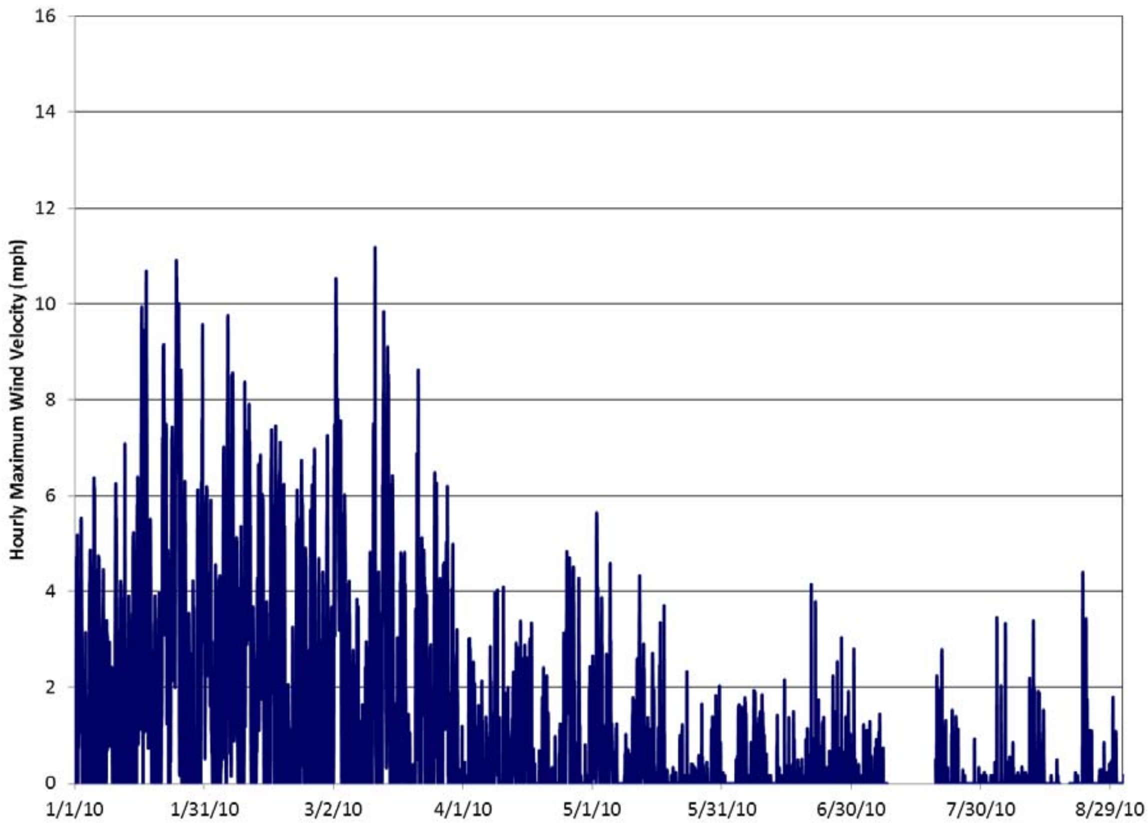

Figure 16. Hourly maximum wind velocity for 2010.

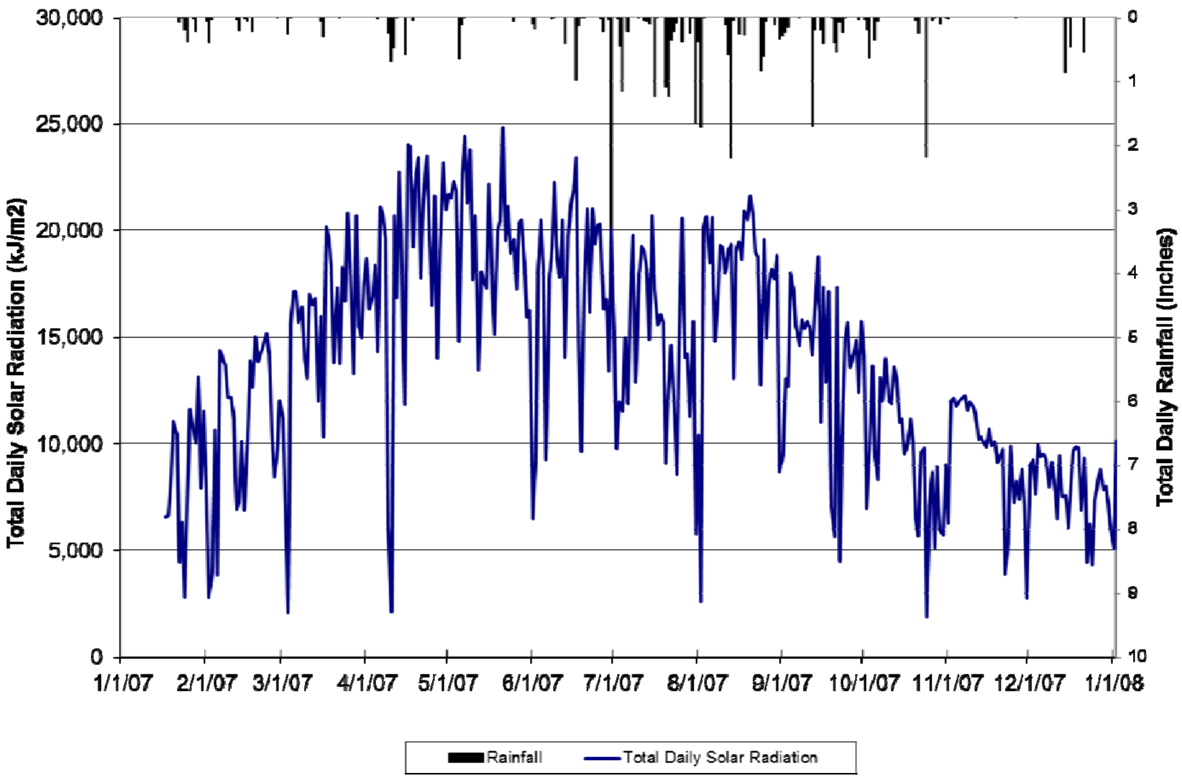

Figure 17. Total daily solar radiation and rainfall for 2007.

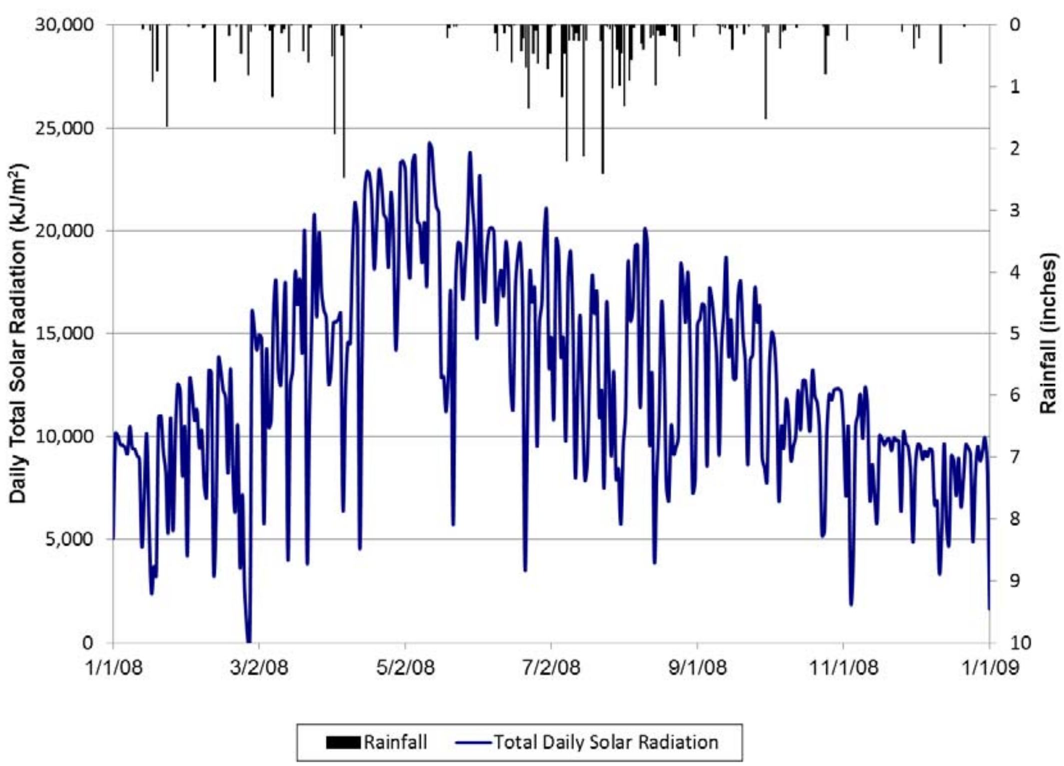

Figure 18. Total daily solar radiation and rainfall for 2008.

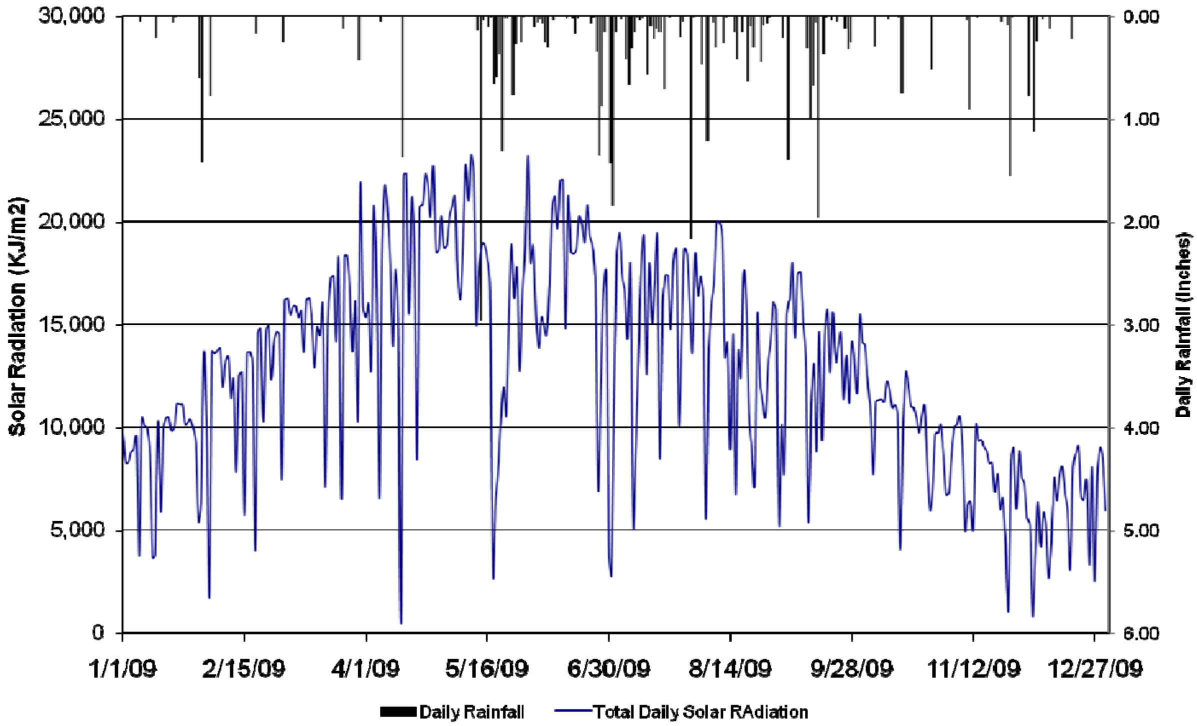

Figure 19. Total daily solar radiation and rainfall for 2009.

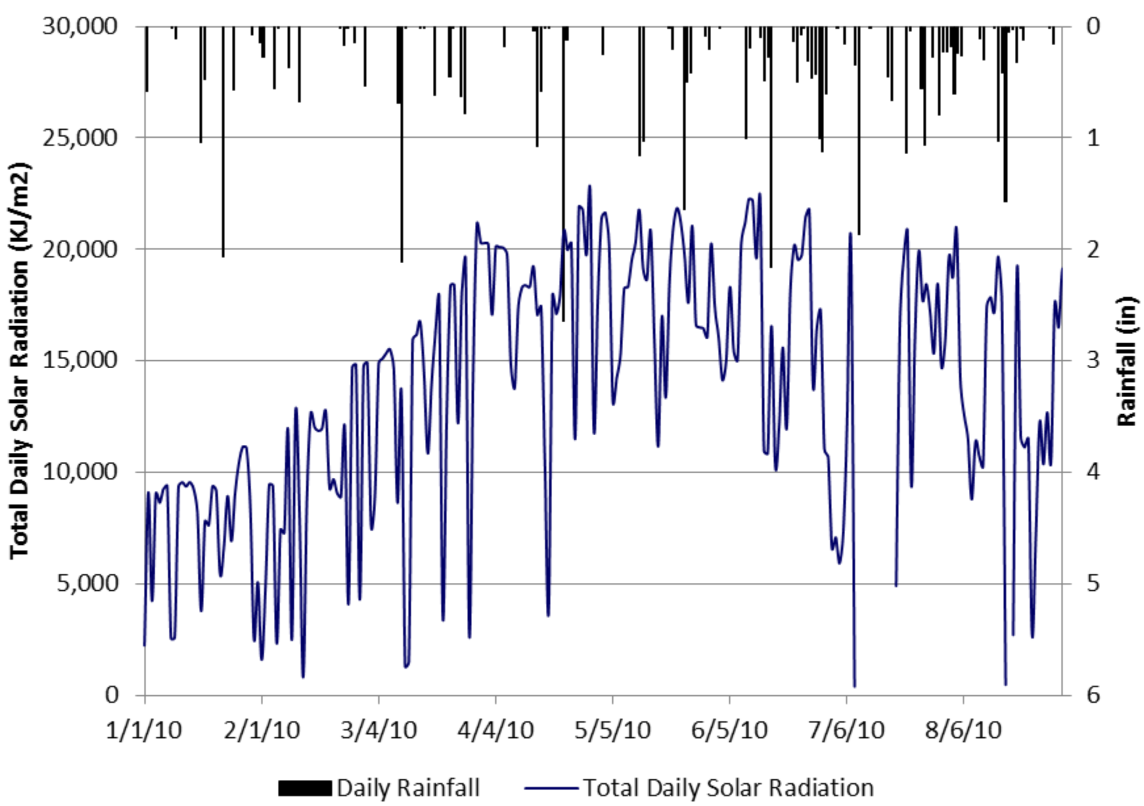

Figure 20. Total daily solar radiation and rainfall for 2010.

Temperature 2007-2010

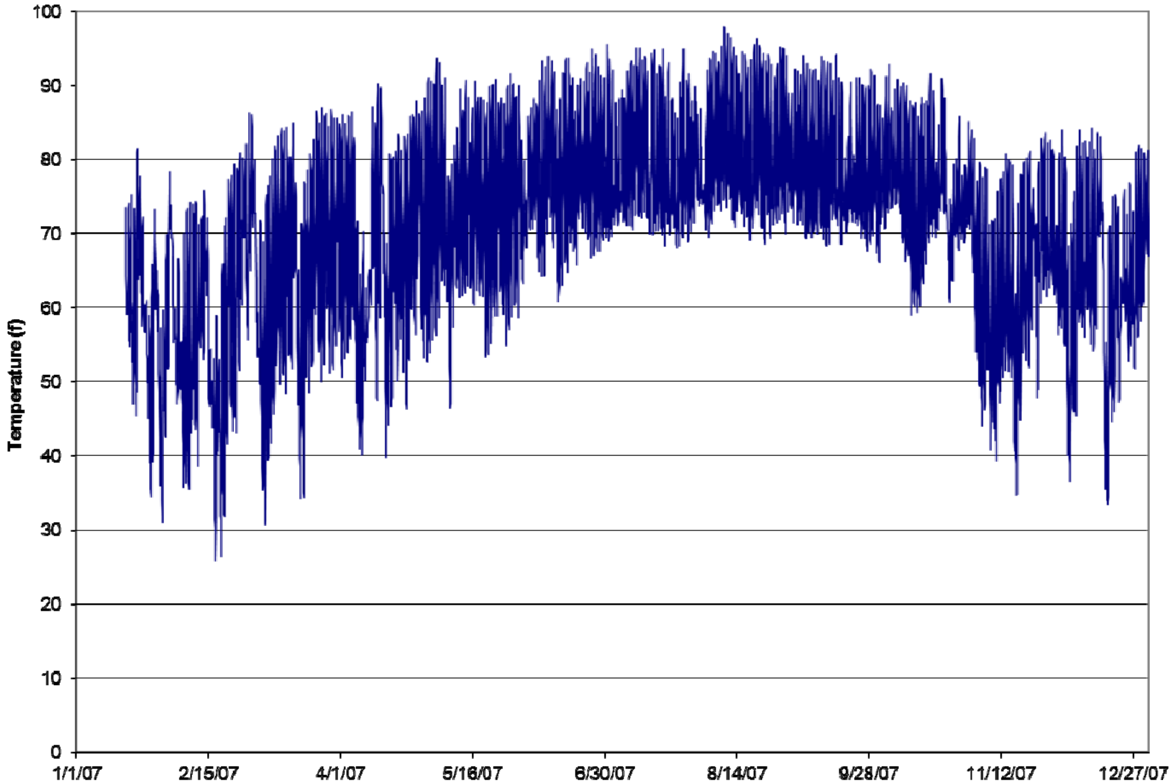

Figure 21. Average hourly temperature for 2007.

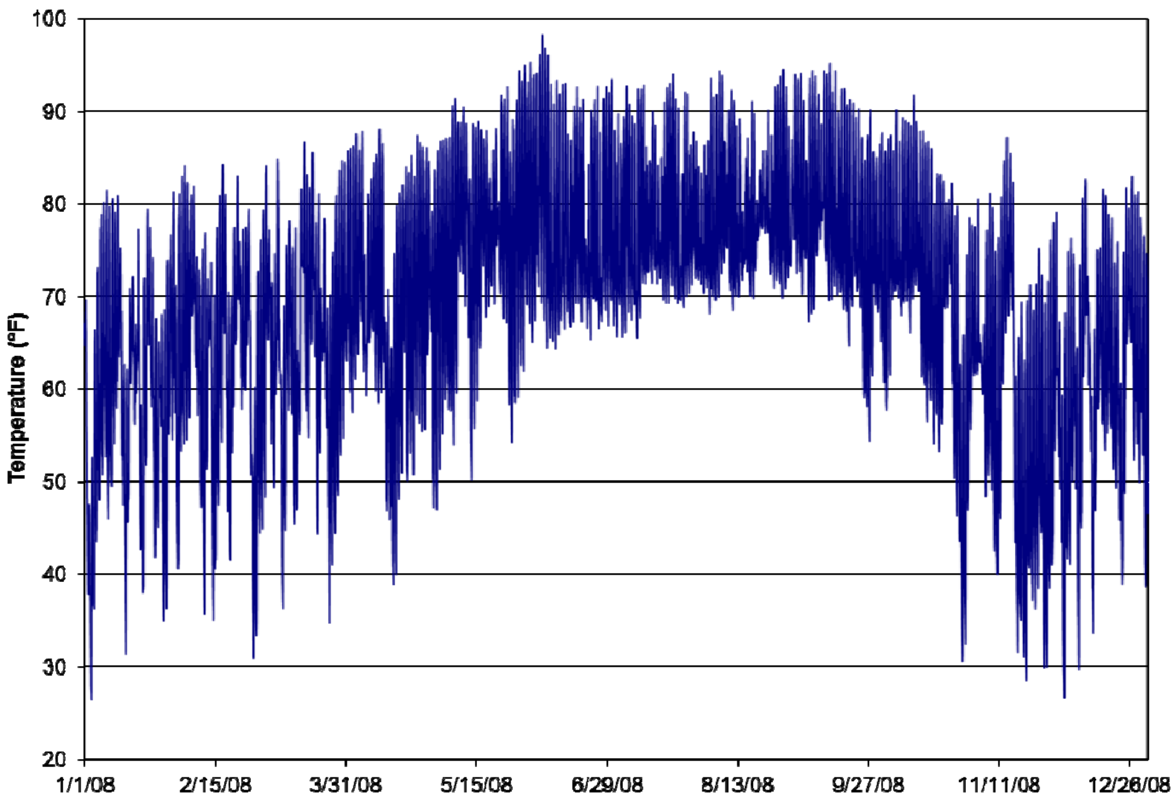

Figure 22. Average hourly temperature for 2008.

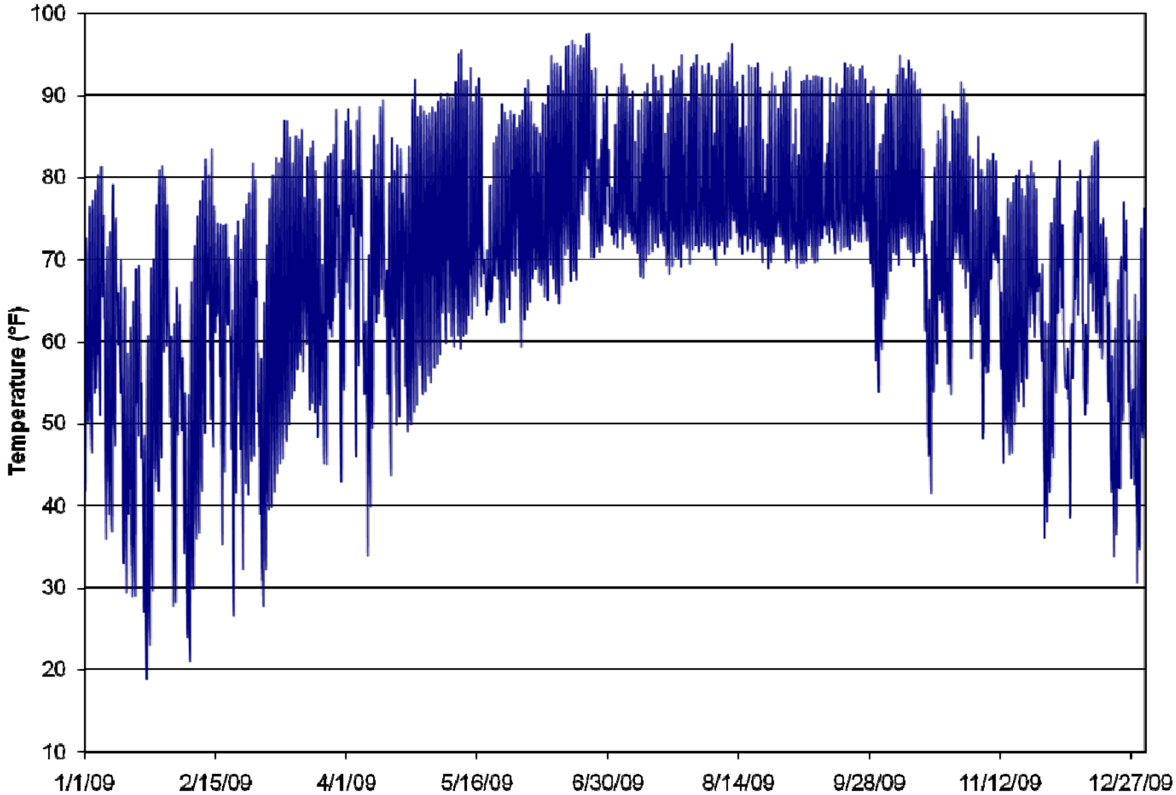

Figure 23. Average hourly temperature for 2009.

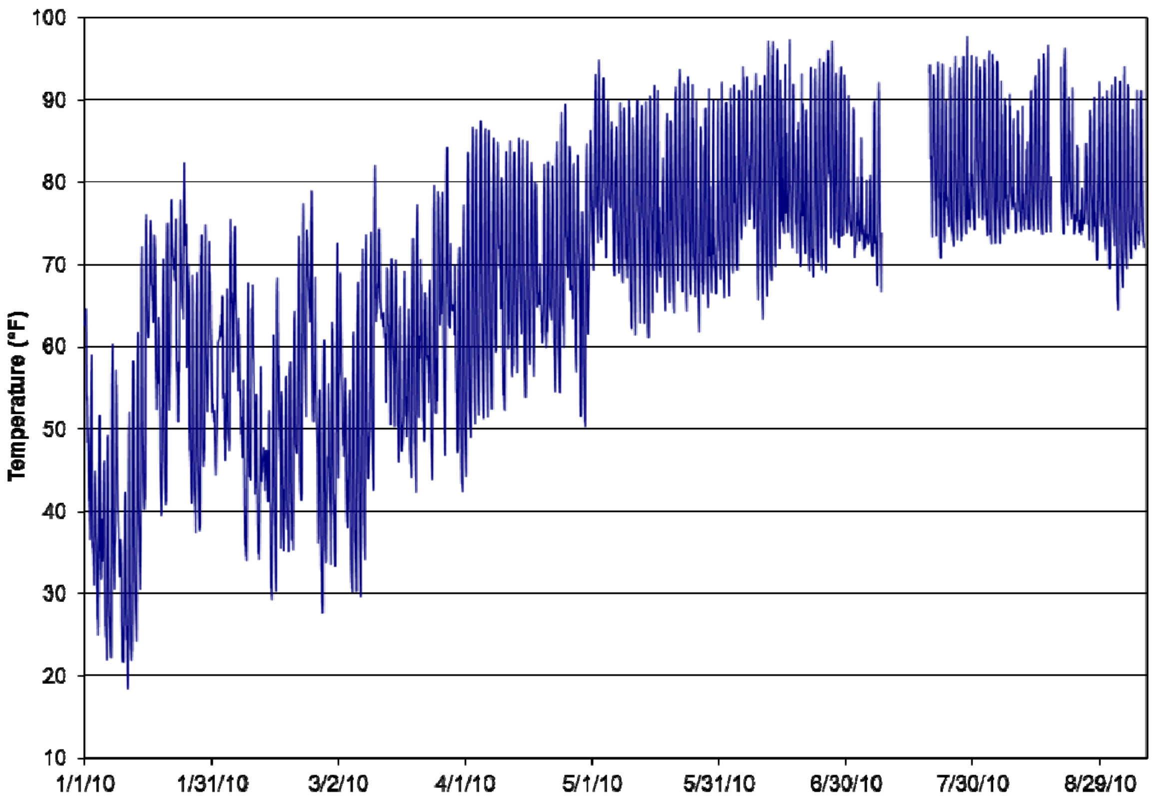

Figure 24. Average hourly temperature for 2010.

Relative Humidity 2007-2010

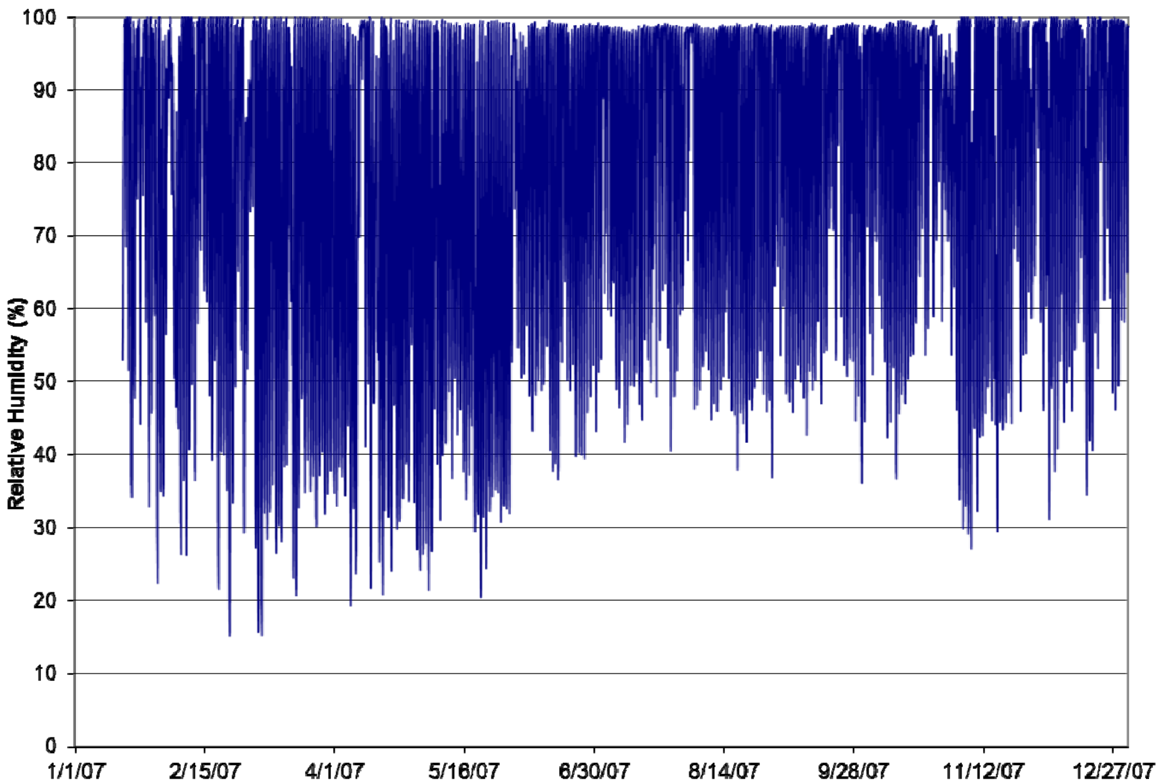

Figure 25. Average hourly relative humidity for 2007.

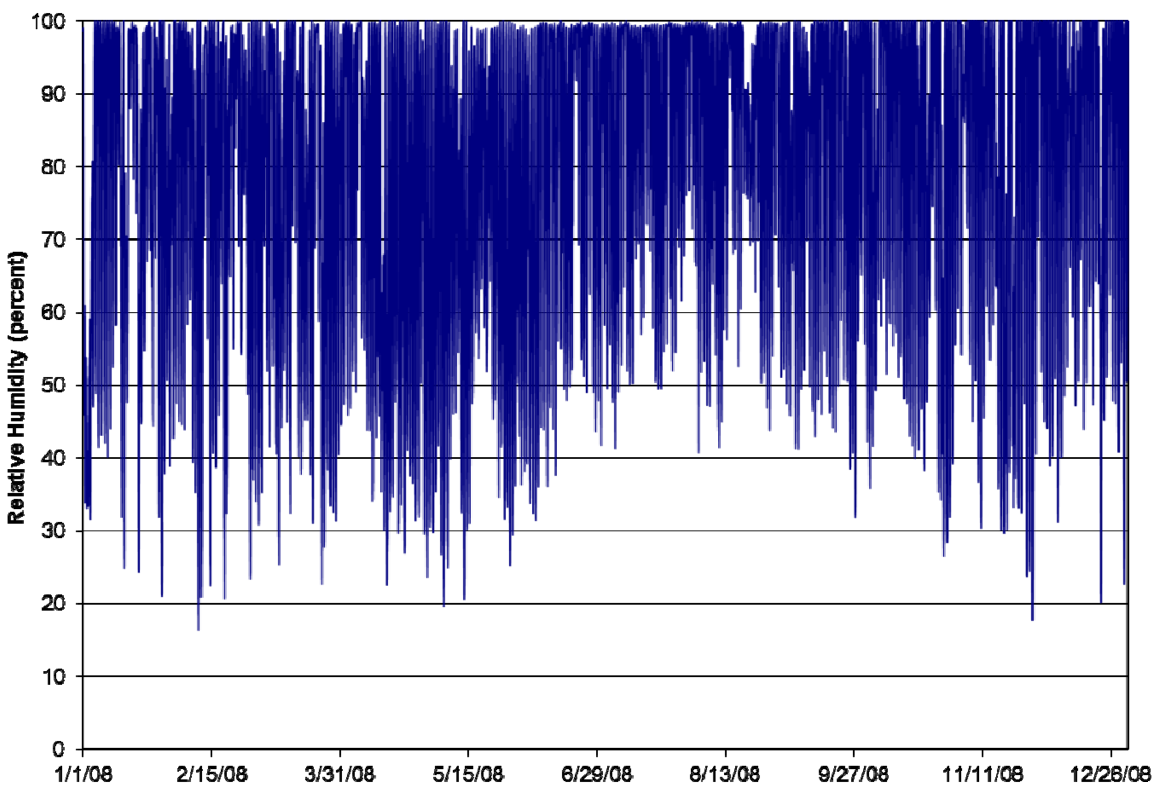

Figure 26. Average hourly relative humidity for 2008.

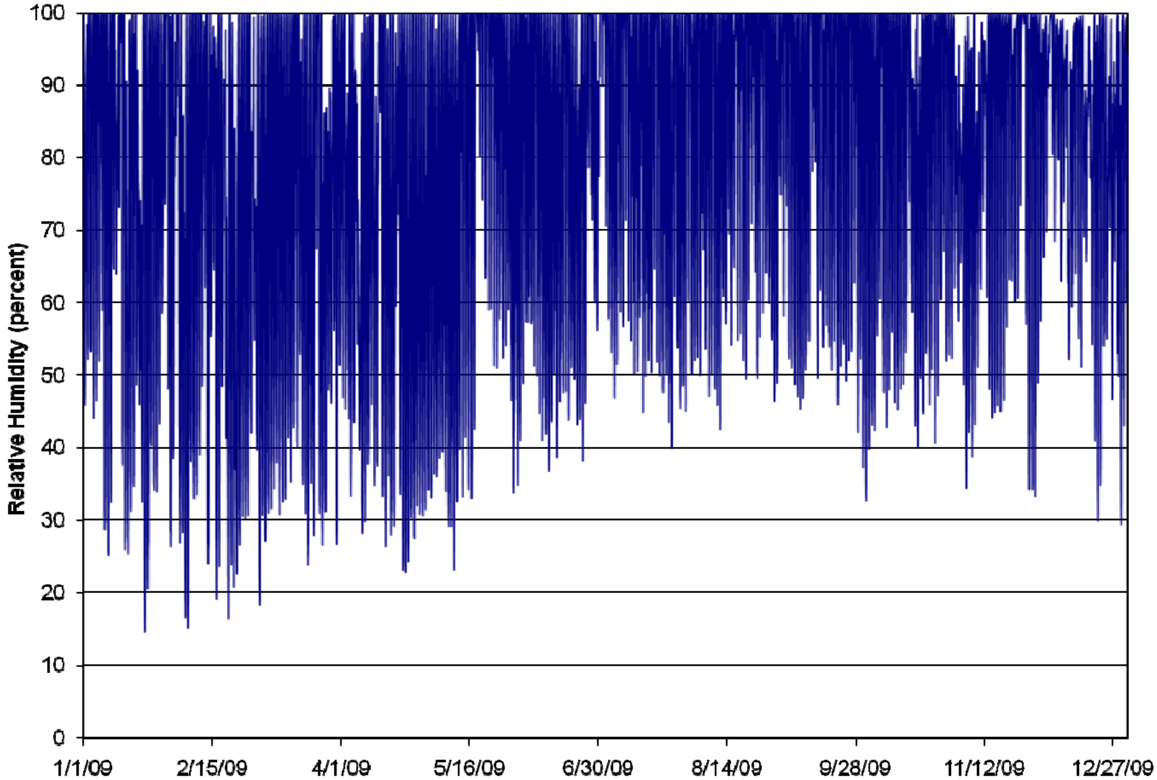

Figure 27. Average hourly relative humidity for 2009.

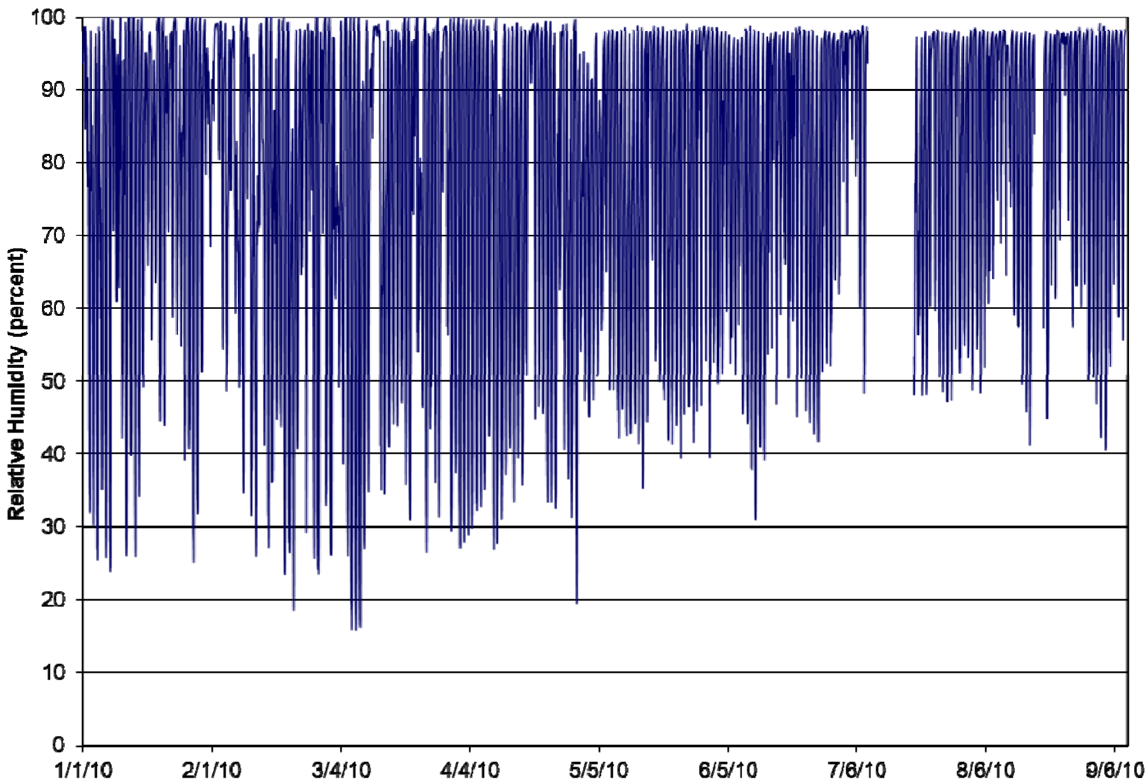

Figure 28. Average hourly relative humidity for 2010.

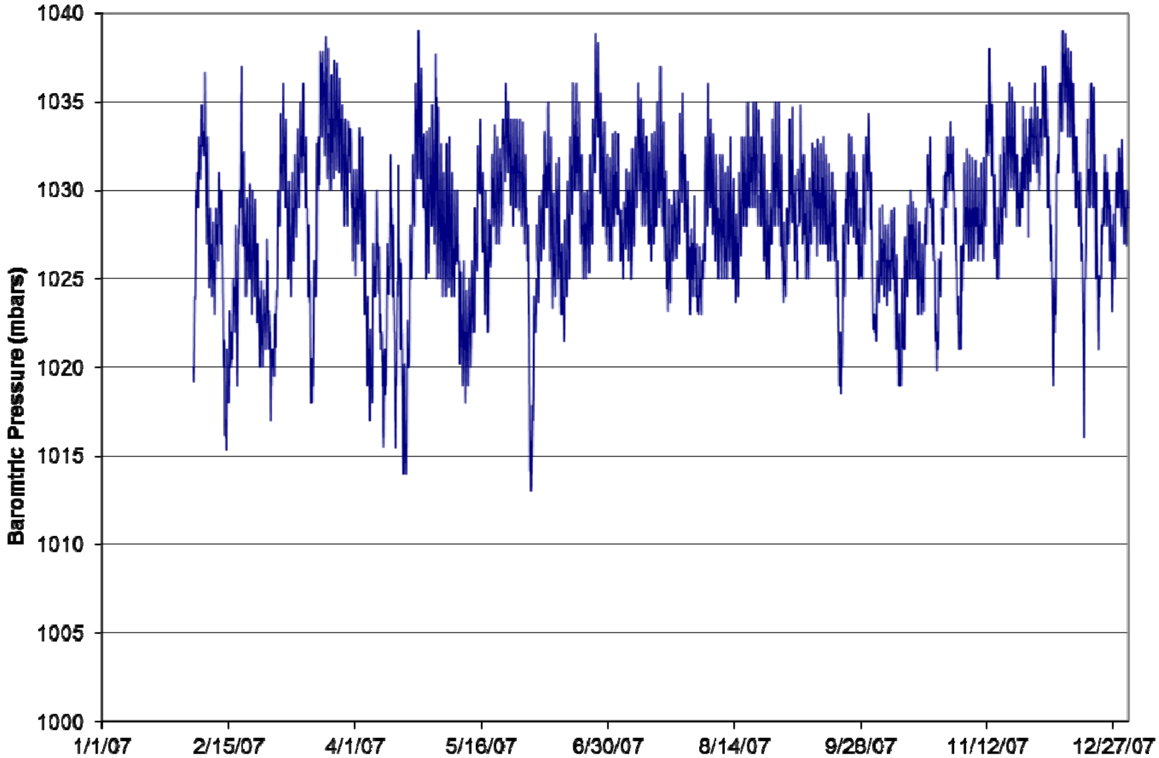

Figure 29. Average hourly barometric pressure for 2007.

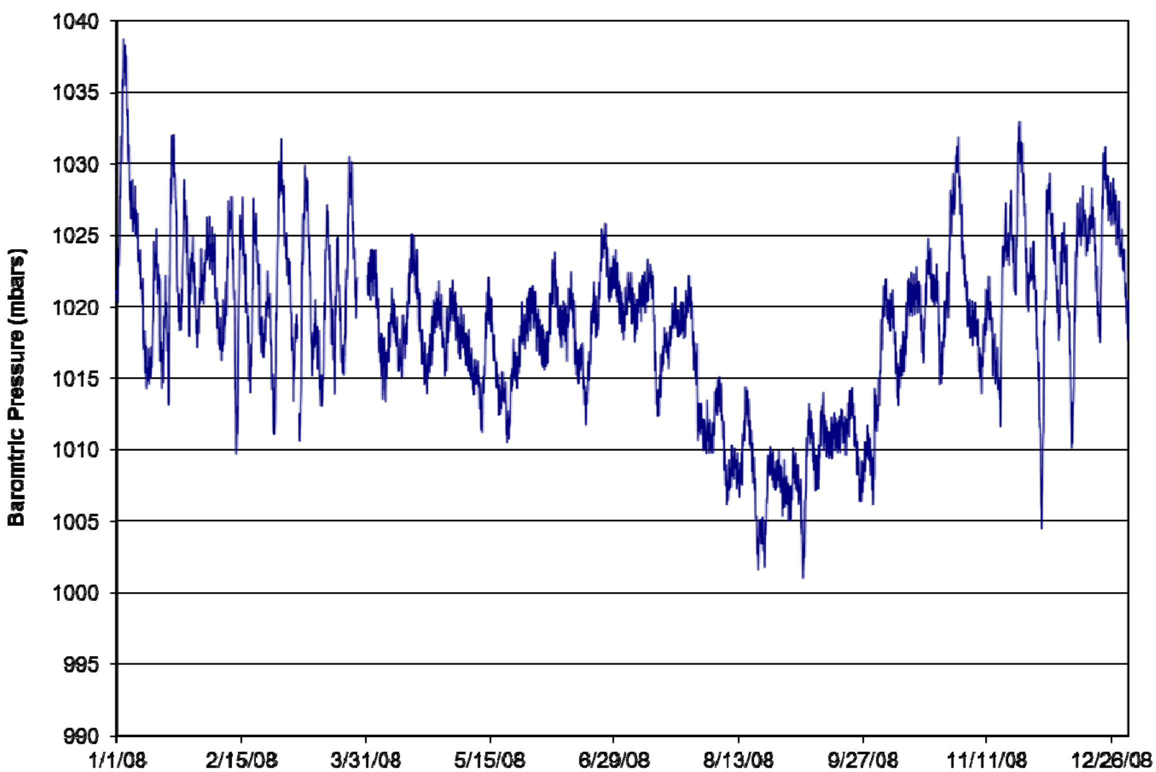

Figure 30. Average hourly barometric pressure for 2008.

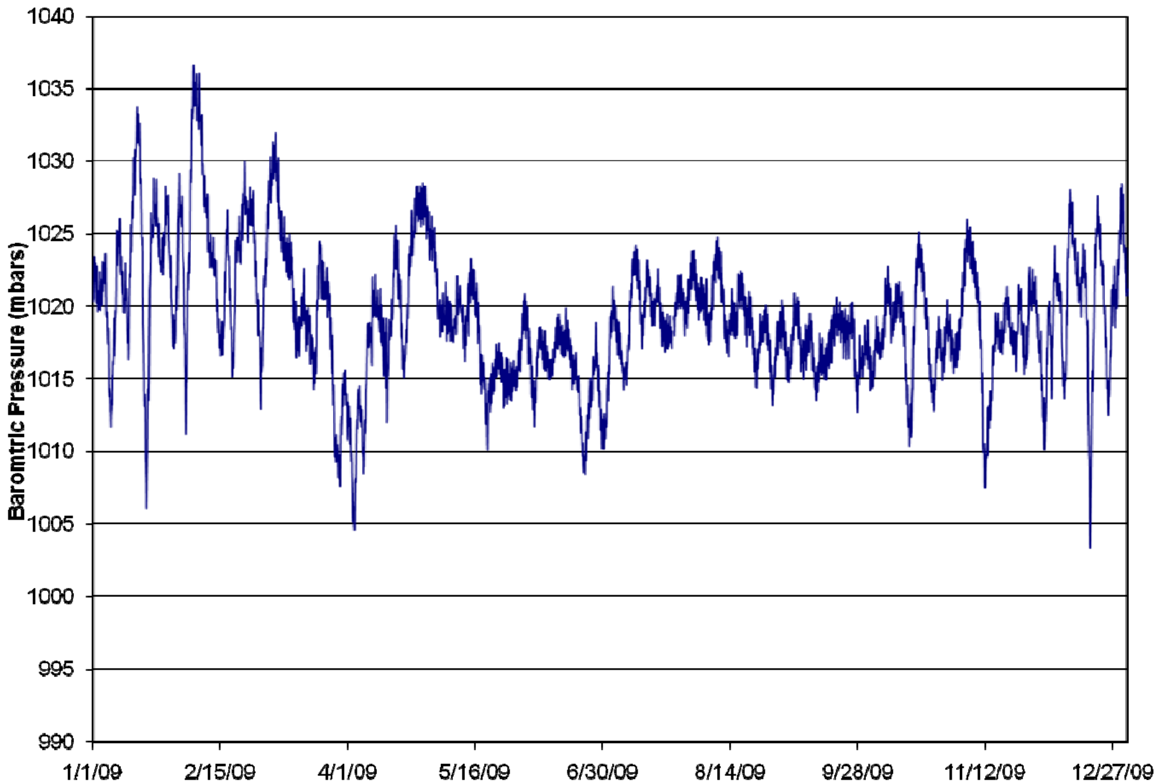

Figure 31. Average hourly barometric pressure for 2009.

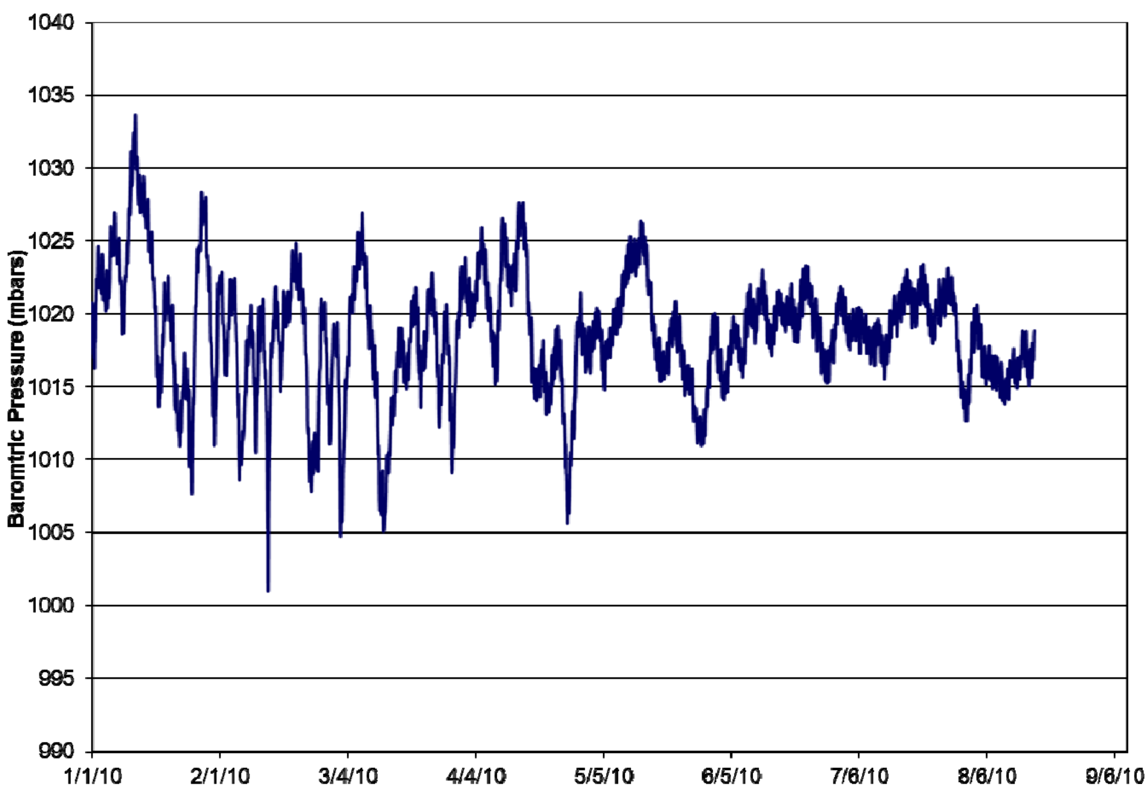

Figure 32. Average hourly barometric pressure for 2010.

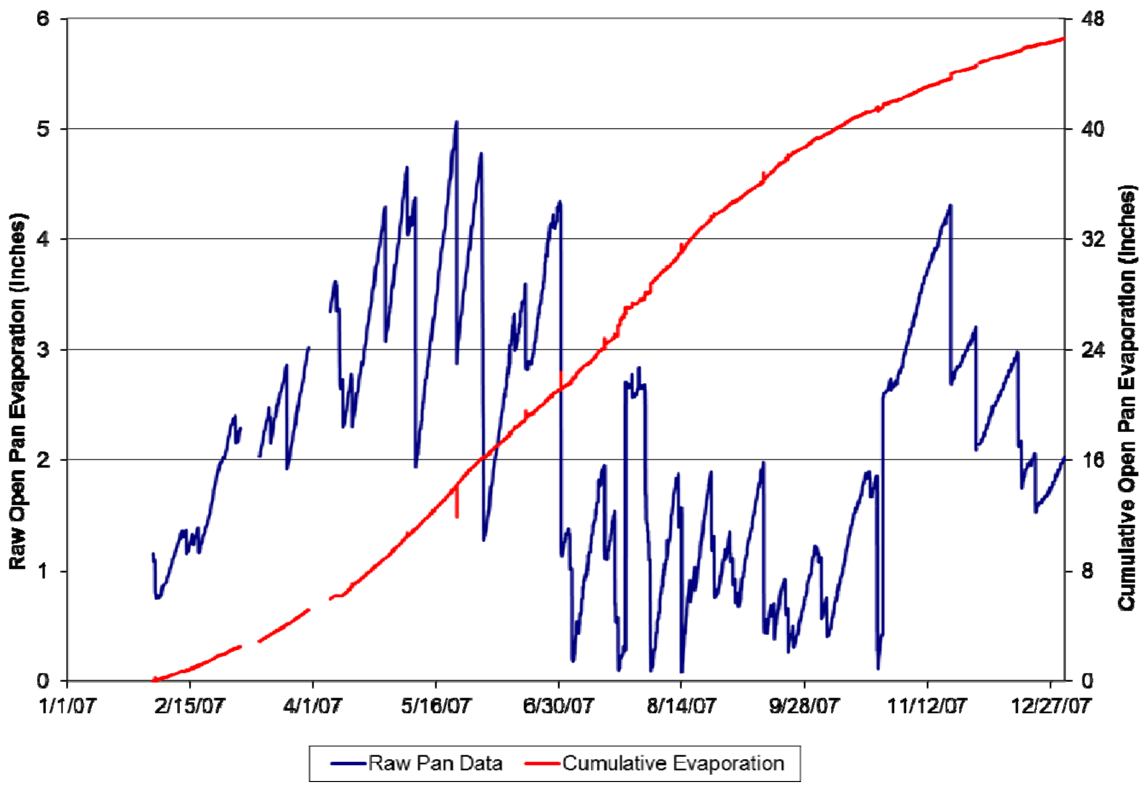

Figure 33. Raw and cumulative open pan evaporation for 2007.

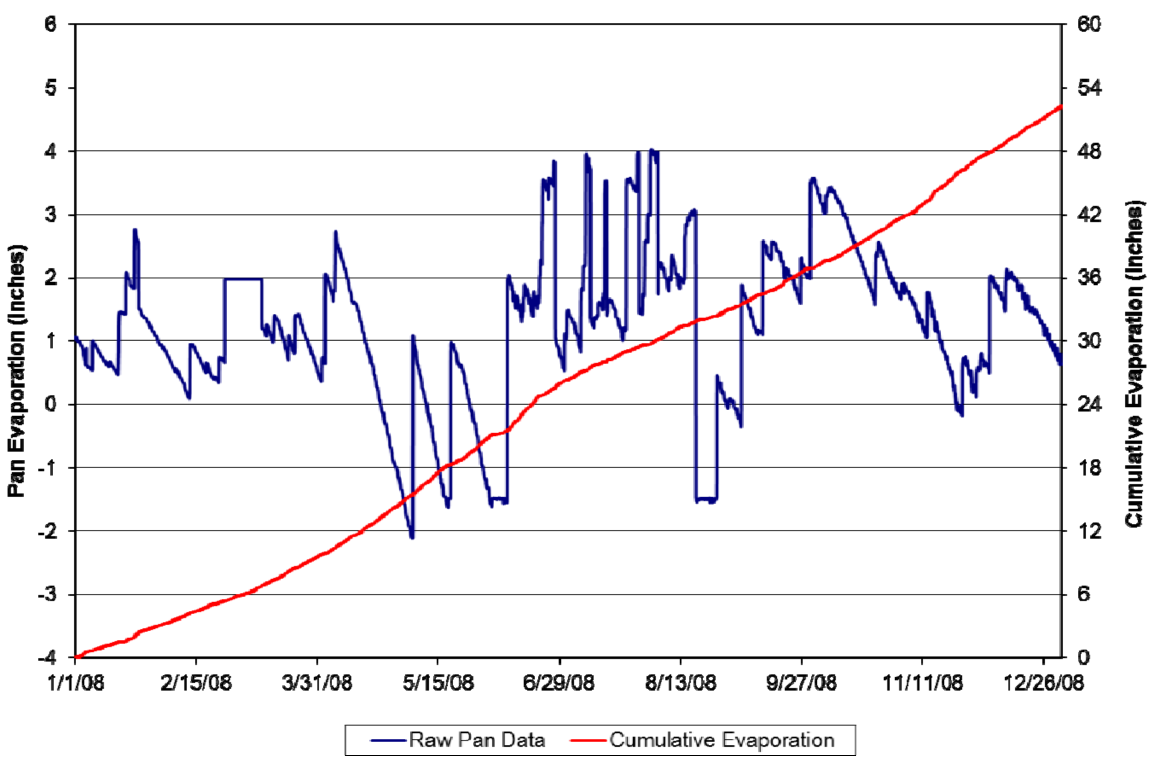

Figure 34. Raw and cumulative open pan evaporation for 2008.

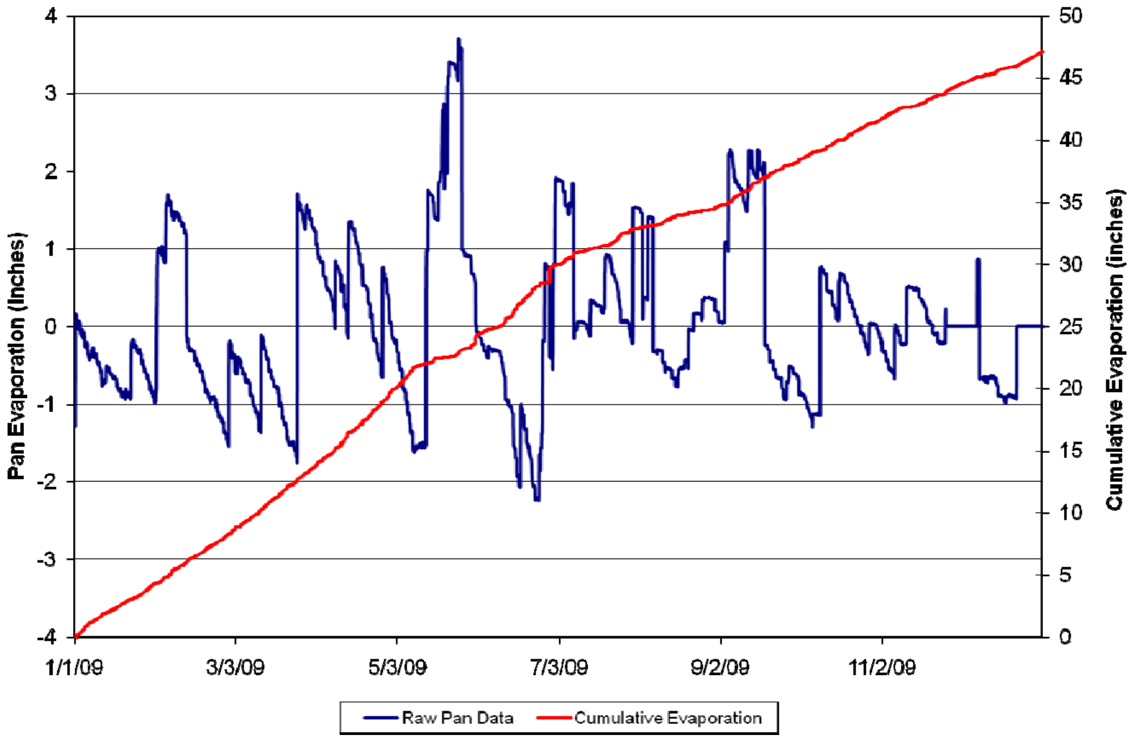

Figure 35. Raw and cumulative open pan evaporation for 2009.

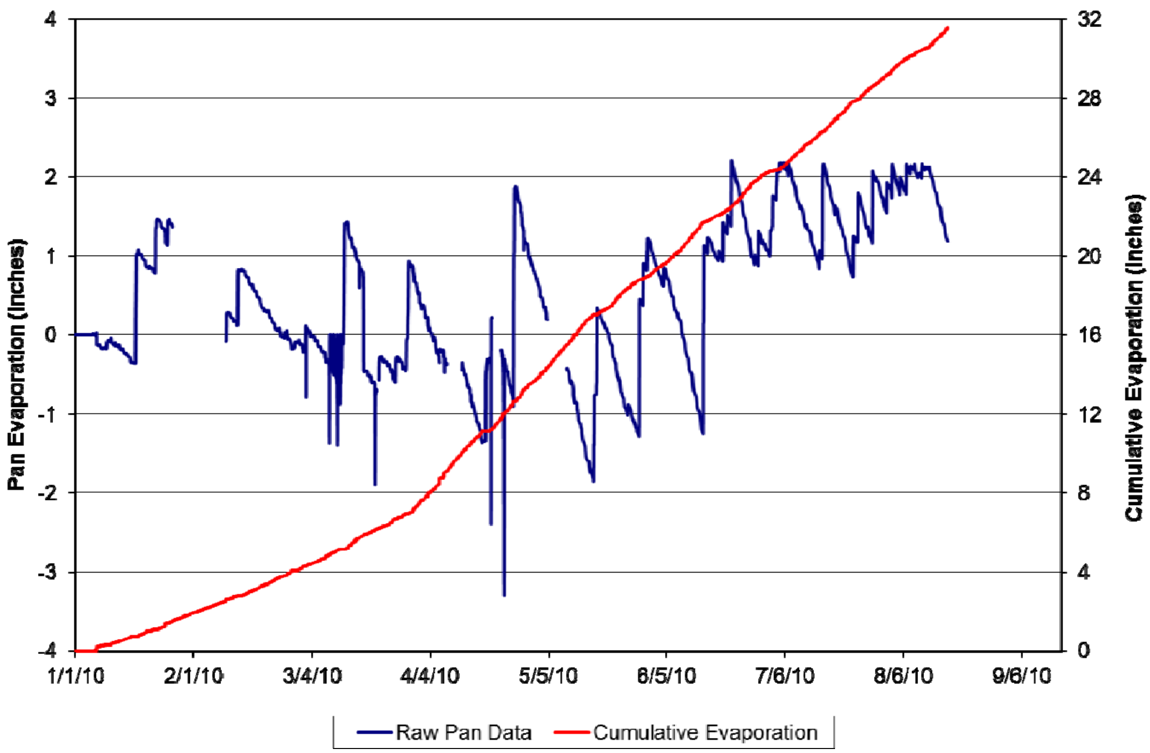

Figure 36. Raw and cumulative open pan evaporation for 2010.

Cumulative Solar Radiation and Evaporation.

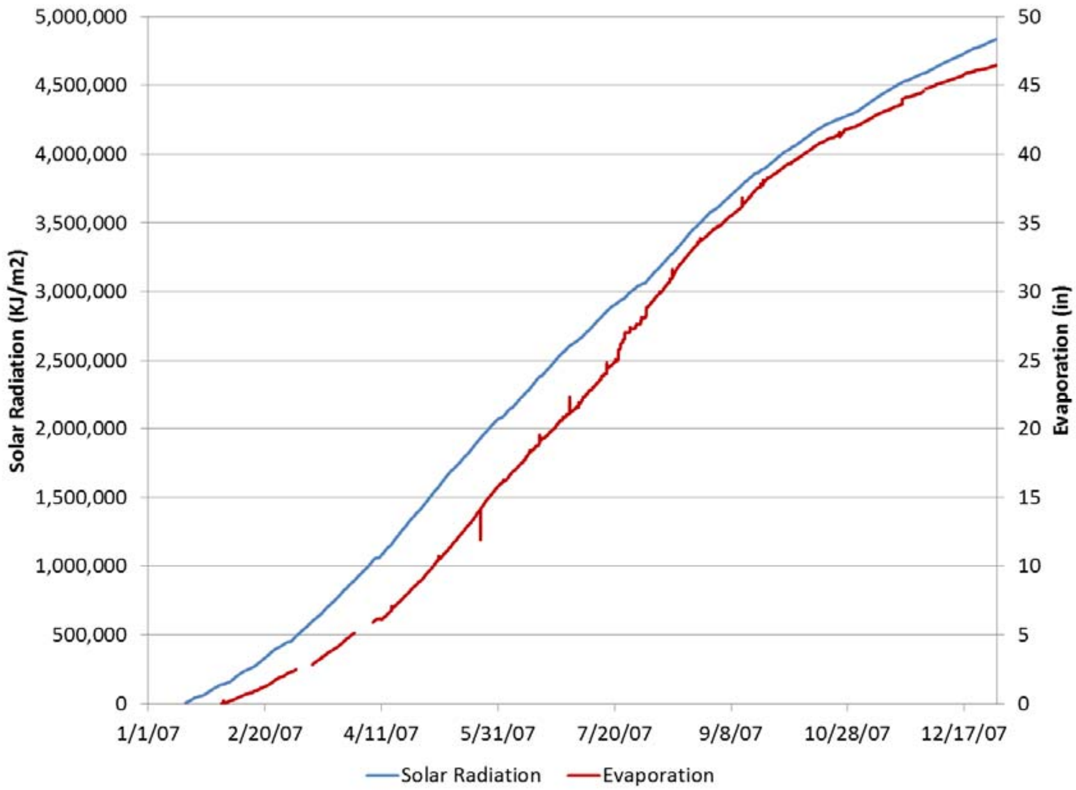

Figure 37. Cumulative solar radiation and cumulative pan evaporation for 2007.

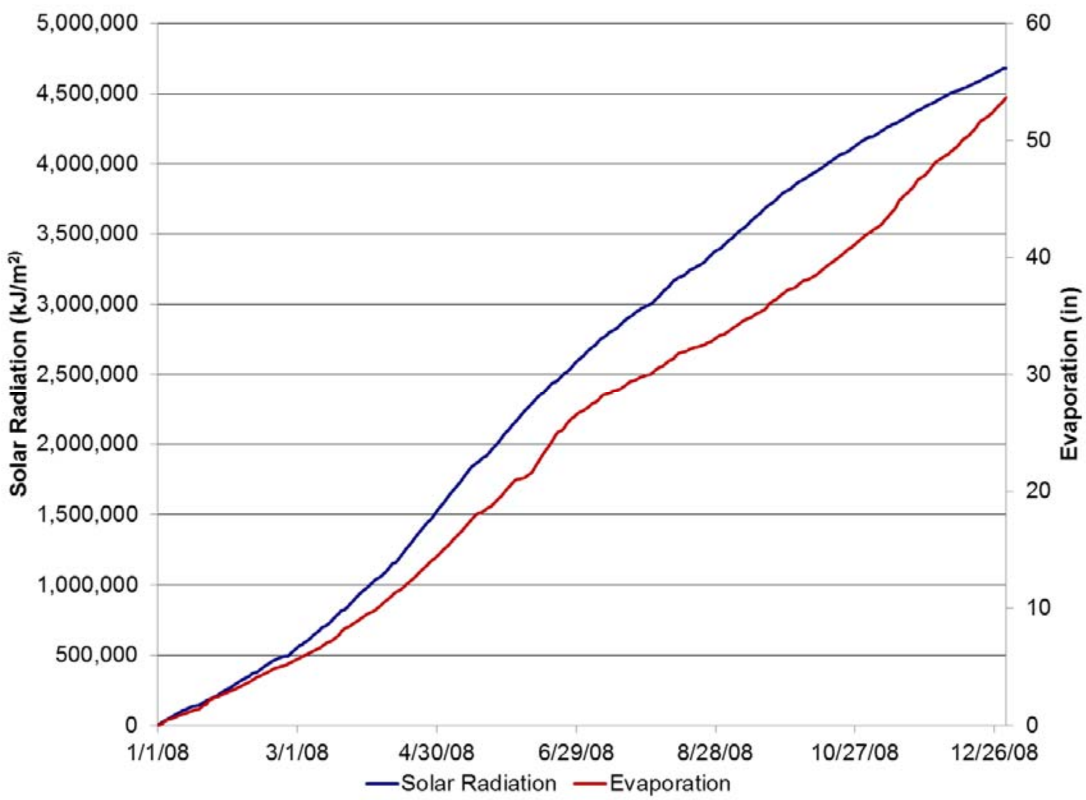

Figure 38. Cumulative solar radiation and cumulative pan evaporation for 2008.

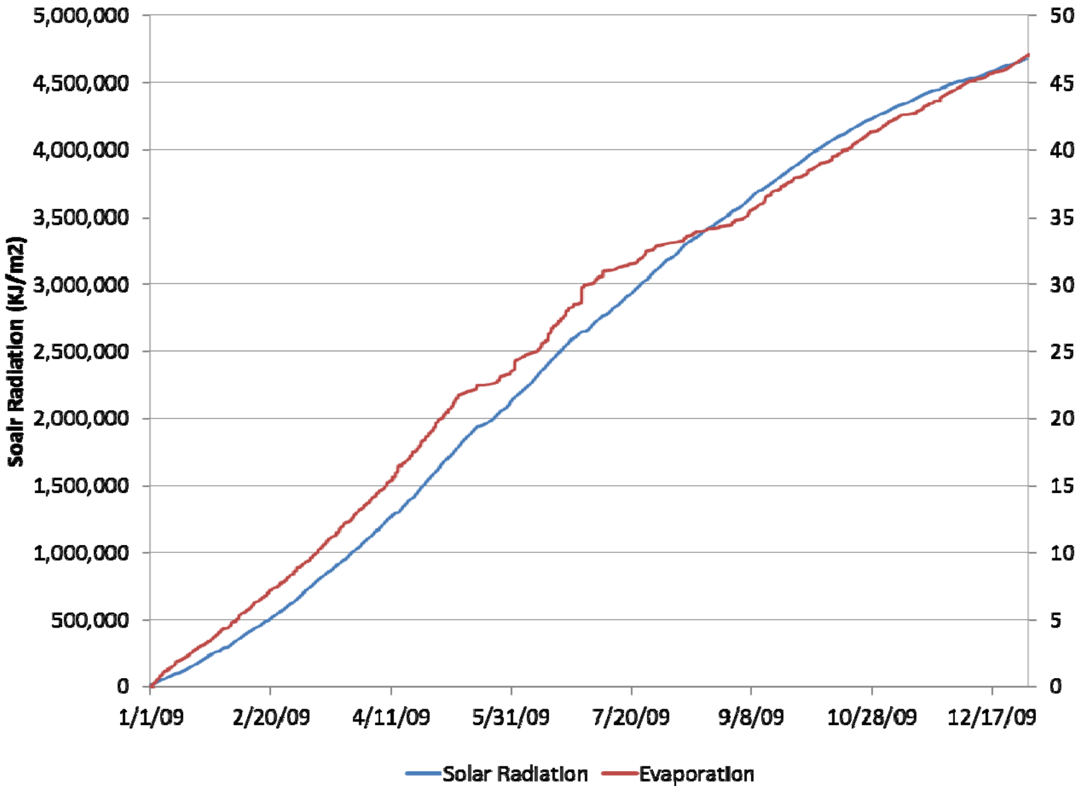

Figure 39. Cumulative solar radiation and cumulative pan evaporation for 2009.

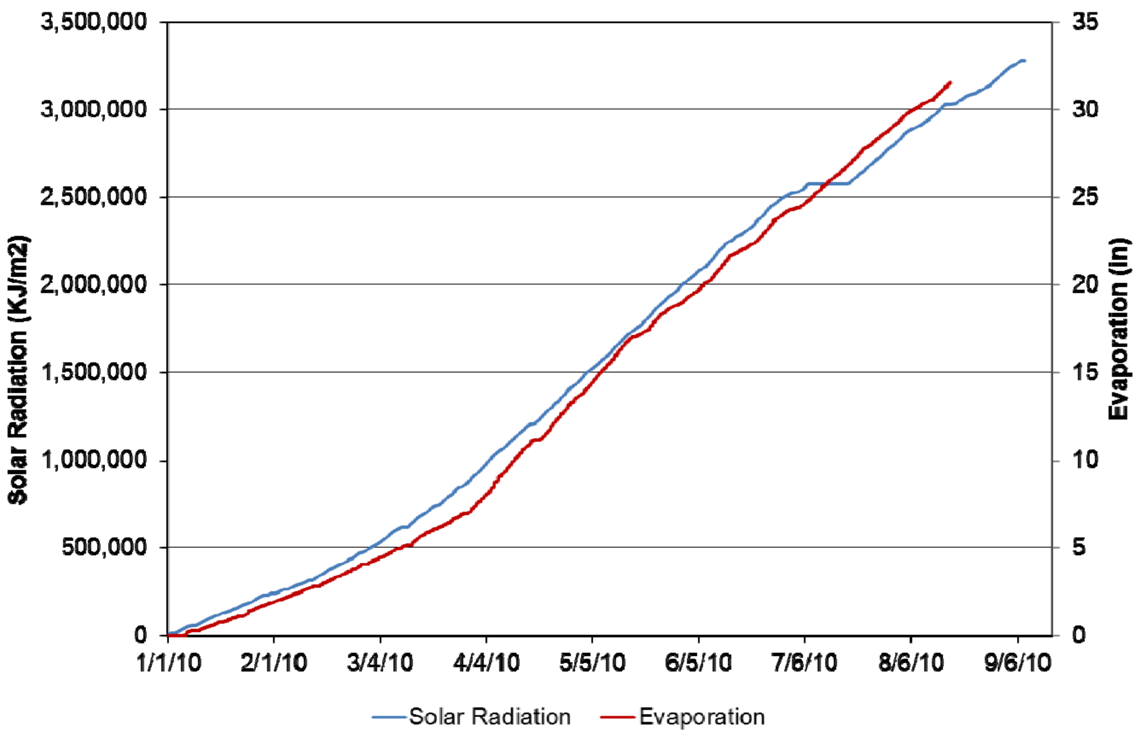

Figure 40. Cumulative solar radiation and cumulative pan evaporation for 2010.

Soil Moisture and Aquifer Water-Level Elevations

SWFWMD contracted for the installation of six surficial-aquifer monitor wells numbered ECO-1 through ECO-6 with ECO-1 at the highest elevation and ECO-6 at the lowest elevation and two Floridan aquifer monitor wells (Figure 41). ECO-1 and ECO-2 have been dry for almost all of the study period. 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 have been surveyed and their water levels corrected to NGVD. Soil moisture sensors were installed at all six ECO sites.

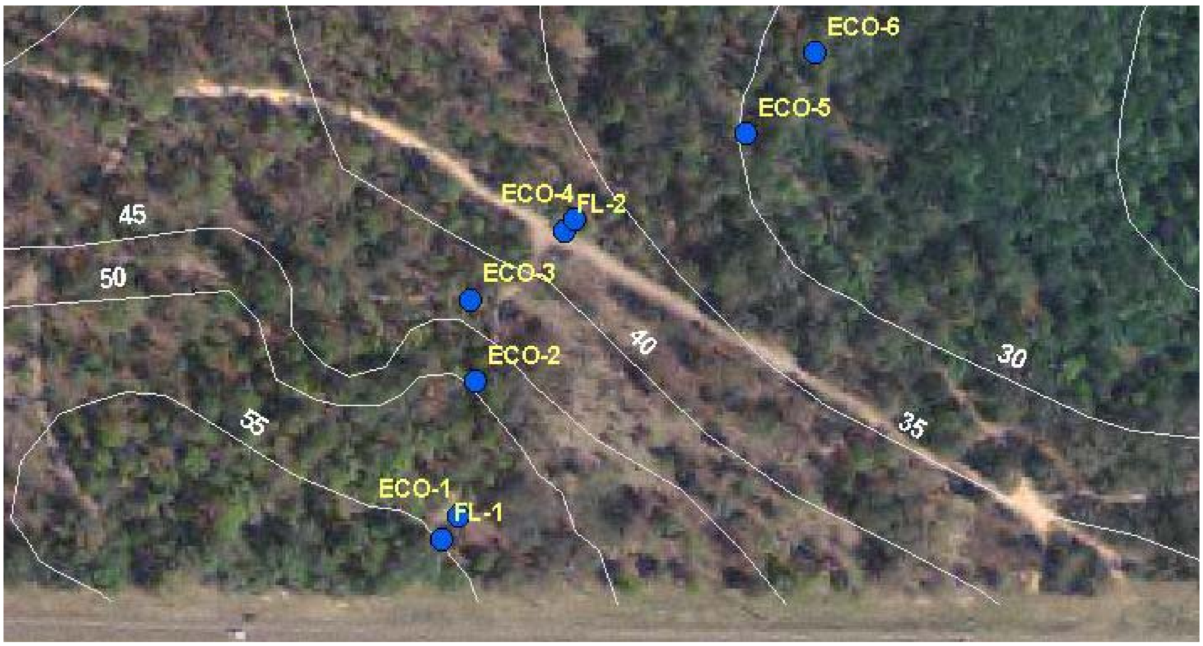

Figure 41. Soil moisture and aquifer monitoring sites.

The general stratigraphy of the site consists of a top layer of fine dune sand varying in thickness from 14 to 22 feet. Below the sand is a discontinuous layer of clay which overlays the limestone of the Floridan aquifer. The clay was about 20 feet thick at FL-1 and FL-2, the only sites where the clay was fully penetrated. Clay was absent at ECO-4 which is adjacent to FL-2. Limestone was encountered at 38 feet at FL-1, 44 feet at FL-2 and 27 feet at ECO-4. Figure 42 illustrates the generalized site geology. The water levels at FL-2 and ECO-4 were the same during the study indicating that the limestone at the two sites was part of the Floridan aquifer system and that ECO-4 was not measuring a local water table. Well logs and photographs of the cores are in Appendix A.

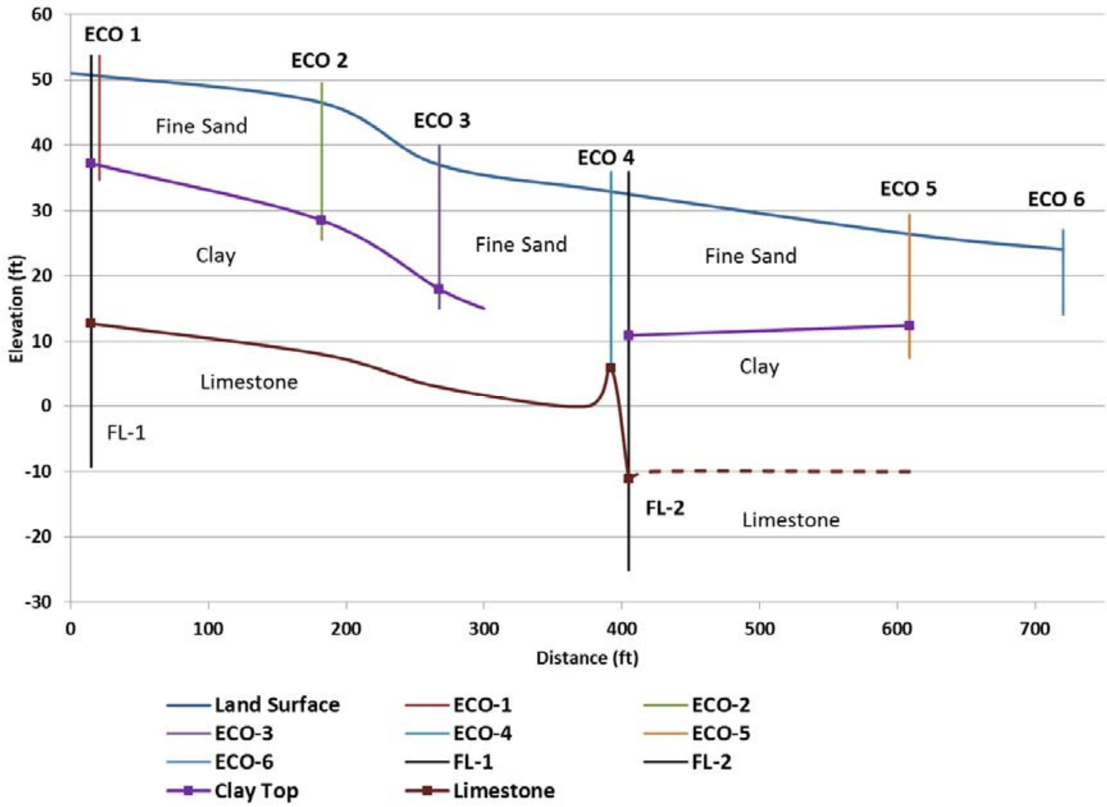

Figure 42. Hillslope profile and generalized geology of data collection sites.

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 42 illustrates a cross-section view of the site. Figure 43 is a three-dimensional representation of the site, Figure 44 is a slope map of the site and Table 2 summarizes the slopes at each site. During the wet summer period, the water table reaches land surface at ECO-6. Figures 45-50 are photographs of the monitoring sites.

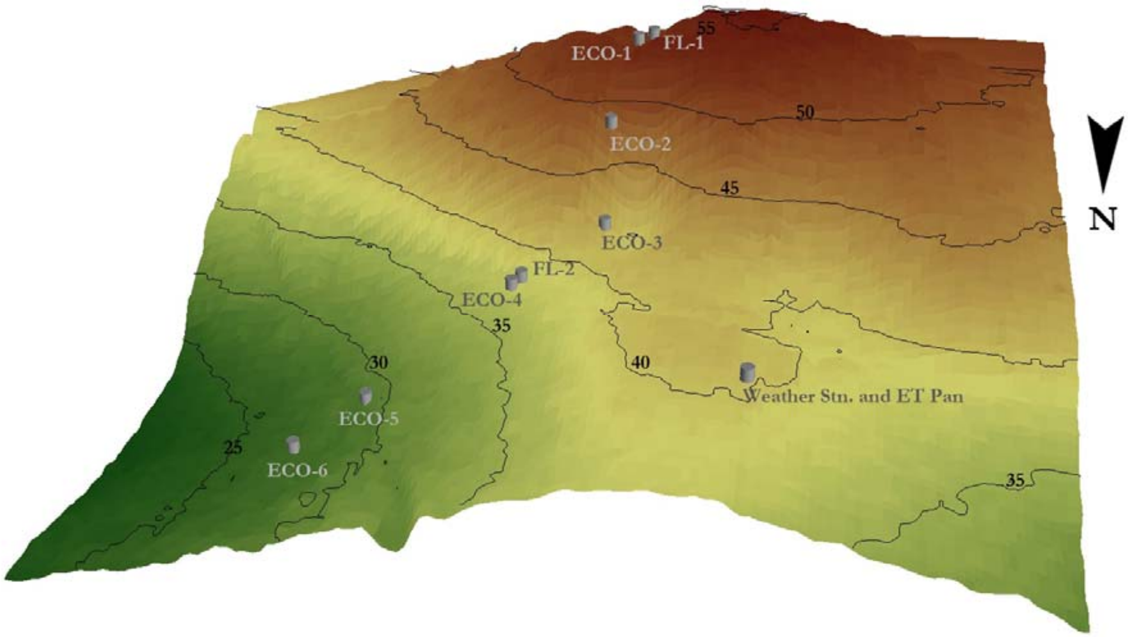

Figure 43. Three-dimensional representation of the Eco Site (vertical exaggeration 50x).

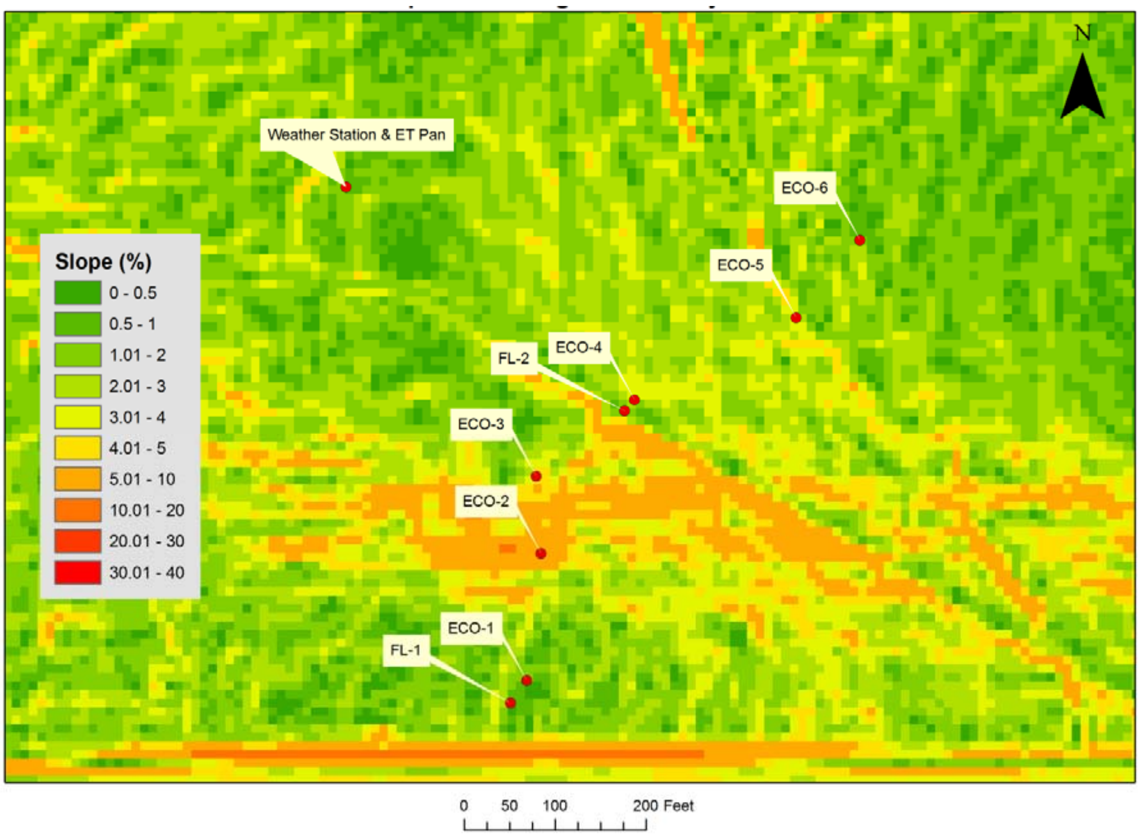

Figure 44. Slope map of the Eco Site.

Table 2. Slope at each location.

EcoID	10-ft Radius Avg. Slope (%)
ECO-1	1.01
ECO-2	9.05
ECO-3	3.14
ECO-4	3.13
ECO-5	2.81
ECO-6	1.40
FL-1	2.10
FL-2	3.44
Weather Station	1.11

Figure 45. ECO-1 Soil moisture sensor and data logger box.

Figure 46. ECO-2 Soil moisture sensor, data logger box and well (next to stake).

Figure 47. ECO-3 near tree at center of photo.

Figure 48. 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 49. ECO-5.

Figure 50. 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.

The following figures show the observations of hourly average soil moisture from 2007 through August 2010 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 through ECO-6, exhibit moisture contents consistent with water table observations near land surface with pronounced periods of partial to full column saturation.

In general, the soil moisture observations illustrate that the largest moisture fluctuations are seen in the upper 1m of the soil column associated with infiltration and evapotranspiration (ET) stress periods. This verifies that the sensors are rapidly responding to the expected dynamics of the upper column, exhibiting the bulk of the root zone and the effectiveness of this layer at trapping and utilizing most of the available infiltration moisture. The range of volumetric moisture content in the upper column is nearly the limits for the fine sandy soils at the site, which range from near saturation (40%) to wilting content (2%). In contrast, the lower moisture sensors show a much more subtle response and range of variability in the deep water table stations (ECO-1 - ECO-3) and constant effective saturation contents in the lowest (+150 cm) sensors for the shallow water table sites (ECO-4 to ECO-6). The lower sensors in the deep stations are observed to fluctuate around a more typical moisture content associated with the gravity moisture holding capacity (i.e., field capacity, 12-15%) typical for these soils.

The combination of these results indicate that the soil moisture sensors were: 1) all rapidly responding to rainfall and ET stress; 2) the sensor placements likely extended through, below or at least encompassed the bulk of the root zone for the plant cover in both deep and shallow water table settings; 3) the several brief periods of moisture increase at the lowest sensors in the deep settings were likely the observations of wetting front propagation through the column (resulting in eventual deep recharge fluxes). Integration of the soil moisture observations over the column profile likely yielded reasonable flux estimates for infiltration, ET and recharge.

ECO-1

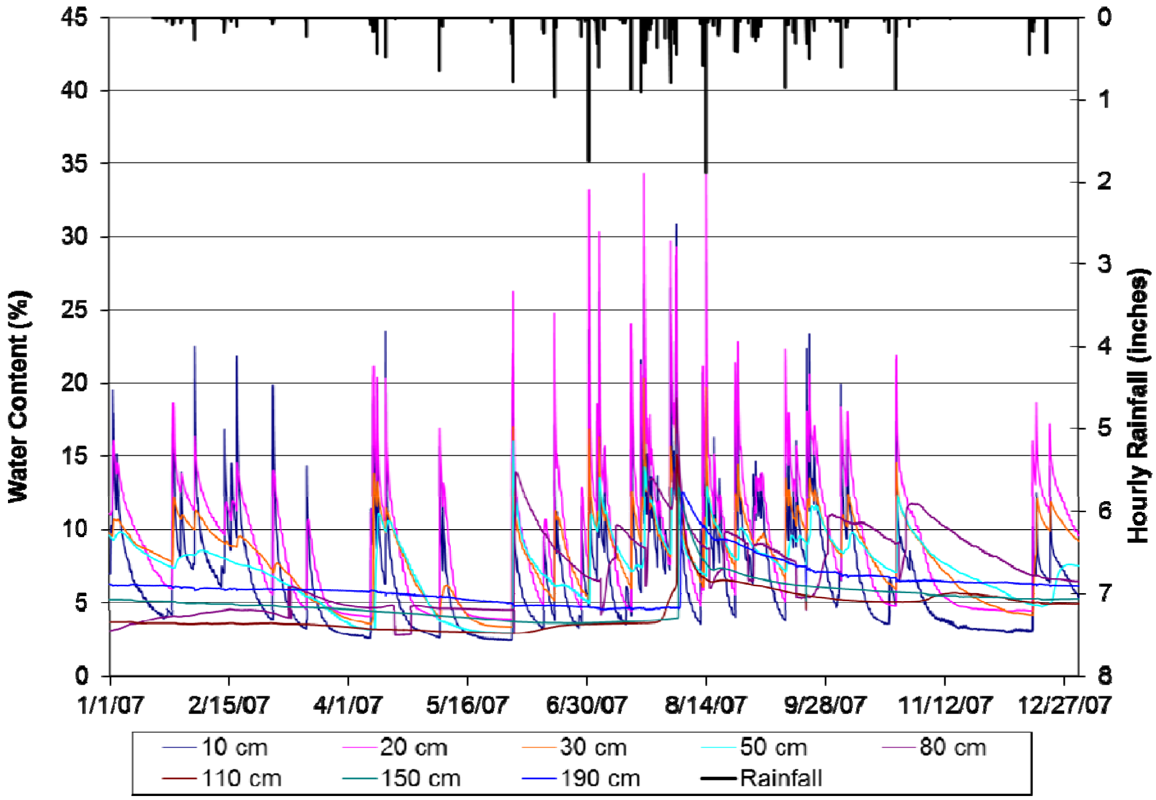

Figure 51. Average hourly soil moisture data from ECO-1 for 2007.

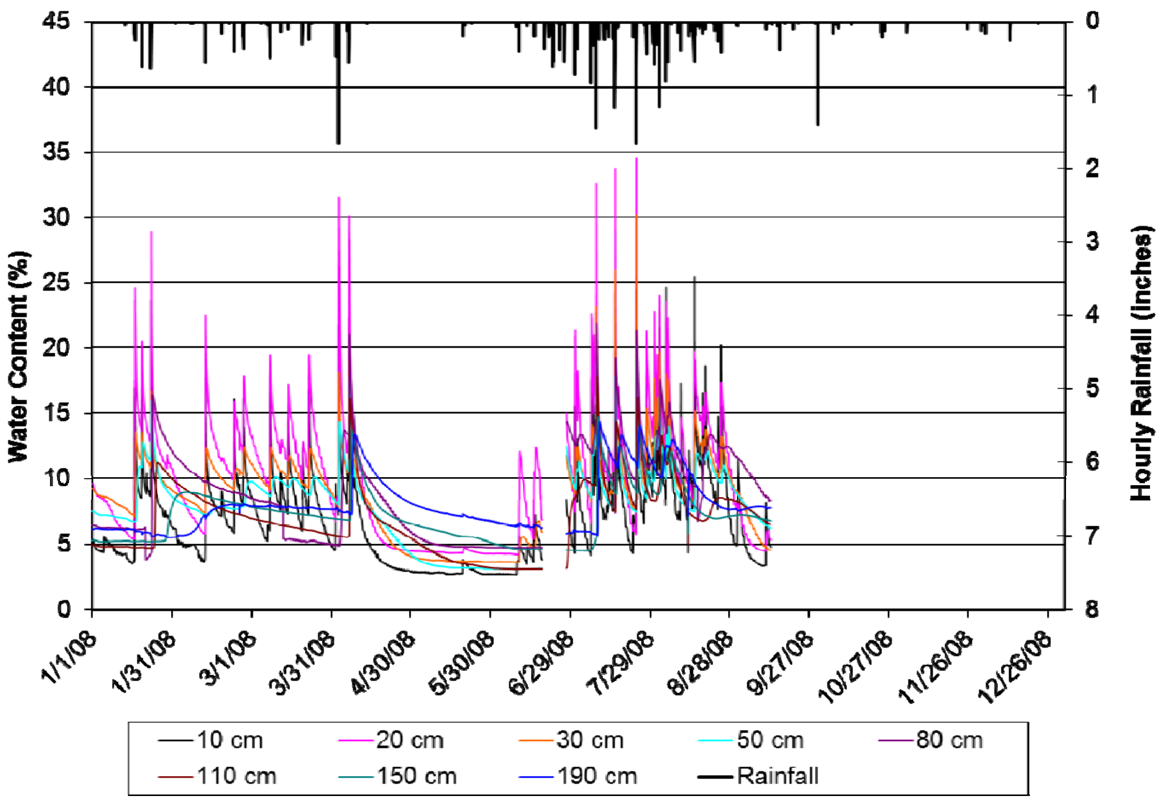

Figure 52. Average hourly soil moisture data from ECO-1 for 2008.

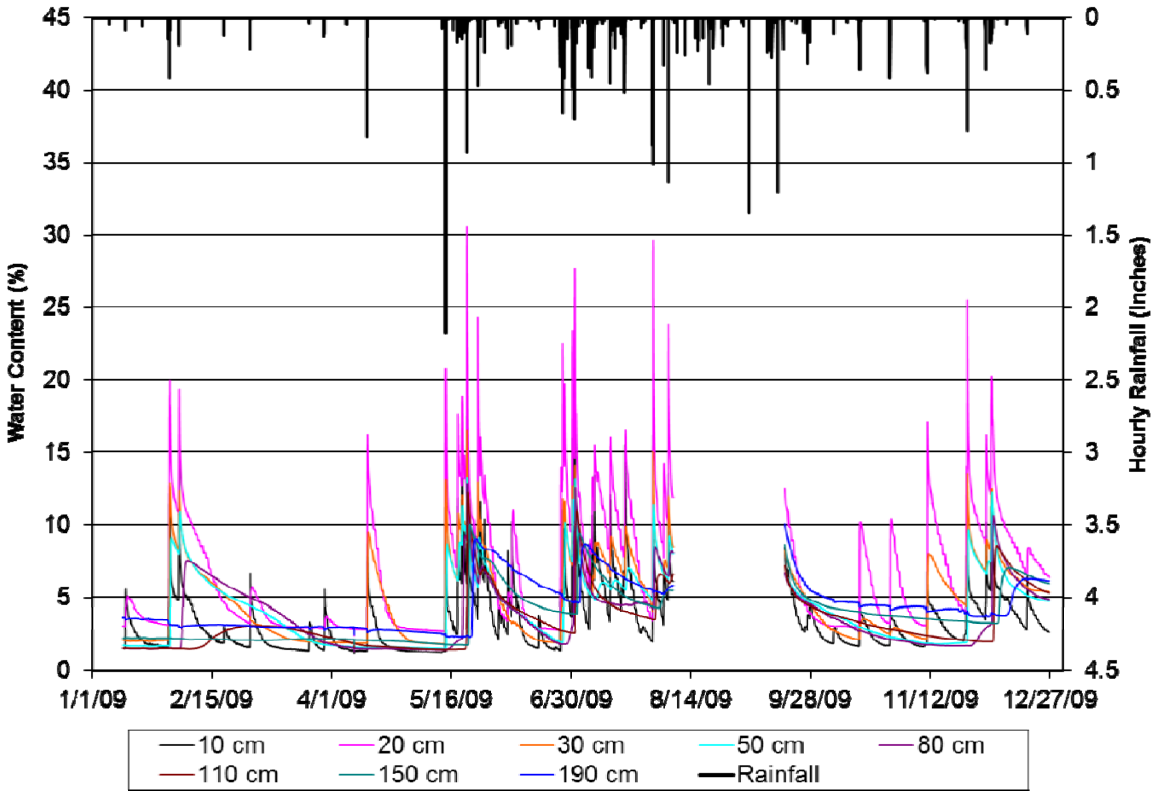

Figure 53. Average hourly soil moisture data from ECO-1 for 2009.

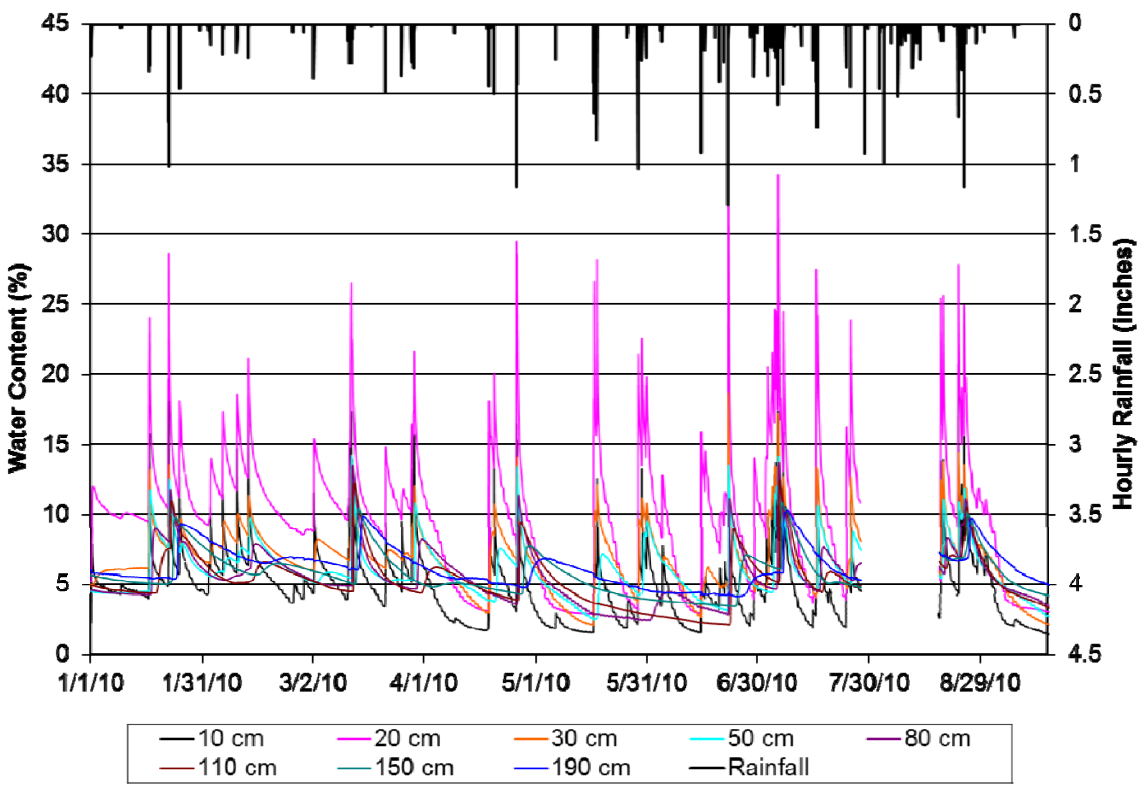

Figure 54. Average hourly soil moisture data from ECO-1 for 2010.

ECO-2

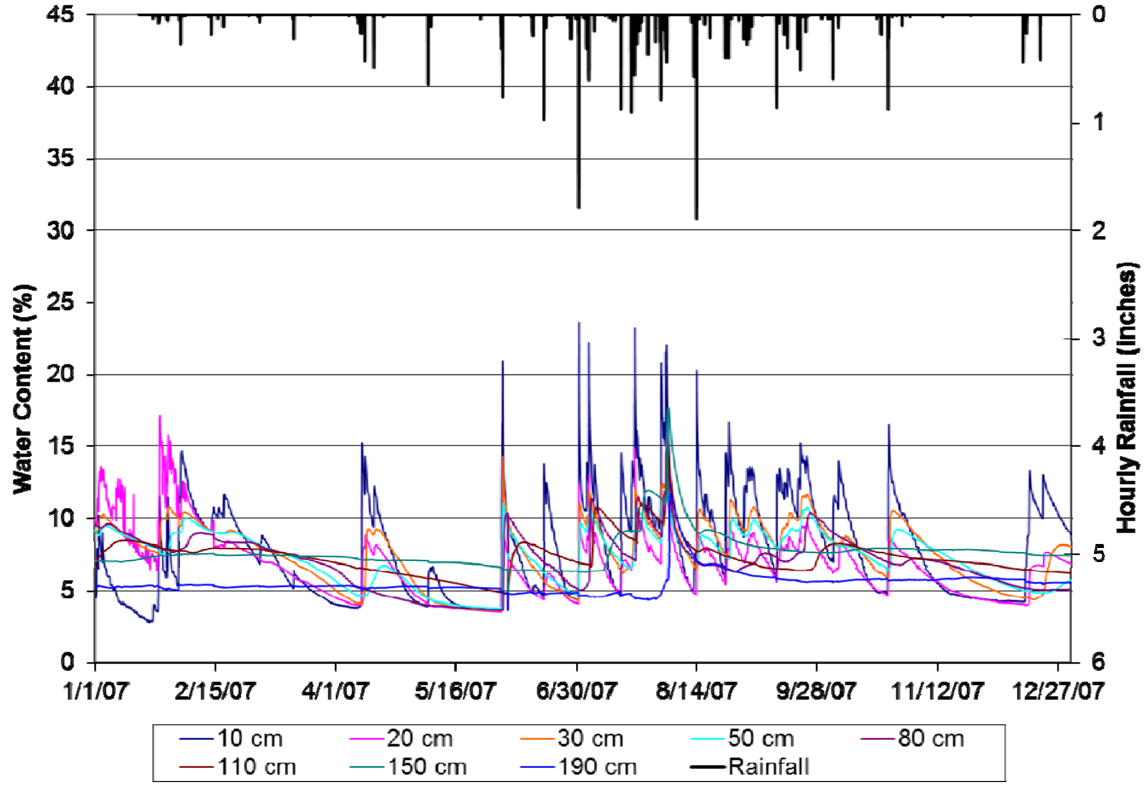

Figure 55. Average hourly soil moisture data from ECO-2 for 2007.

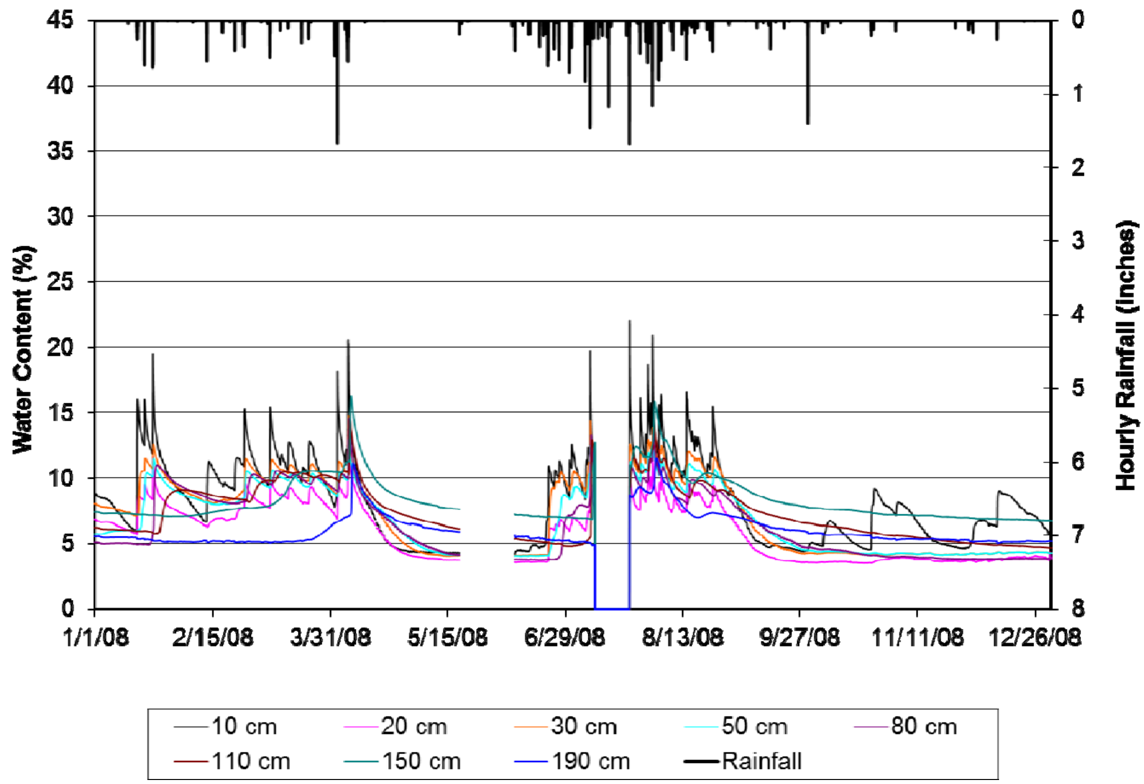

Figure 56.Average hourly soil moisture data from ECO-2 for 2008.

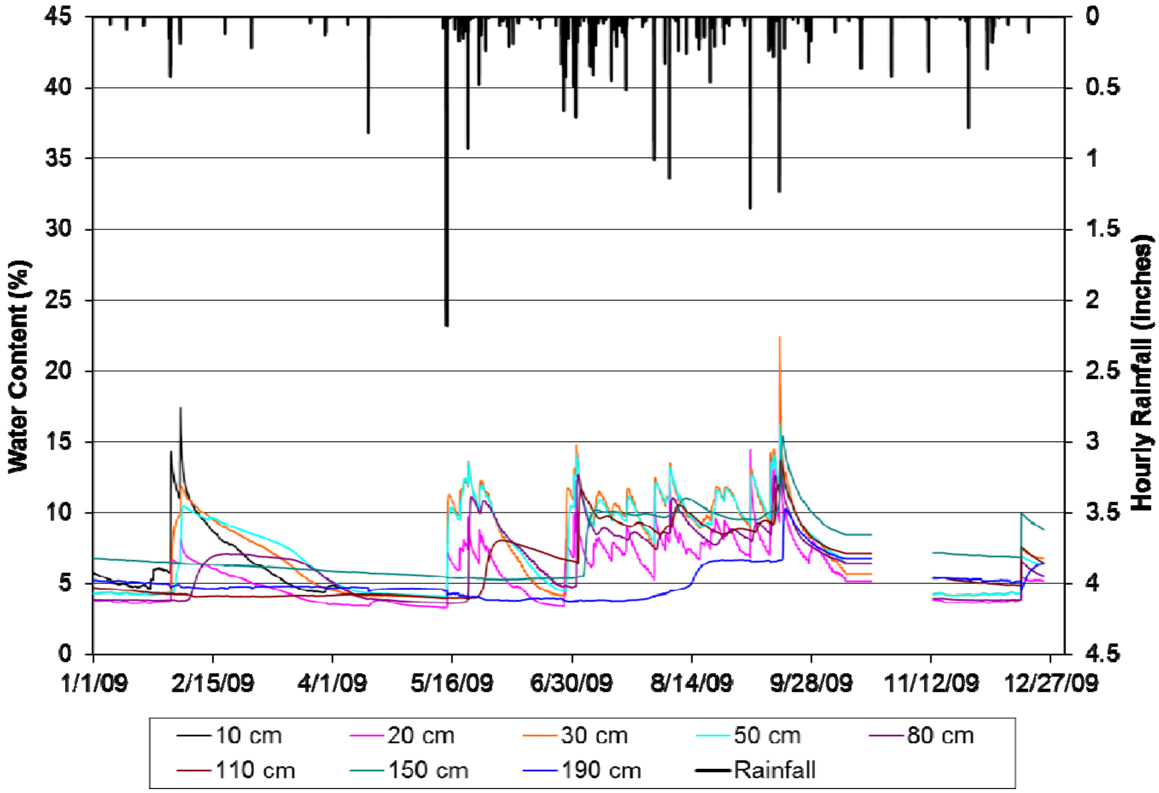

Figure 57. Average hourly soil moisture data from ECO-2 for 2009.

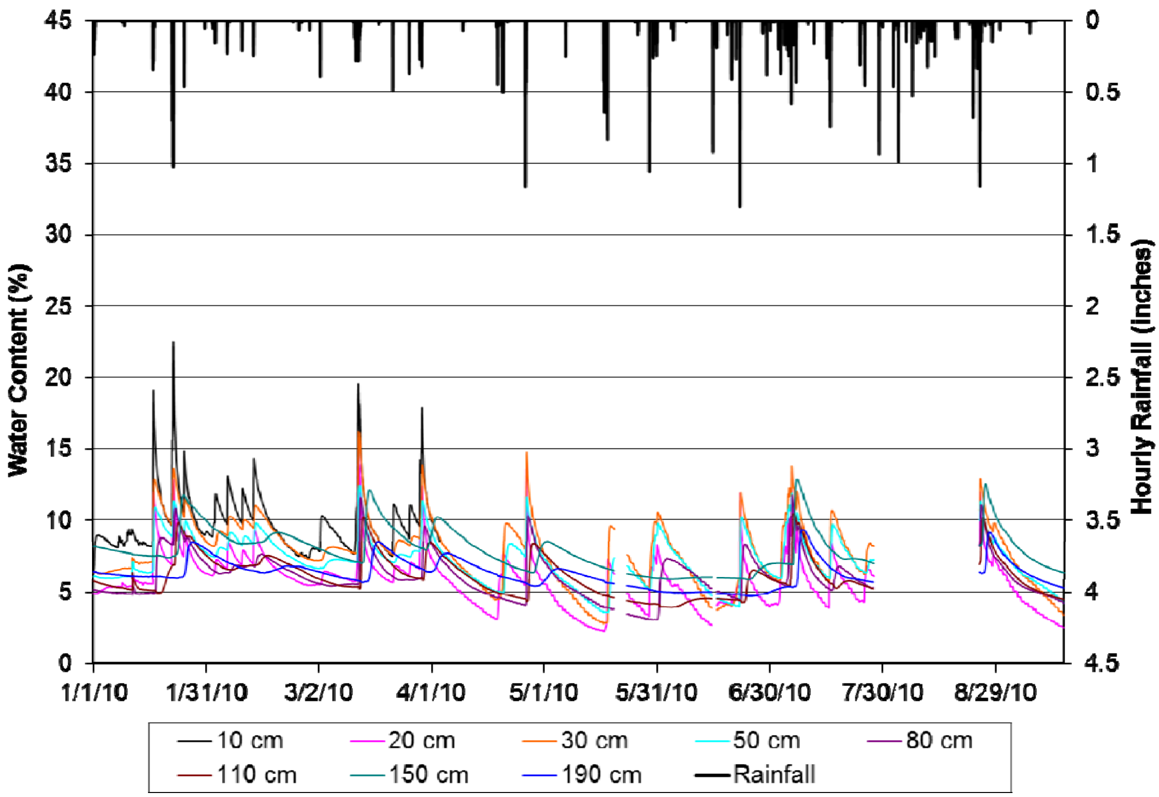

Figure 58. Average hourly soil moisture data from ECO-2 for 2010.

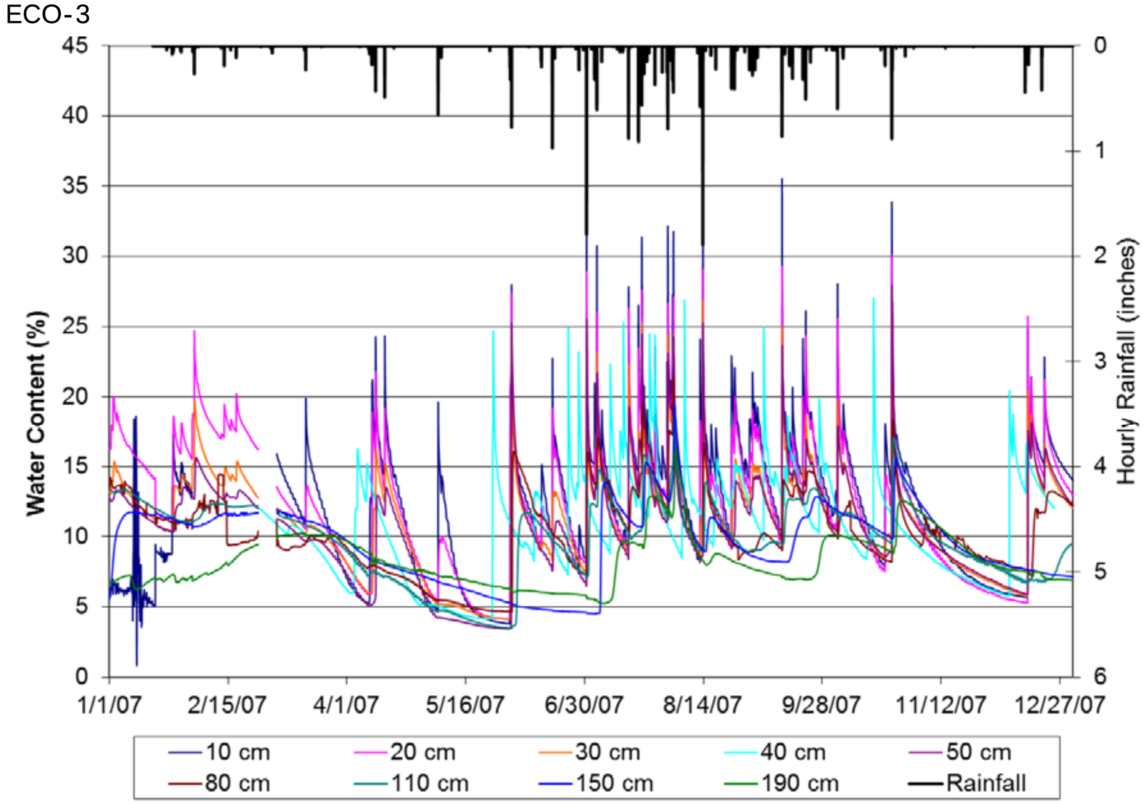

Figure 59. Average hourly soil moisture data from ECO-3 for 2007.

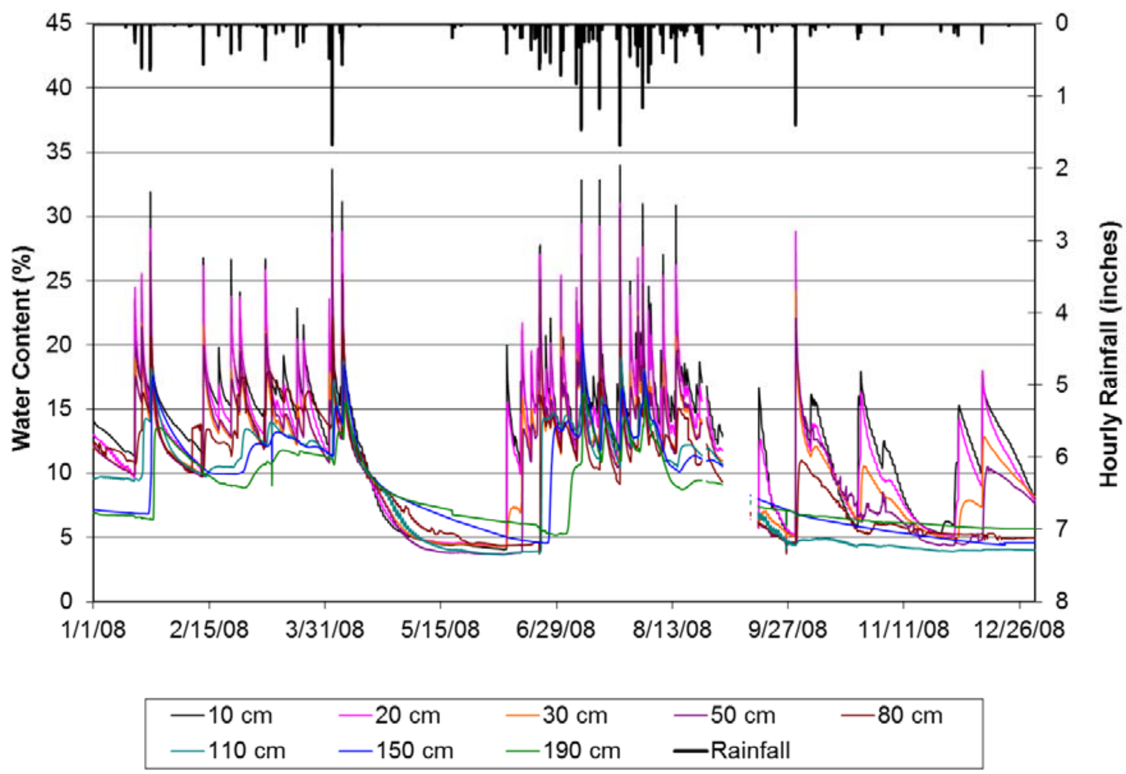

Figure 60. Average hourly soil moisture data from ECO-3 for 2008.

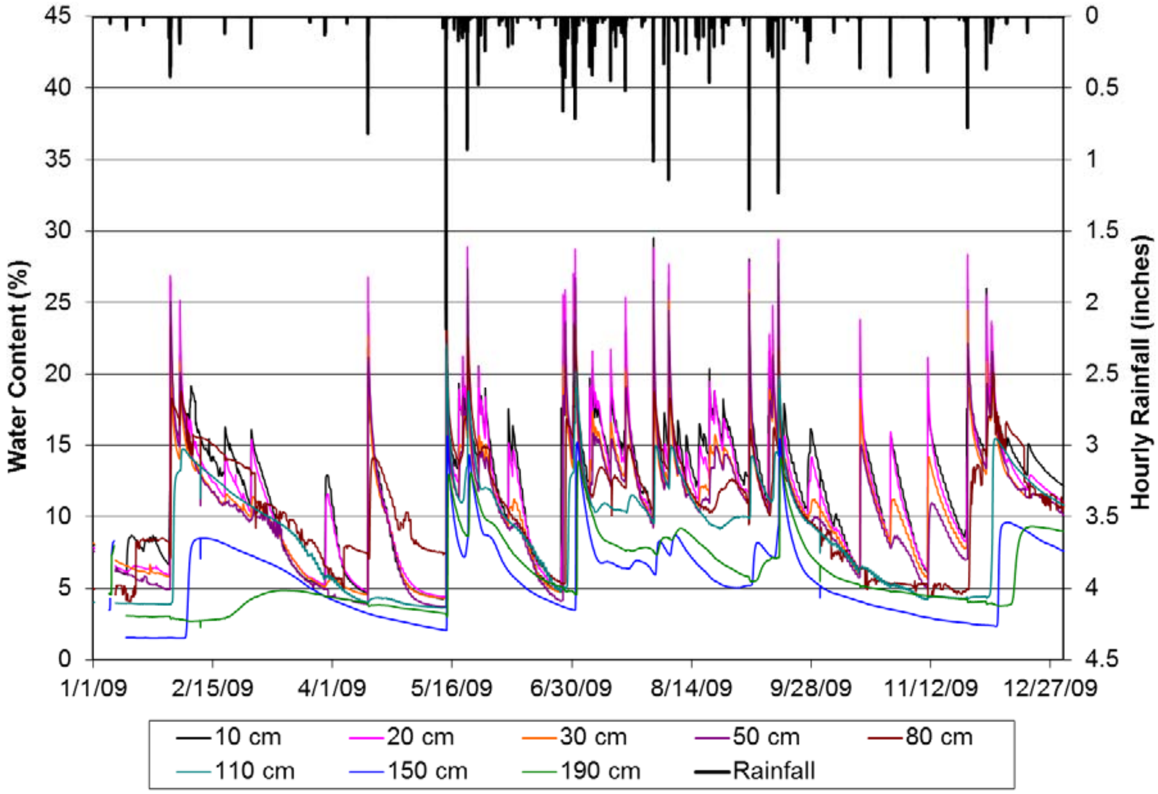

Figure 61. Average hourly soil moisture data from ECO-3 for 2009.

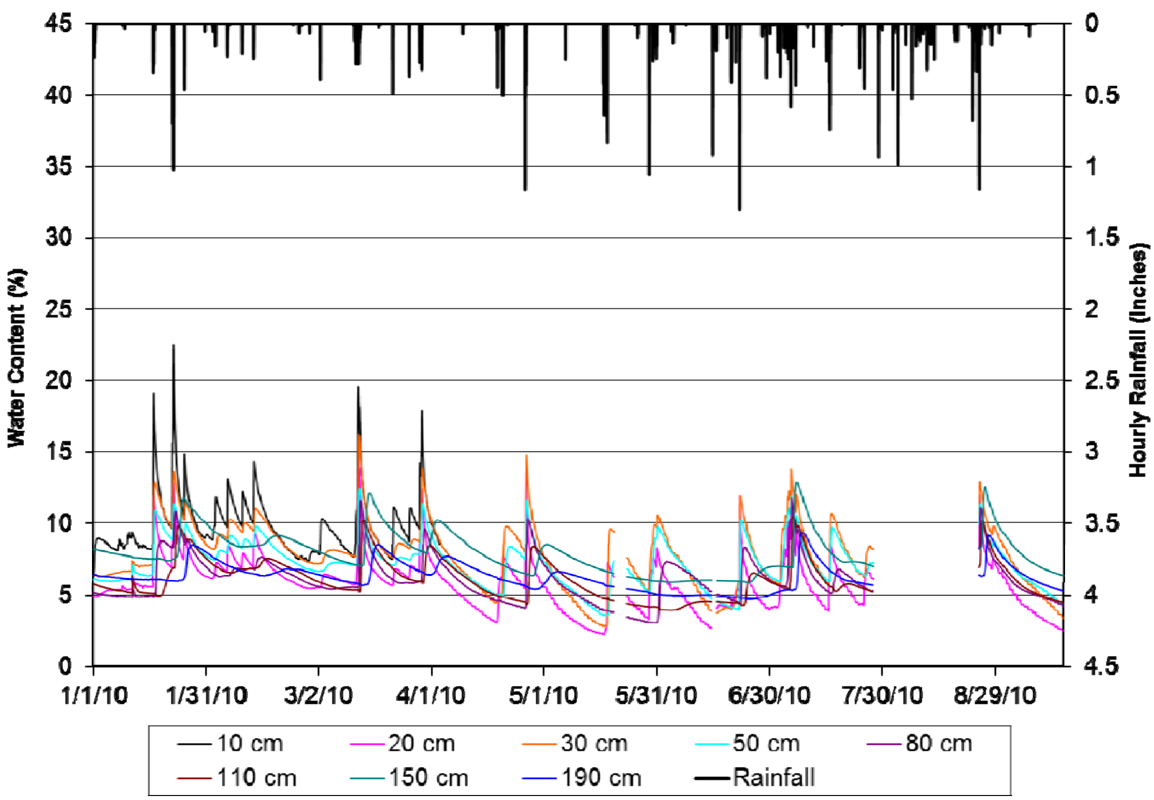

Figure 62. Average hourly soil moisture data from ECO-3 for 2010.

ECO-4

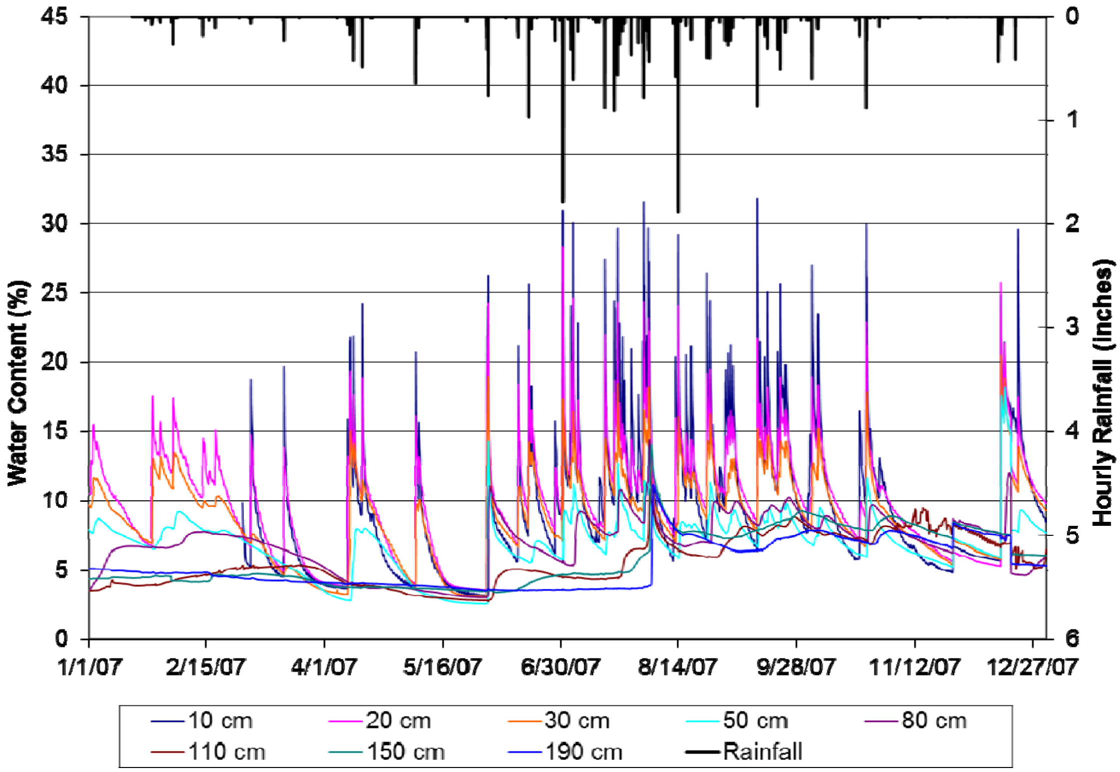

Figure 63. Average hourly soil moisture data from ECO-4 for 2007.

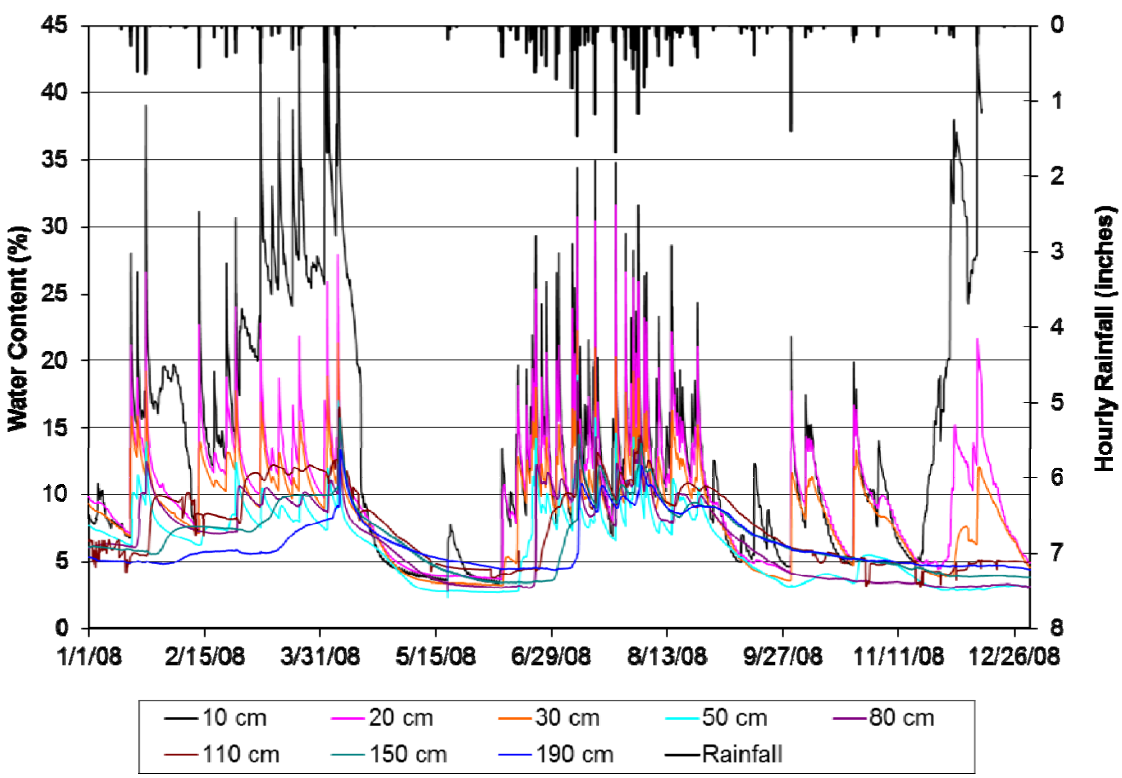

Figure 64. Average hourly soil moisture data at ECO-4 for 2008.

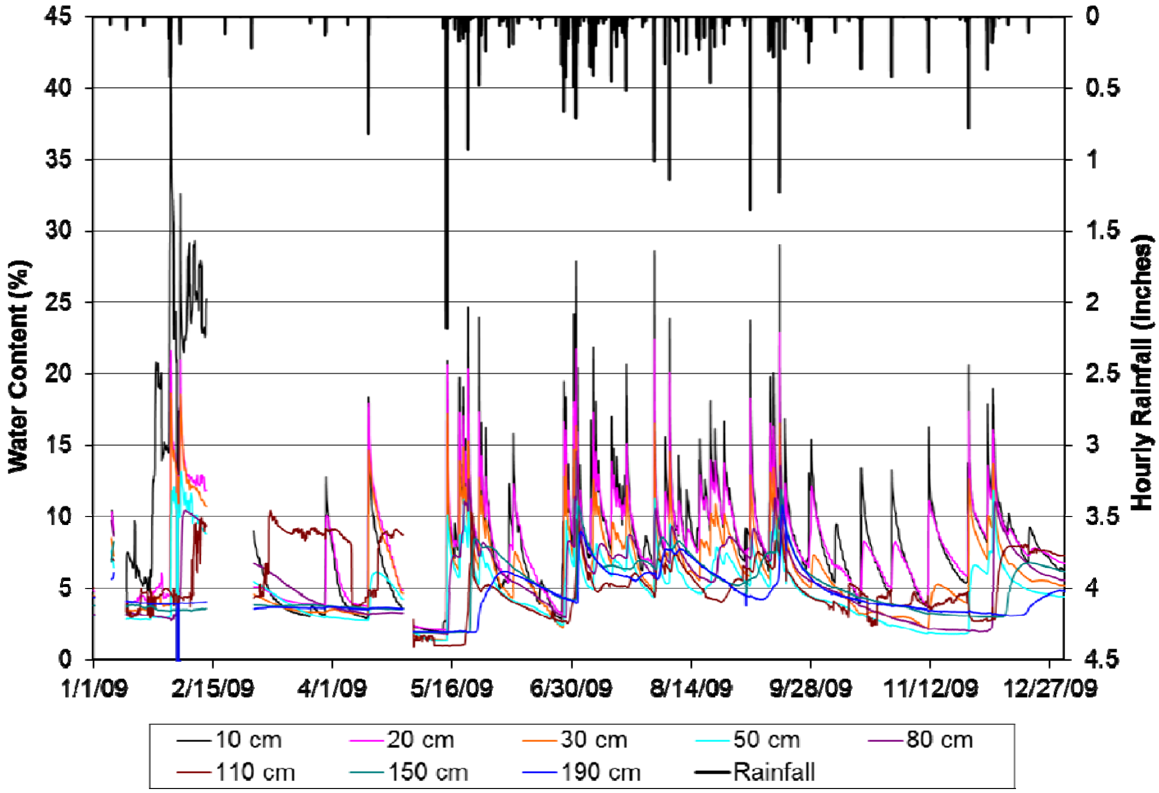

Figure 65. Average hourly soil moisture data at ECO-4 for 2009.

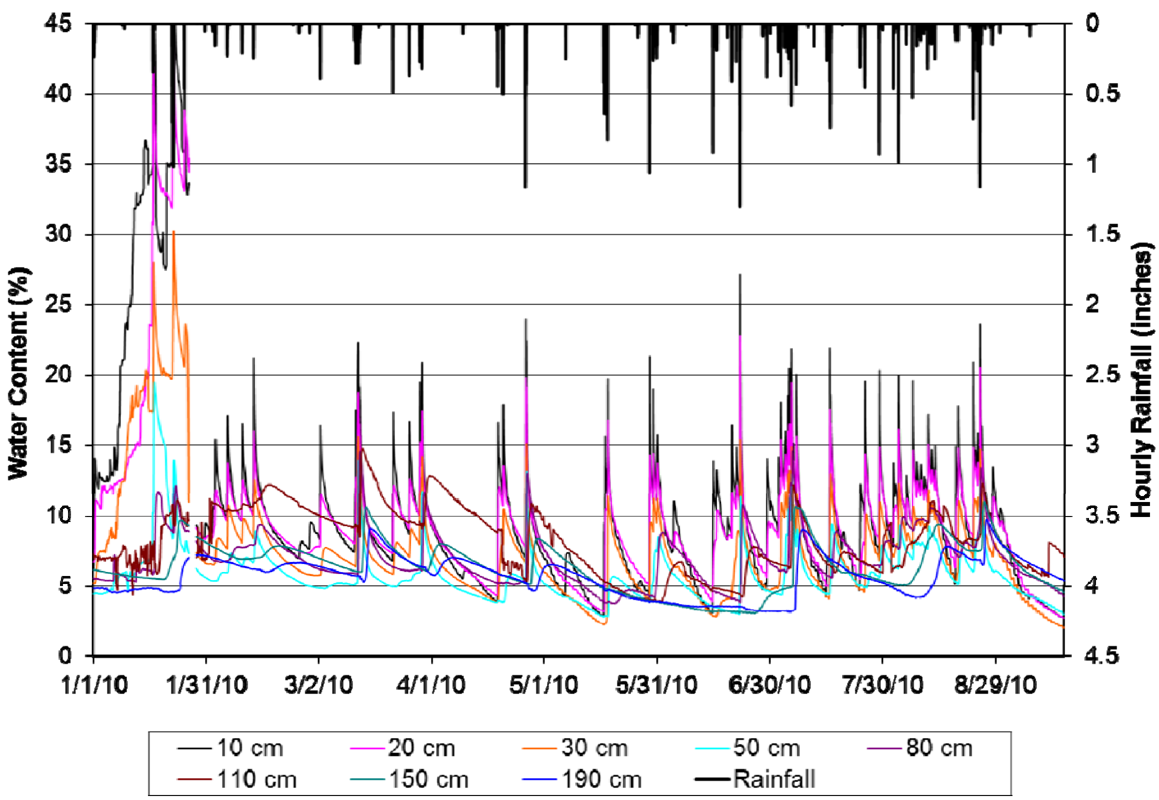

Figure 66. Average hourly soil moisture data at ECO-4 for 2010.

ECO-5

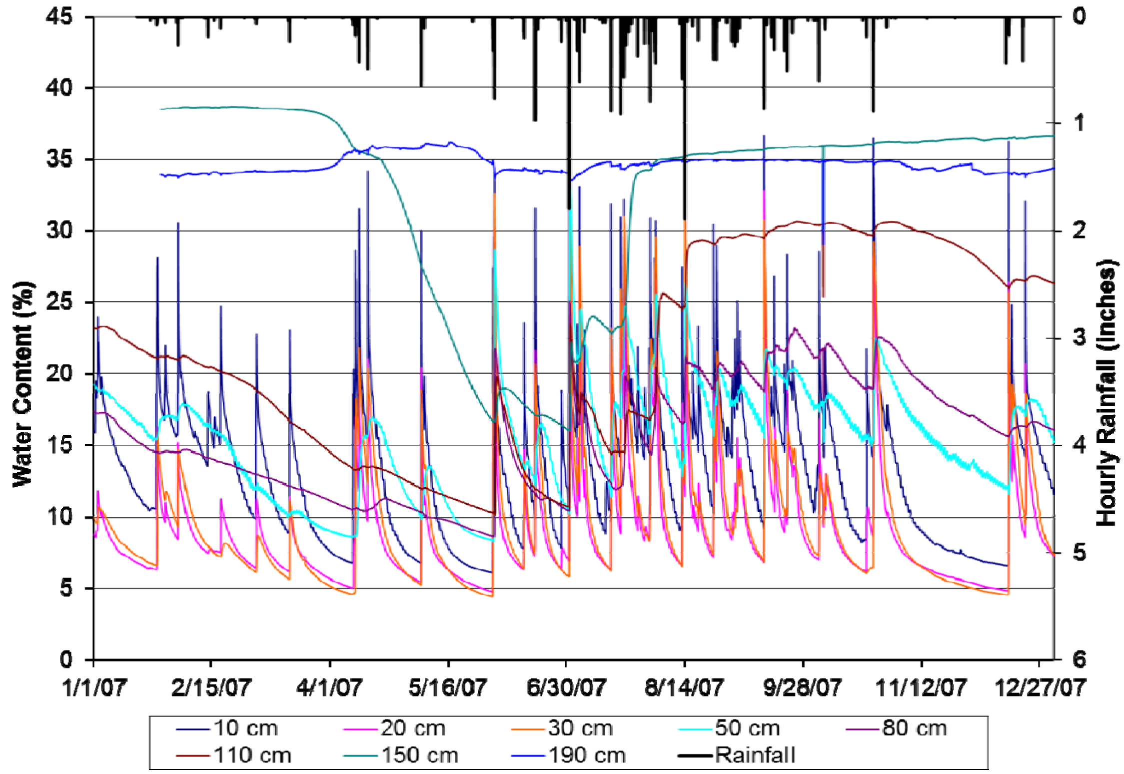

Figure 67. Average hourly soil moisture data at ECO-5 for 2007.

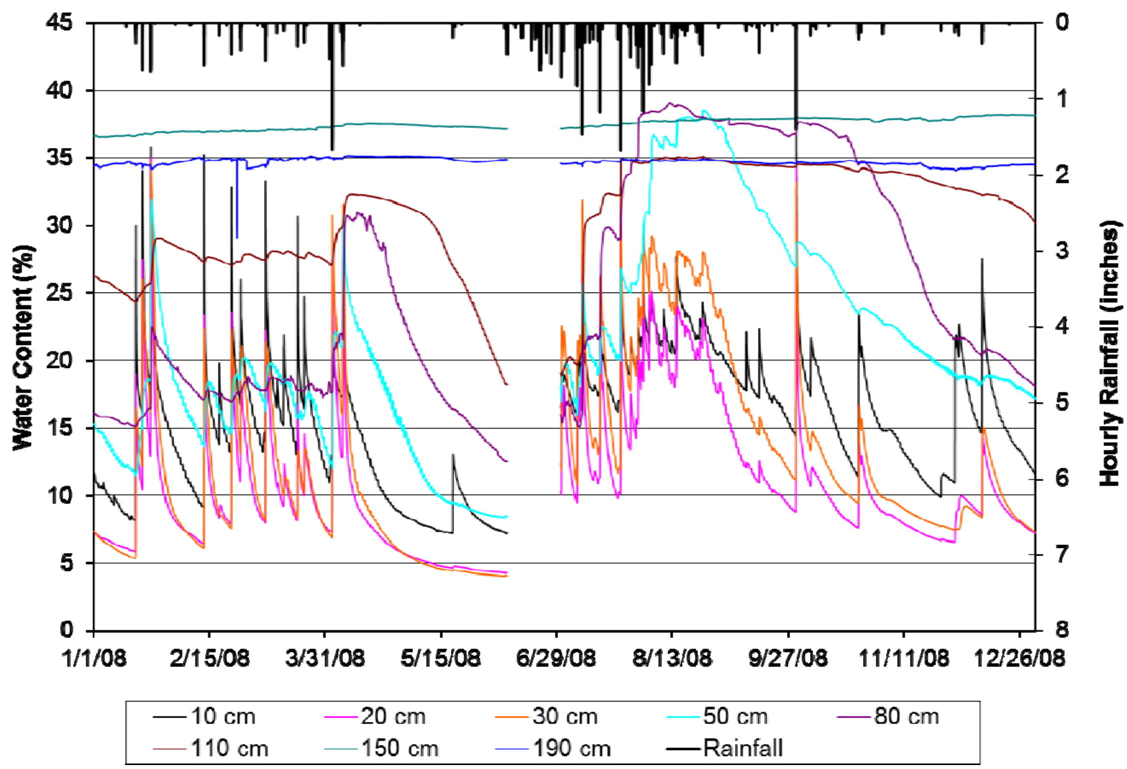

Figure 68.Average hourly soil moisture data at ECO-5 for 2008.

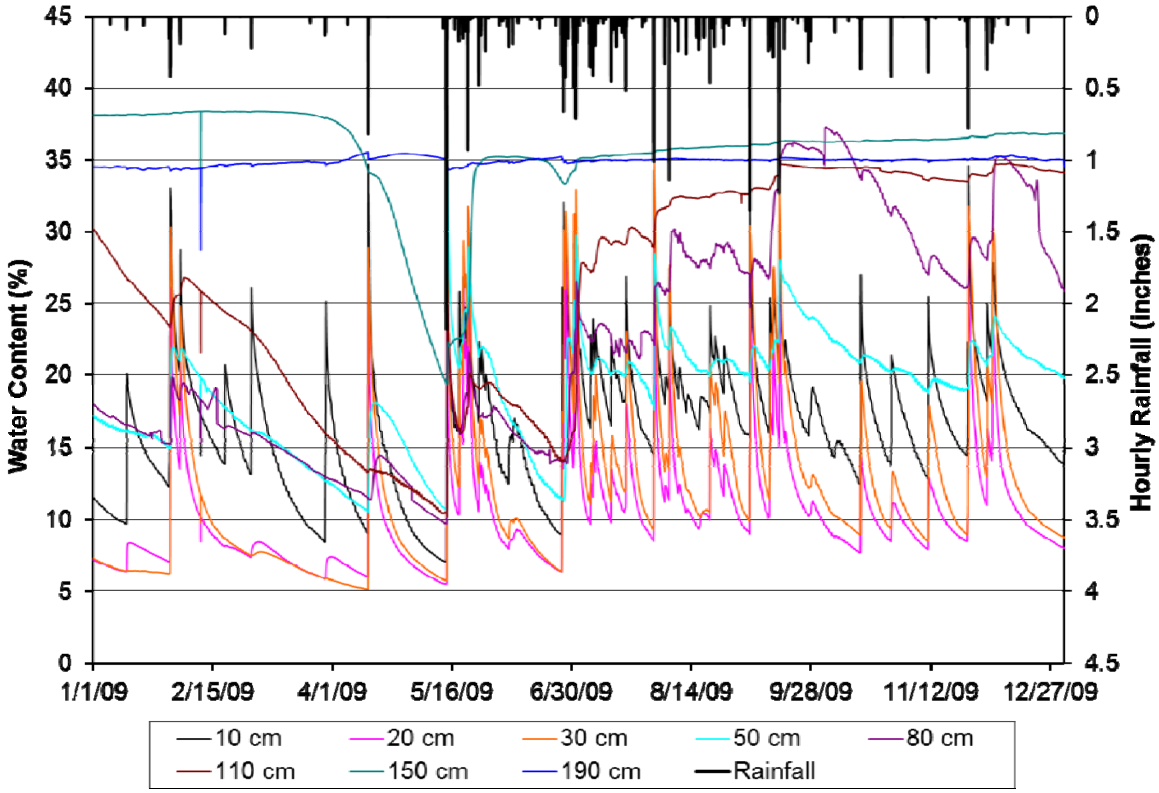

Figure 69. Average hourly soil moisture data at ECO-5 for 2009.

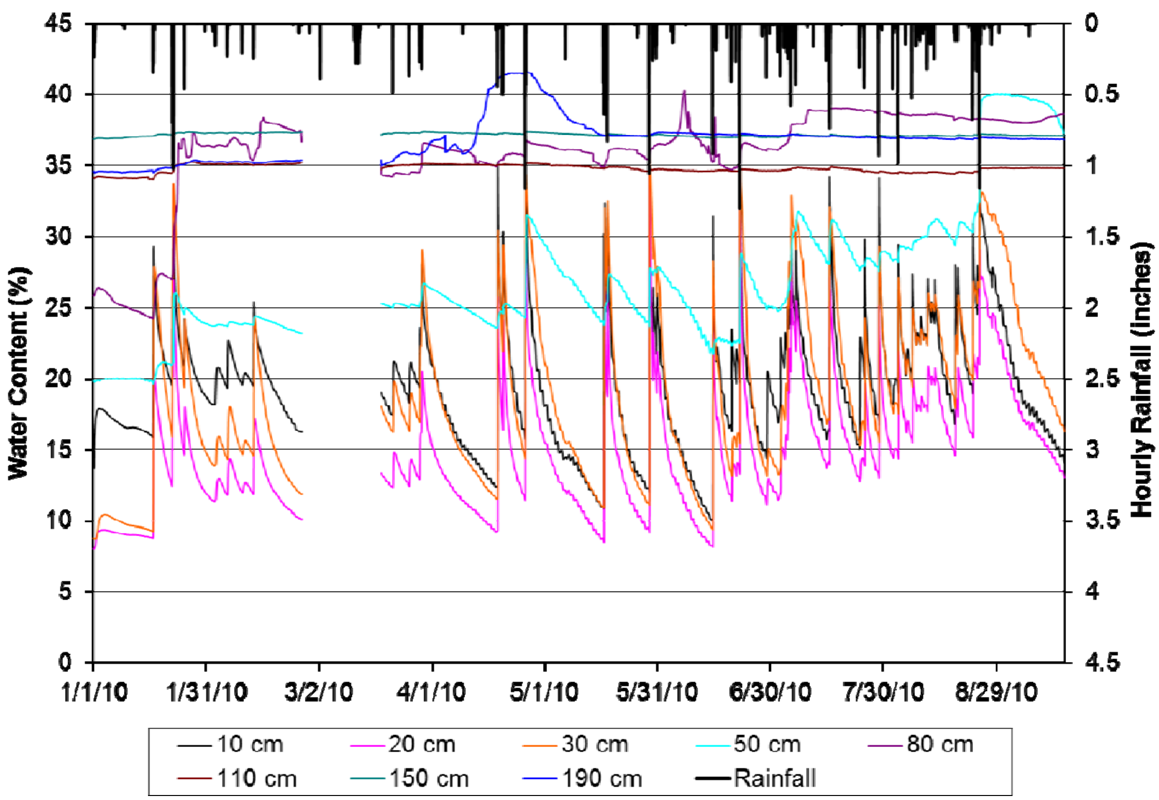

Figure 70.Average hourly soil moisture data at ECO-5 for 2010.

ECO-6

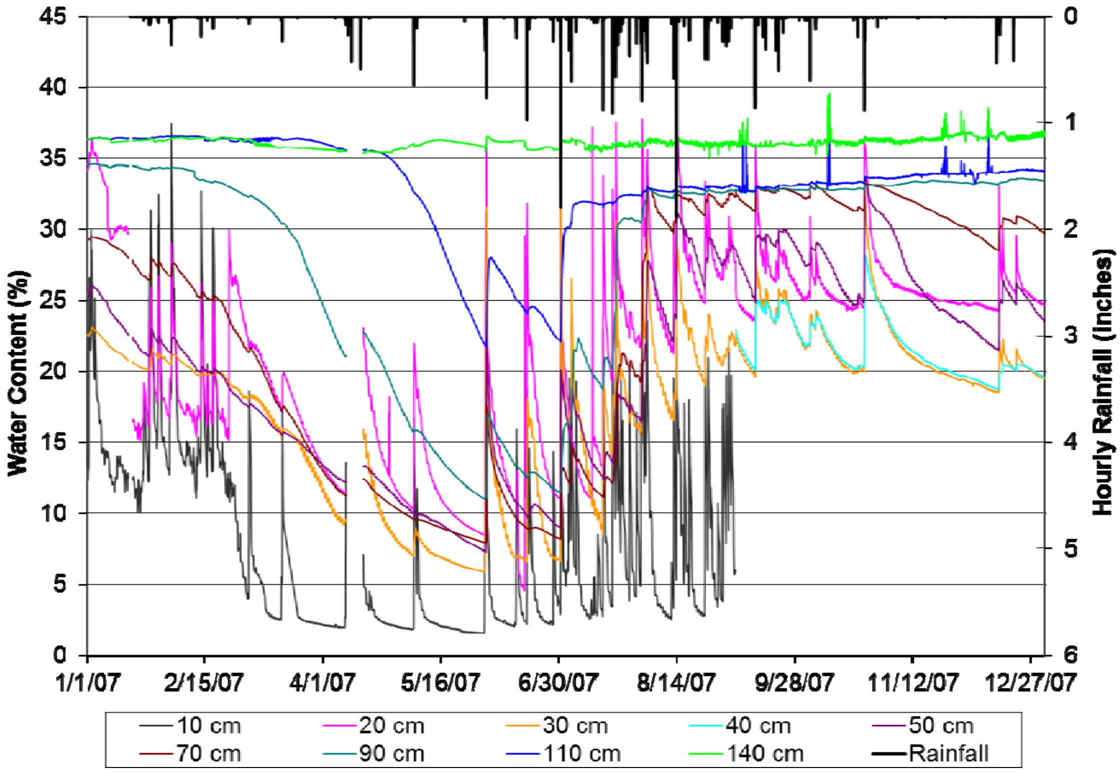

Figure 71. Average hourly soil moisture data at ECO-6 for 2007.

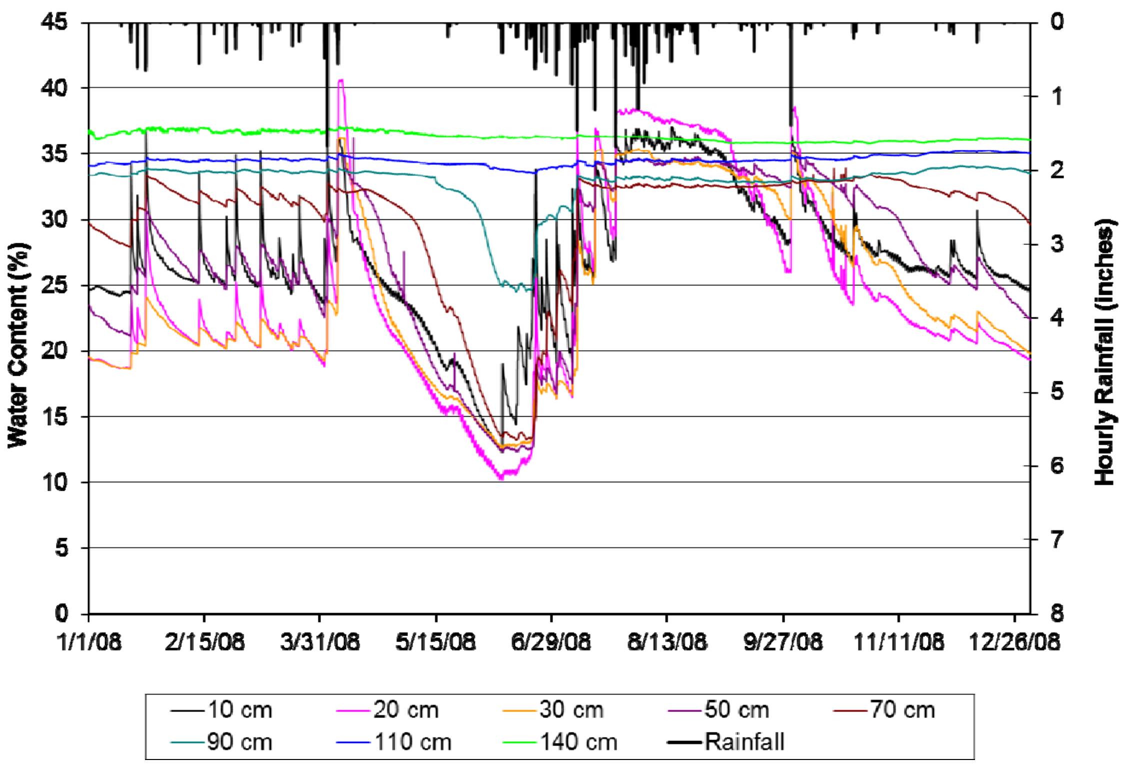

Figure 72. Average hourly soil moisture data at ECO-6 for 2008.

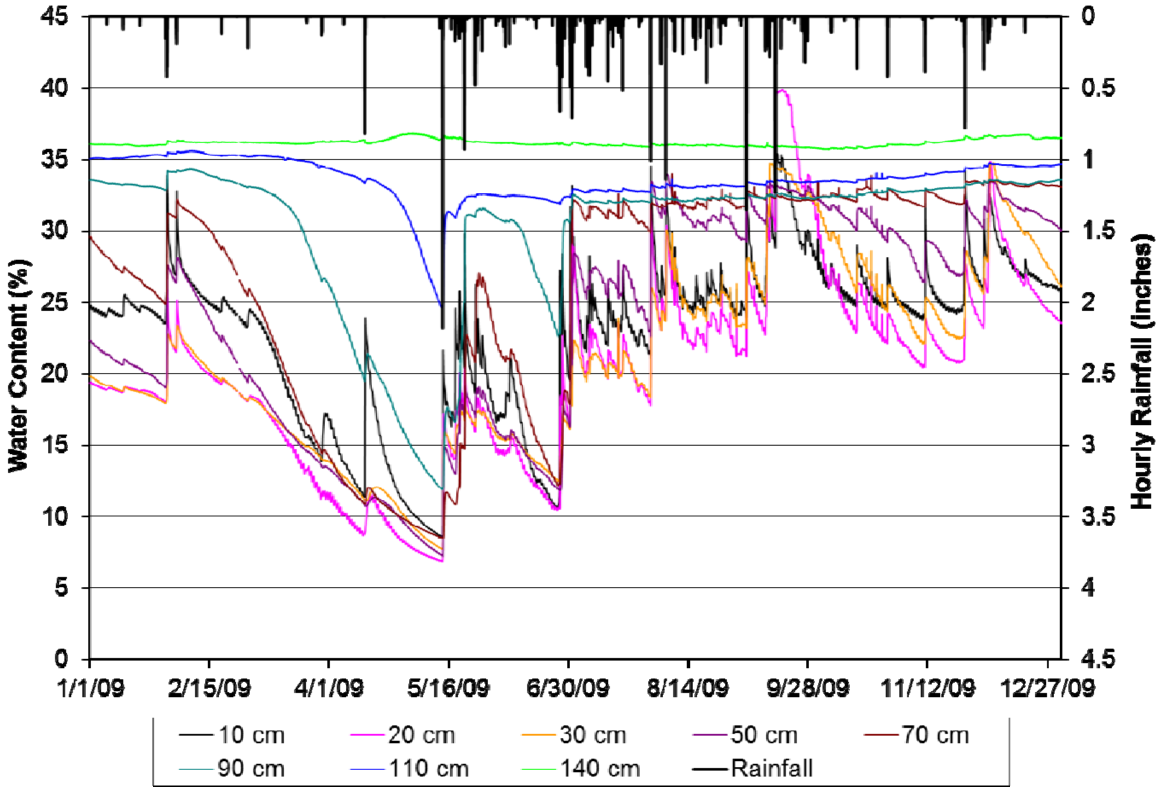

Figure 73. Average hourly soil moisture data at ECO-6 for 2009.

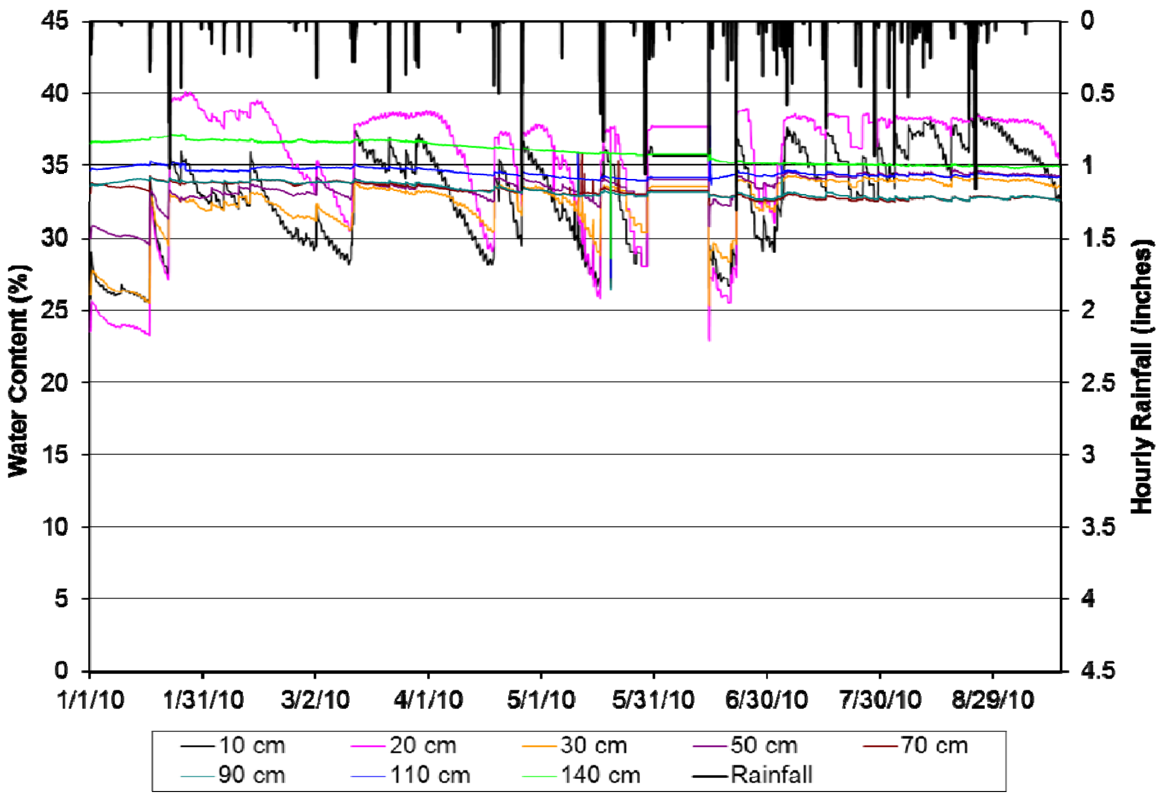

Figure 74. Average hourly soil moisture data at ECO-6 for 2010.

Total Soil Moisture (TSM)

The vertically staggered soil moisture observations can be integrated over the displacement depth to obtain a direct measurement of total soil moisture (TSM) over the entire observation depth (2m). In this manner, the units for TSM become depth either in 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 and results during rainfall events ignored. In this manner TSM(t) was resolved hourly for the entire 4-yr study period. Results for 2009 are plotted in Figures 75 to 80. 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 (2005). The following graphs illustrate the total soil moisture values calculated at each site for the year 2009. Soil moisture for all sites and all years is included in the water balance section of this report.

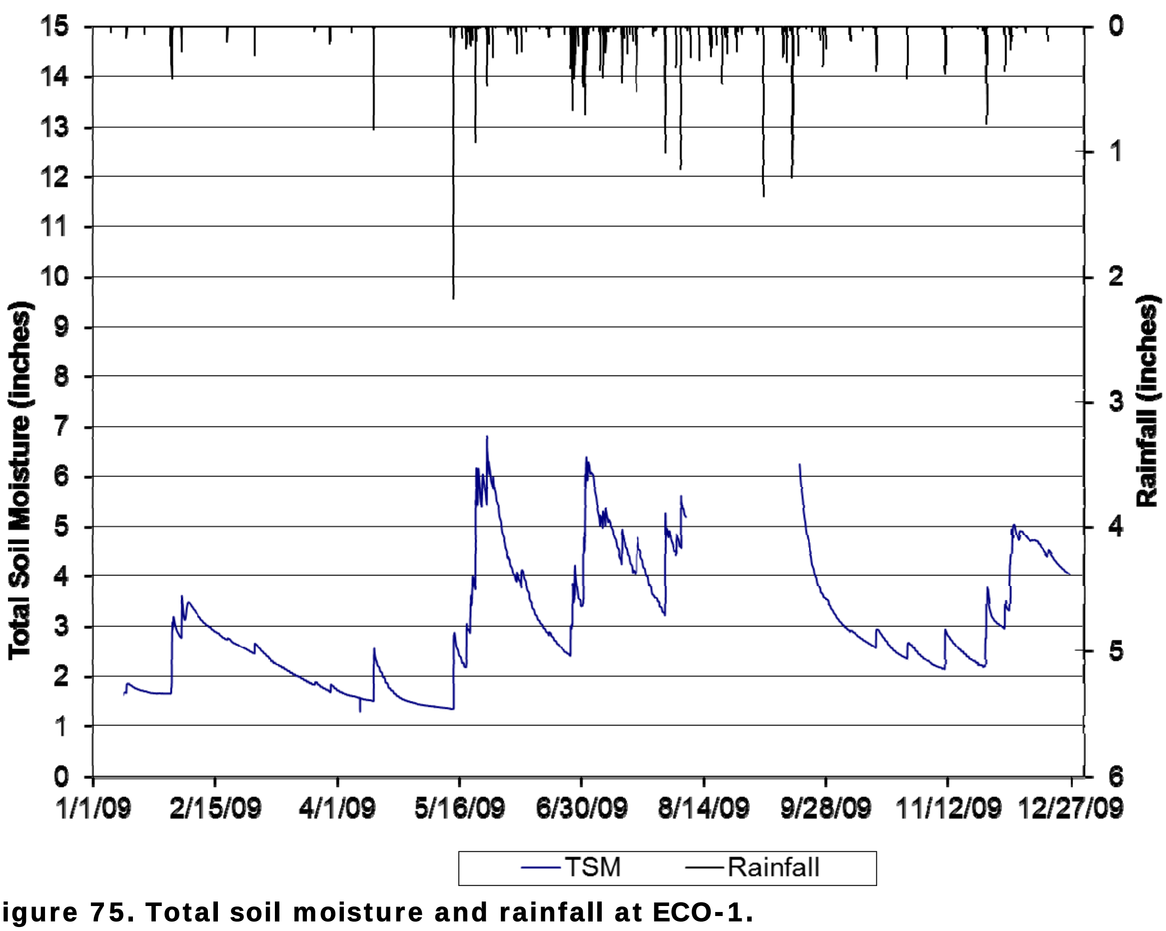

Figure 75. Total soil moisture and rainfall at ECO-1.

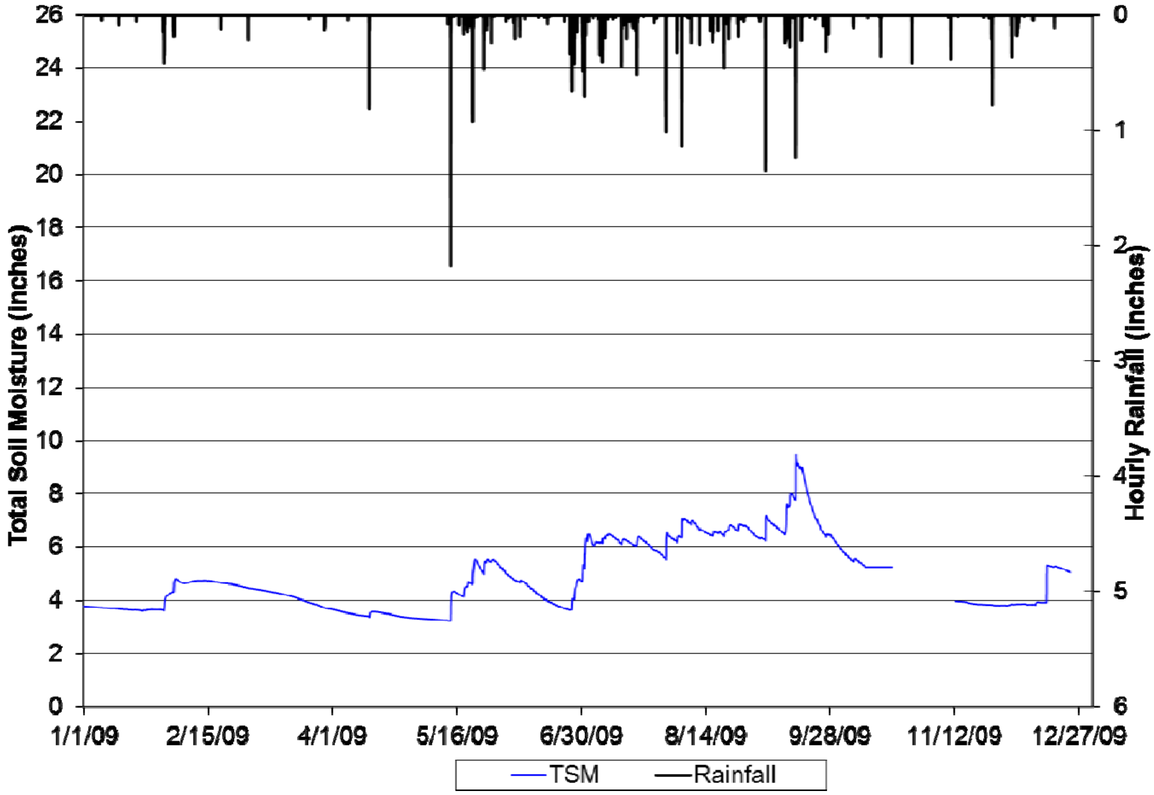

Figure 76. Total soil moisture and rainfall at ECO-2.

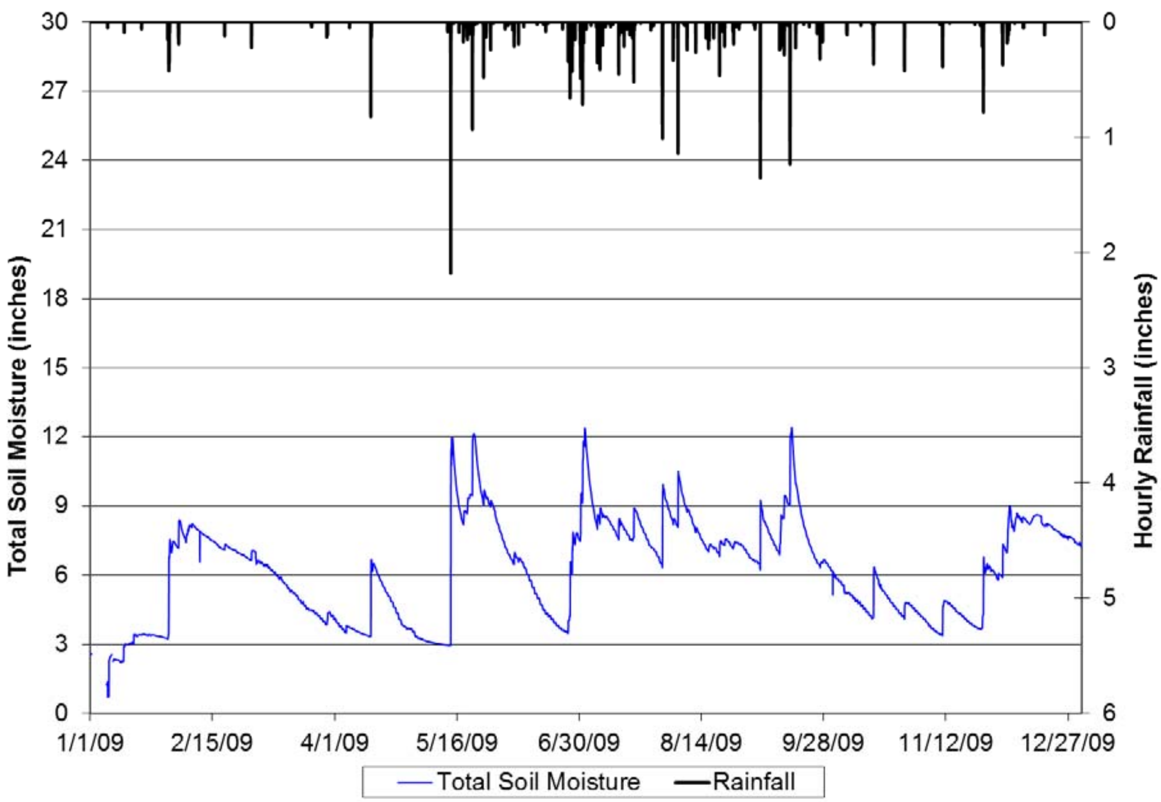

Figure 77. Total soil moisture and rainfall at ECO-3.

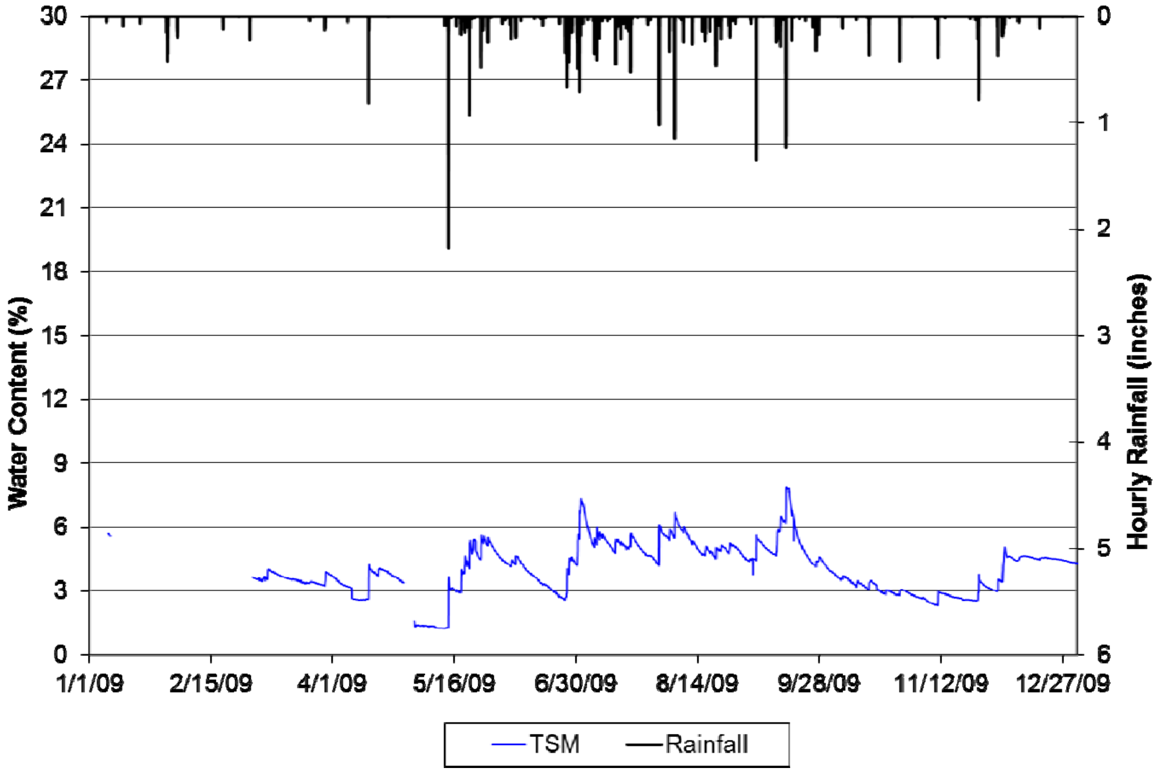

Figure 78. Total soil moisture and rainfall at ECO-4.

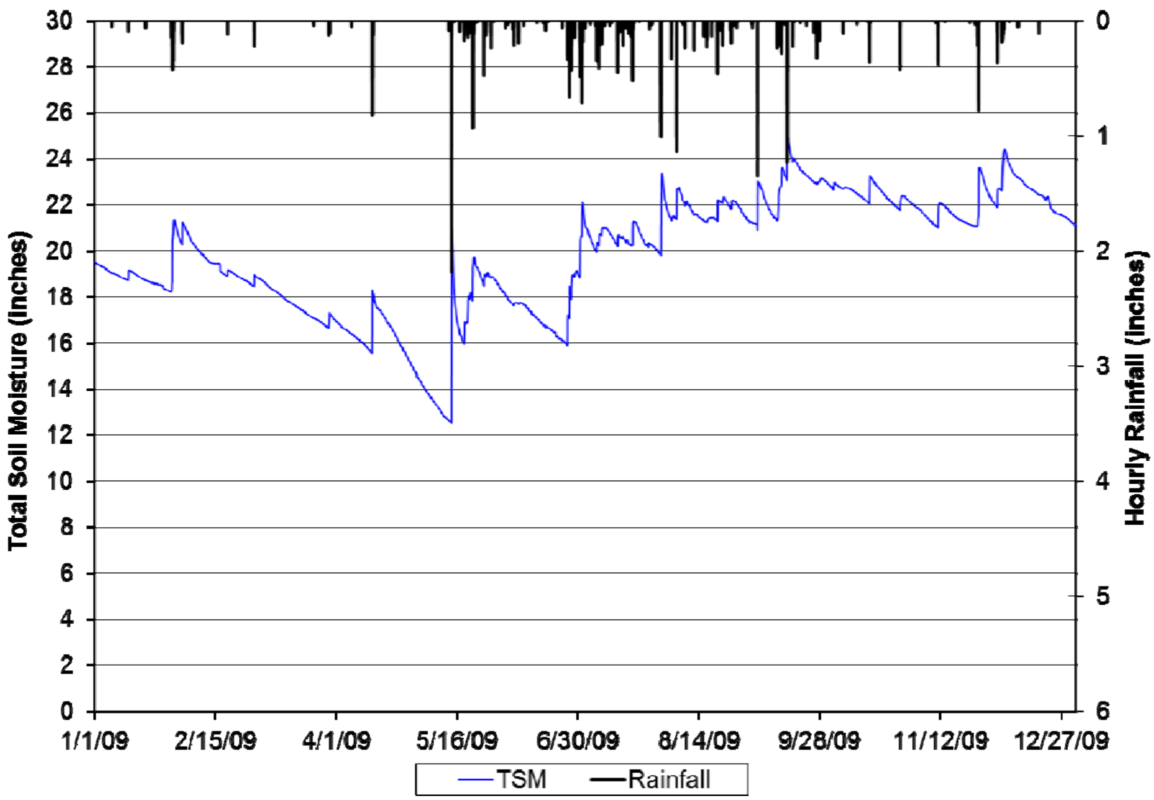

Figure 79. Total soil moisture and rainfall at ECO-5.

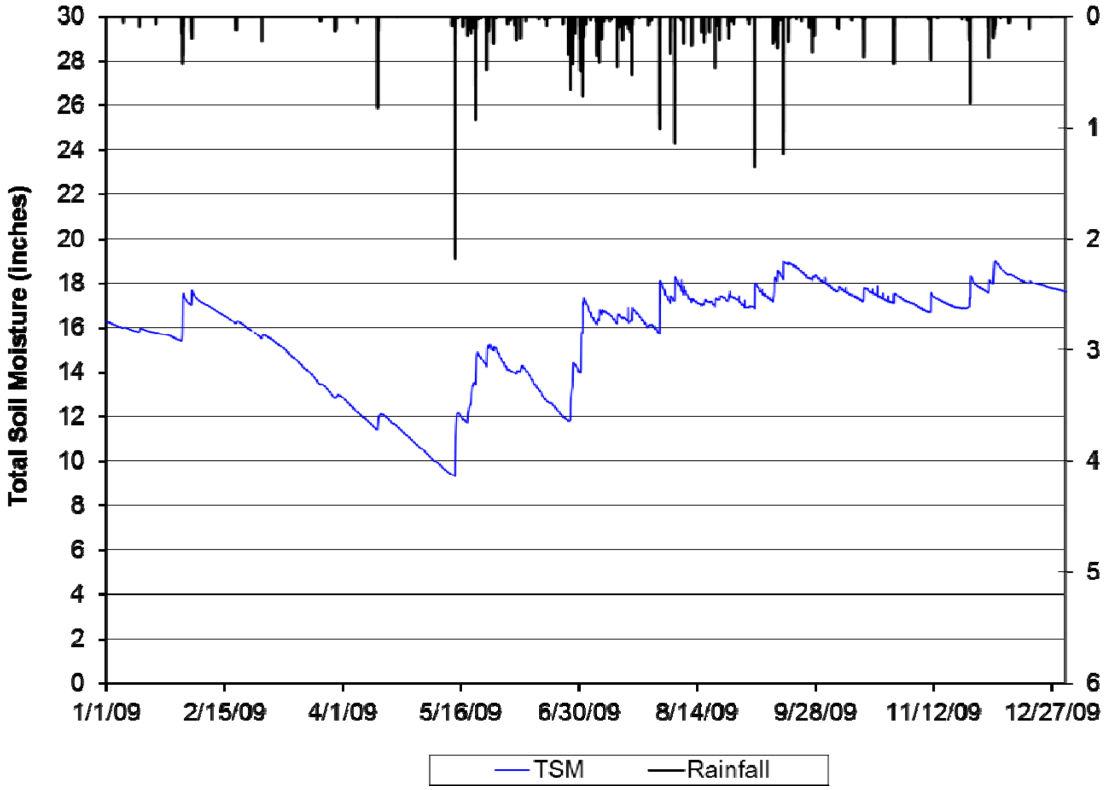

Figure 80. Total soil moisture and rainfall at ECO-6.

Water Table Elevations

Pressure transducers were installed in the monitor wells to record ground water levels. ECO-1 and ECO-2 were dry during the entire study. Both sites were primarily clay extending 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. Unfortunately, the shallow ECO-4 well struck limestone and became a Floridan Aquifer well instead of a surficial aquifer well. A second Floridan well (FL-1) was then installed near ECO-1. All the wells have been surveyed and their water levels corrected to NGVD. The following figures display the continuously recorded water-level elevations (blue line), manual measurements (red box) and cumulative rainfall (pink line) for each of the wells.

The site with the greatest depth to the water table, ECO-3, exhibits a subdued and delayed response to rainfall. The site with the shallowest water table exhibits rapid changes in water table elevation both upward and downward in response to rainfall. The quick change in water table elevation at ECO-6 was accentuated by the decrease in specific yield as the water table approaches the land surface generally confined to the top 2m of the soil column (Ross et al., 2006). ECO-5 shows a response to rainfall between that of ECO-3 and ECO-6. Figure 81 illustrates the water elevations during the study at the three Floridan wells (FL-01, FL-02 and ECO-4) and the three surficial wells (ECO-3, ECO-5 and ECO-6). Overall for the site during the study period there was a 2 to 4 foot downward head gradient between the surficial and Floridan aquifer water elevations.

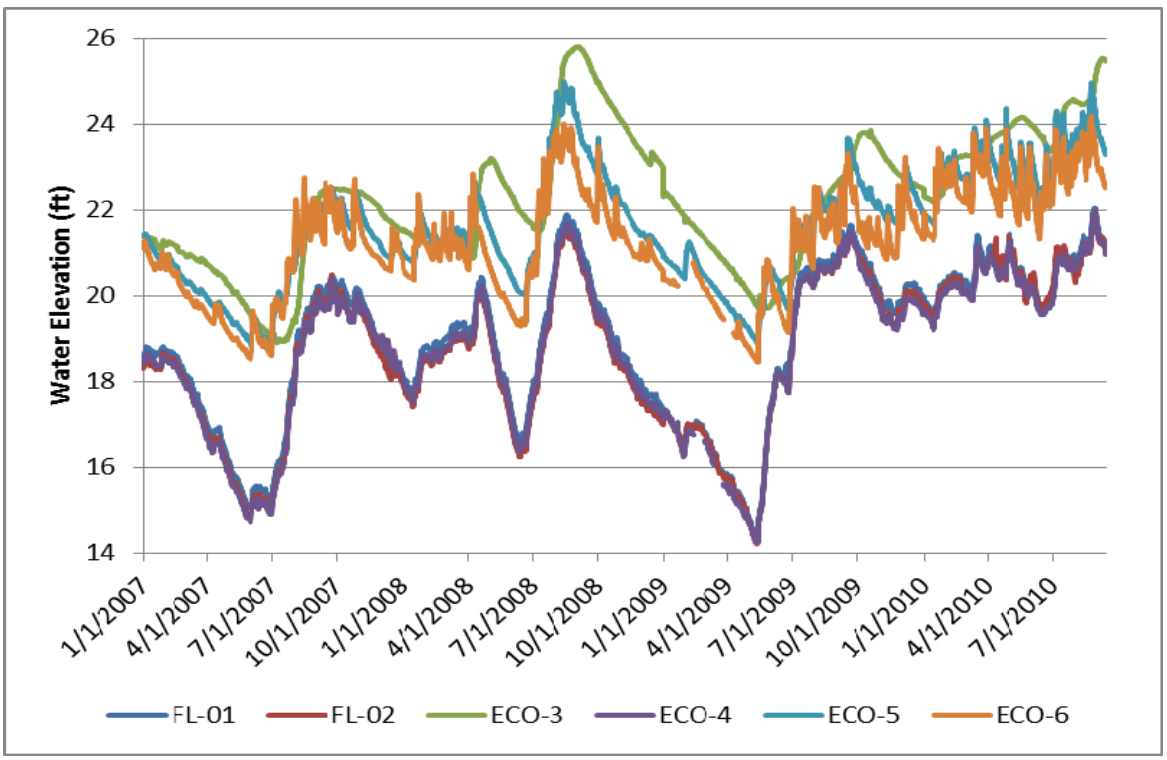

Figure 81. Aquifer water elevations during the study period.

ECO-3

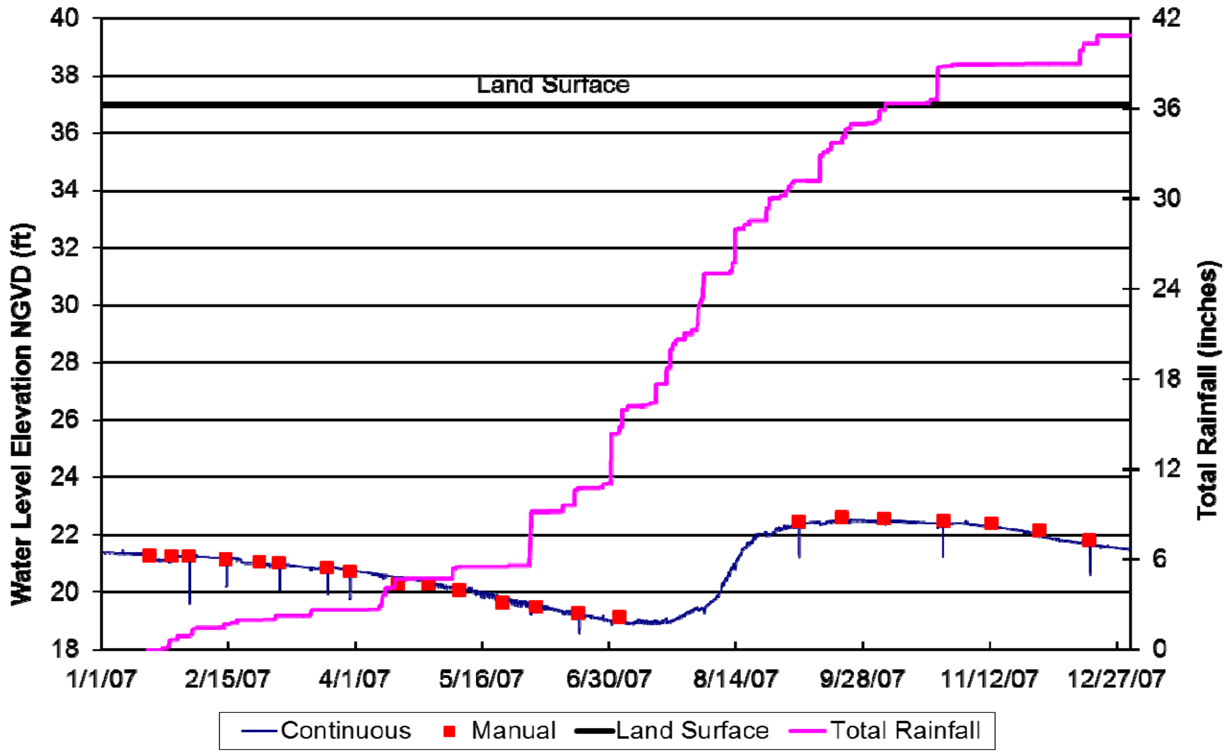

Figure 82. Continuous water-table measurements at ECO-3 with manual measurements and total rainfall for 2007.

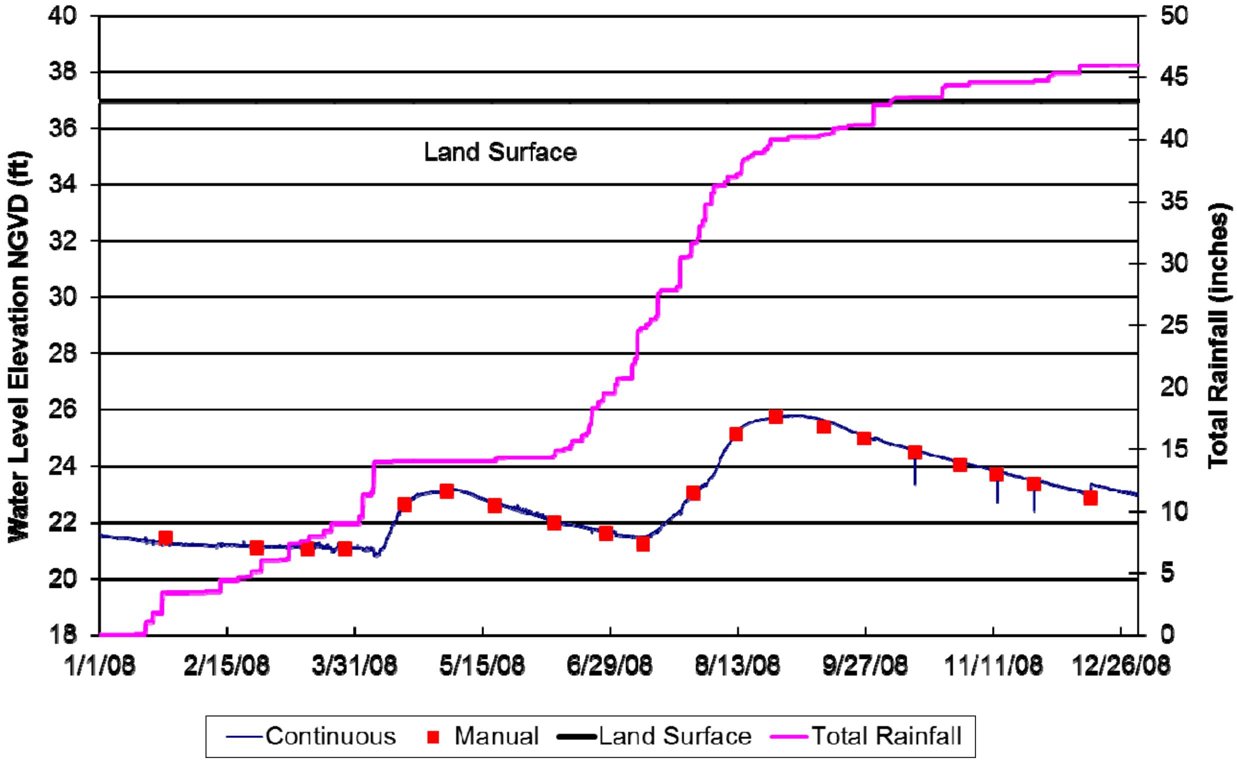

Figure 83. Continuous water-table measurements at ECO-3 with manual measurements and total rainfall for 2008.

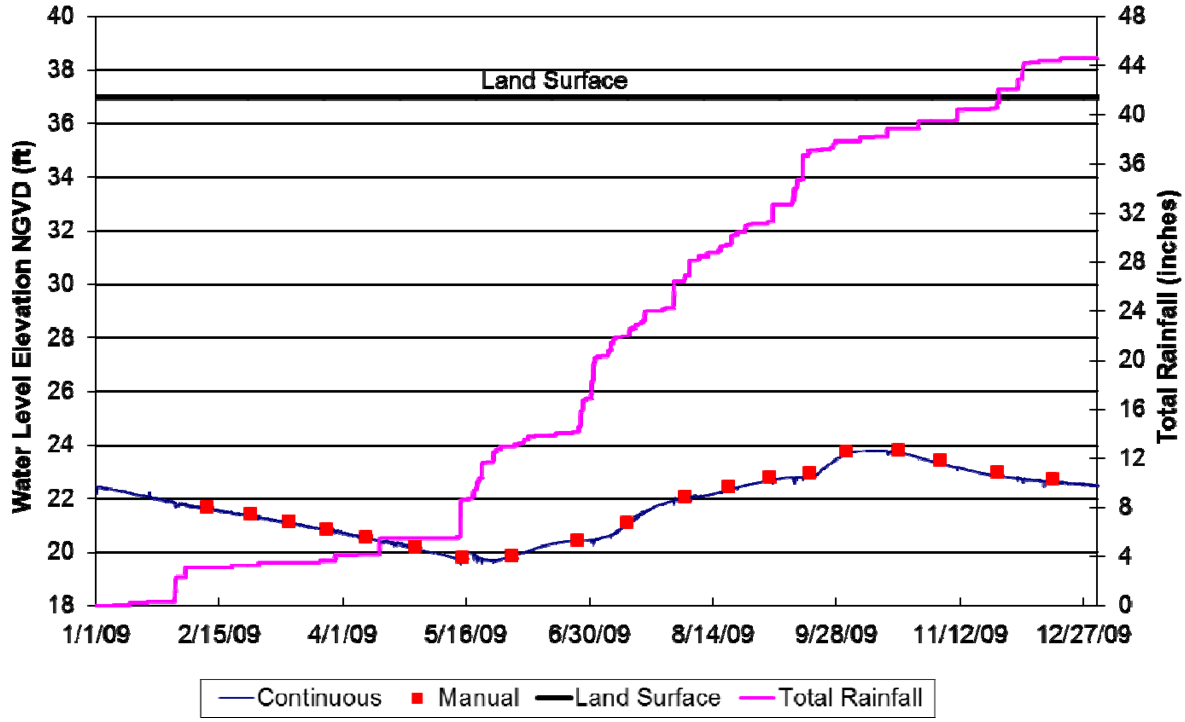

Figure 84. Continuous water-table measurements at ECO-3 with manual measurements and total rainfall for 2009.

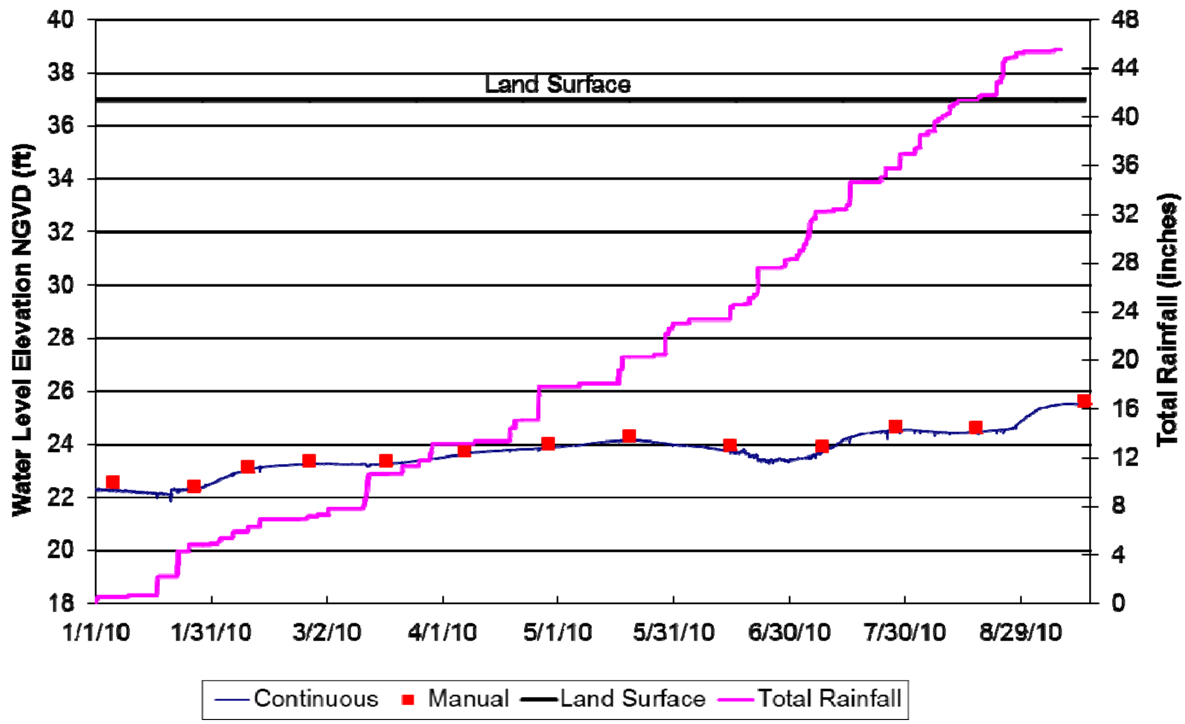

Figure 85. Continuous water-table measurements at ECO-3 with manual measurements and total rainfall for 2010.

ECO-4

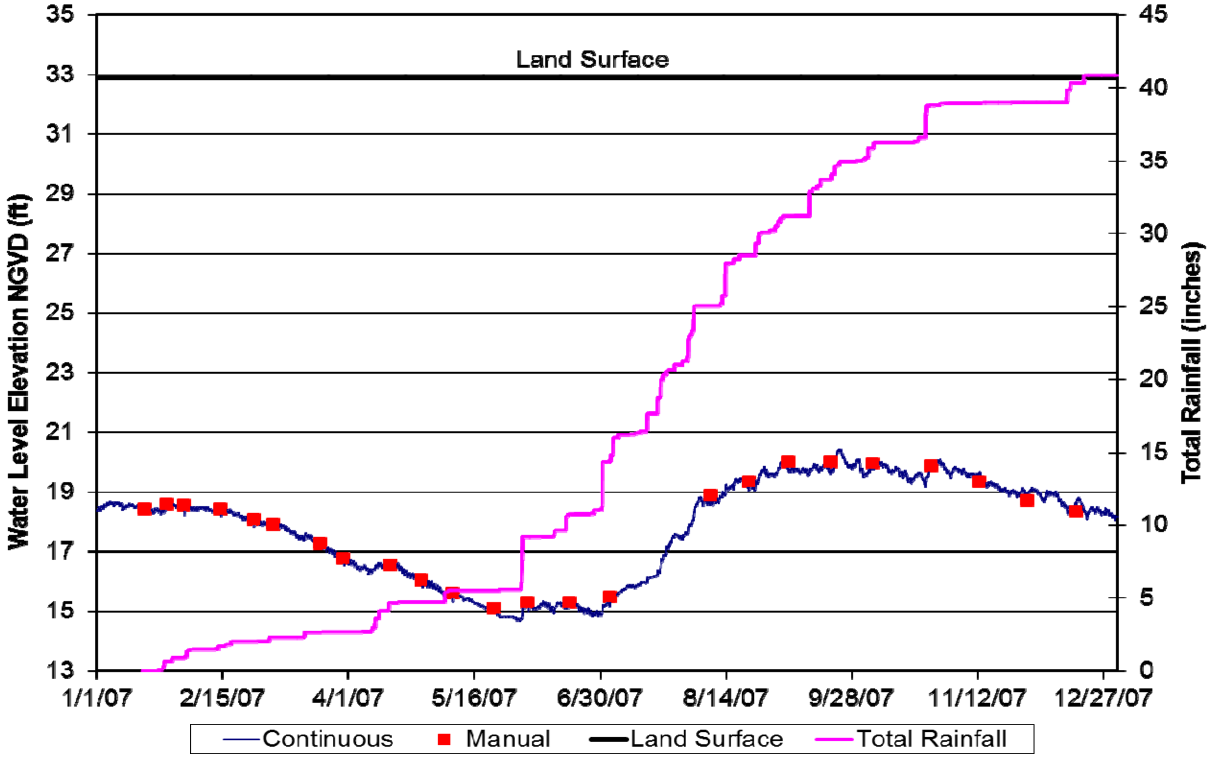

Figure 86. Continuous water-table measurements at ECO-4 with manual measurements and total rainfall for 2007.

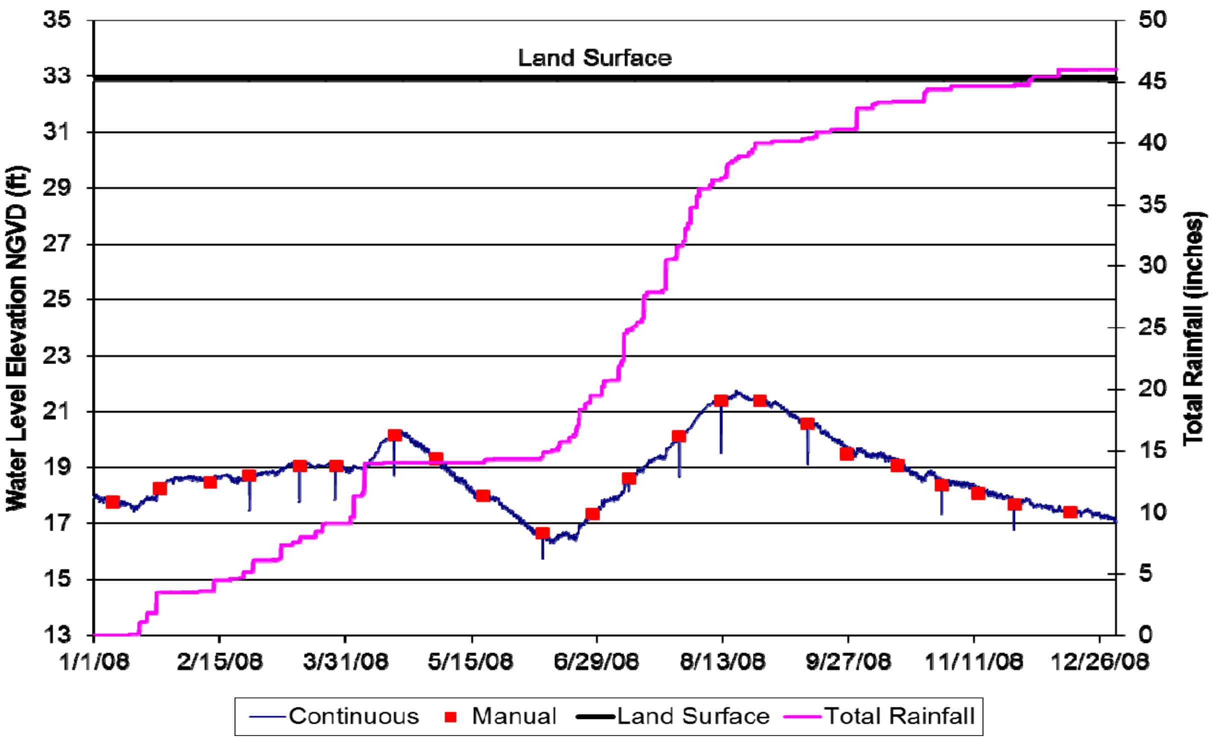

Figure 87. Continuous water-table measurements at ECO-4 with manual measurements and total rainfall for 2008.

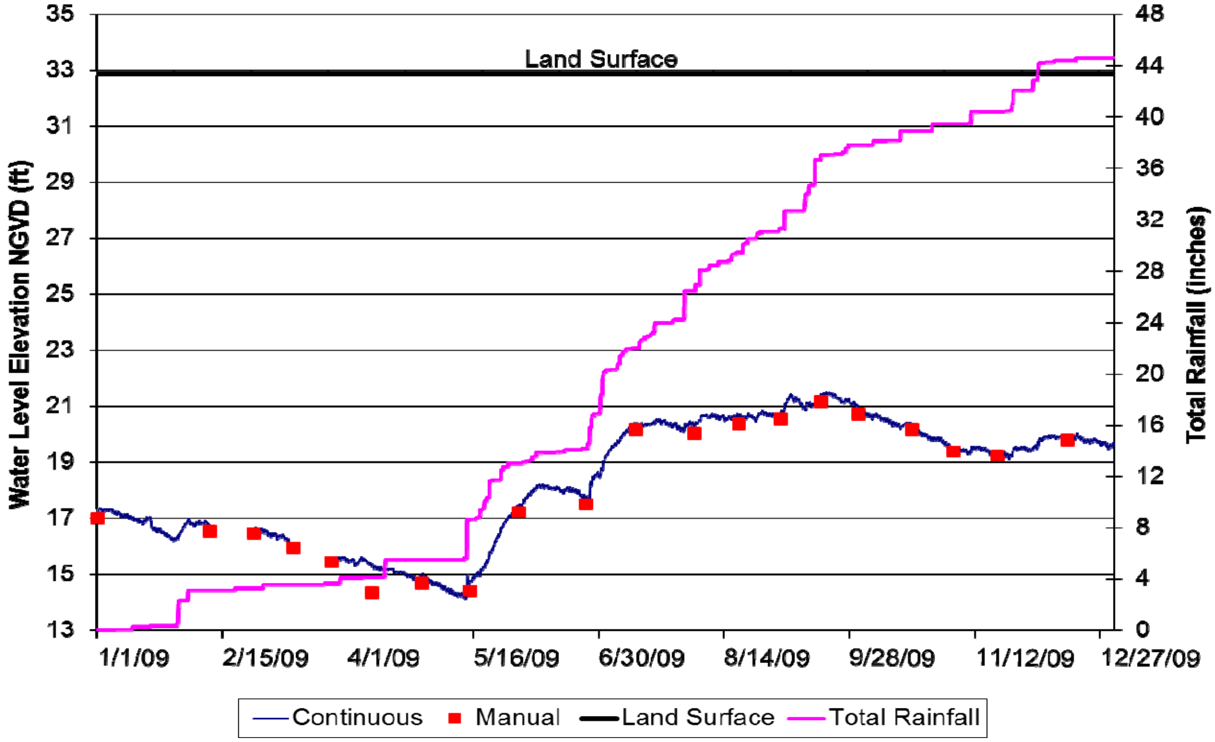

Figure 88. Continuous water-table measurements at ECO-4 with manual measurements and total rainfall for 2009.

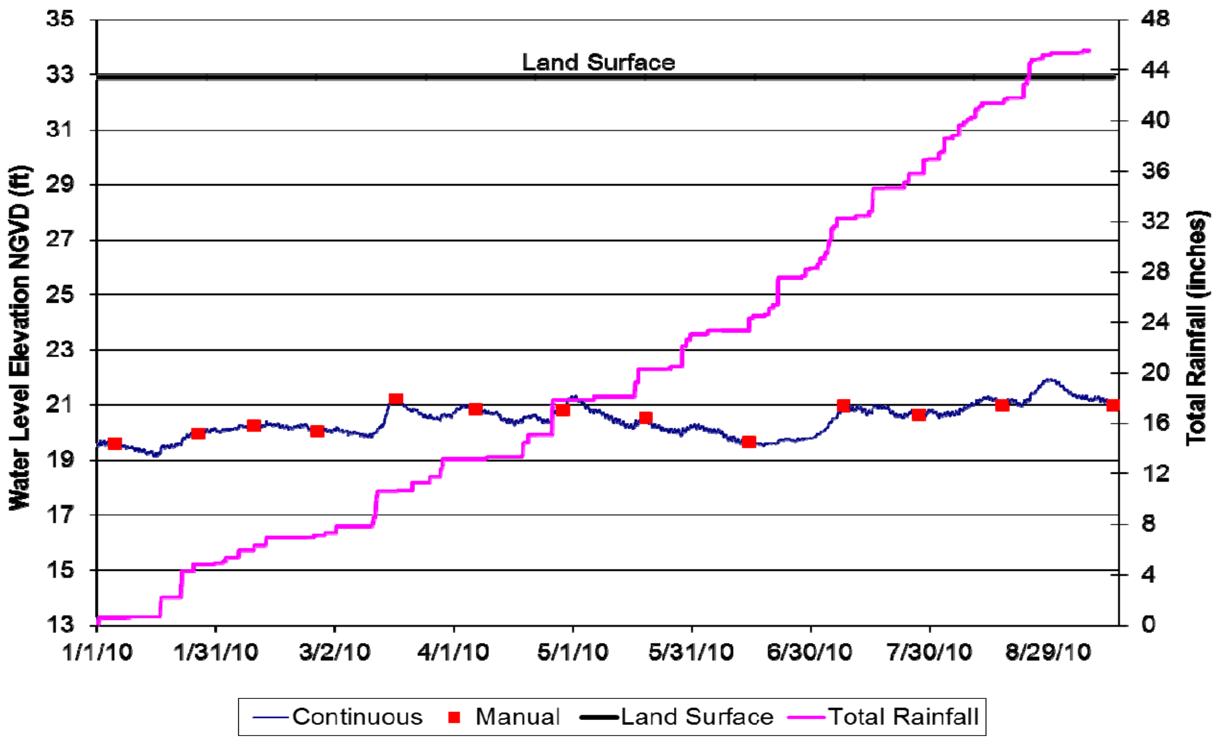

Figure 89. Continuous water-table measurements at ECO-4 with manual measurements and total rainfall for 2010.

ECO-5

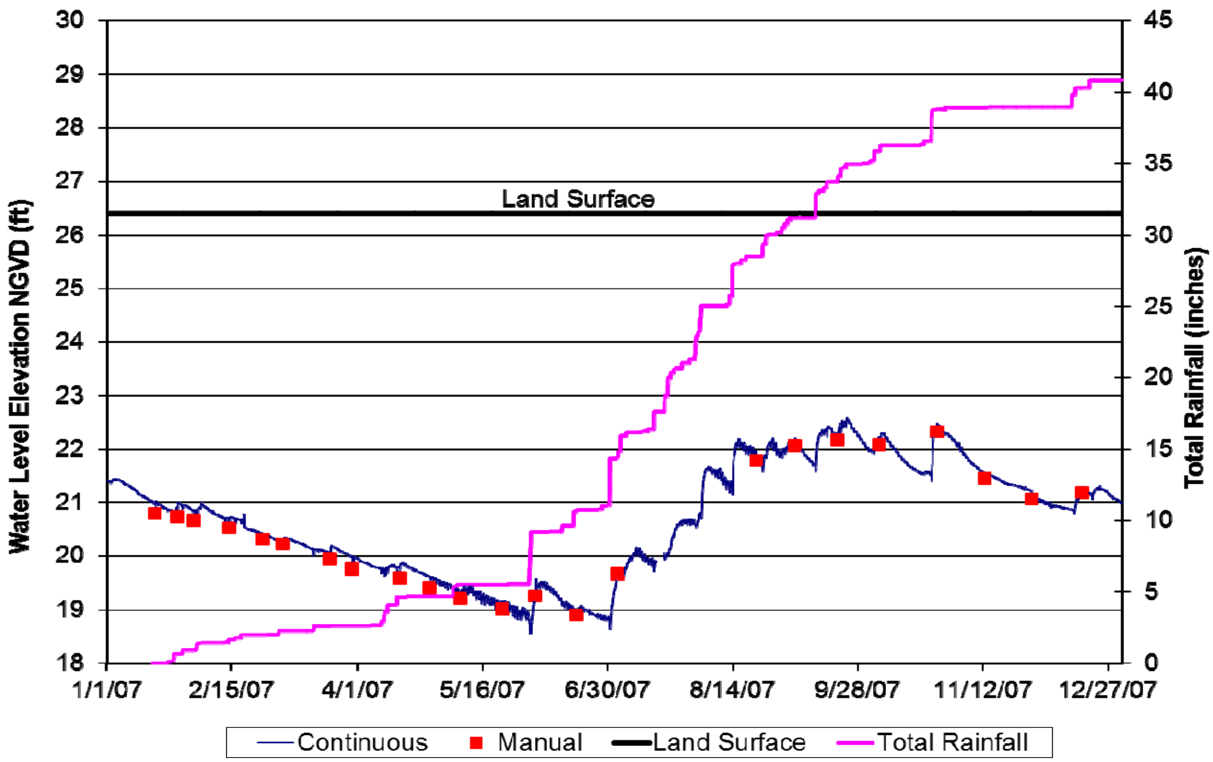

Figure 90. Continuous water-table measurements at ECO-5 with manual measurements and total rainfall for 2007.

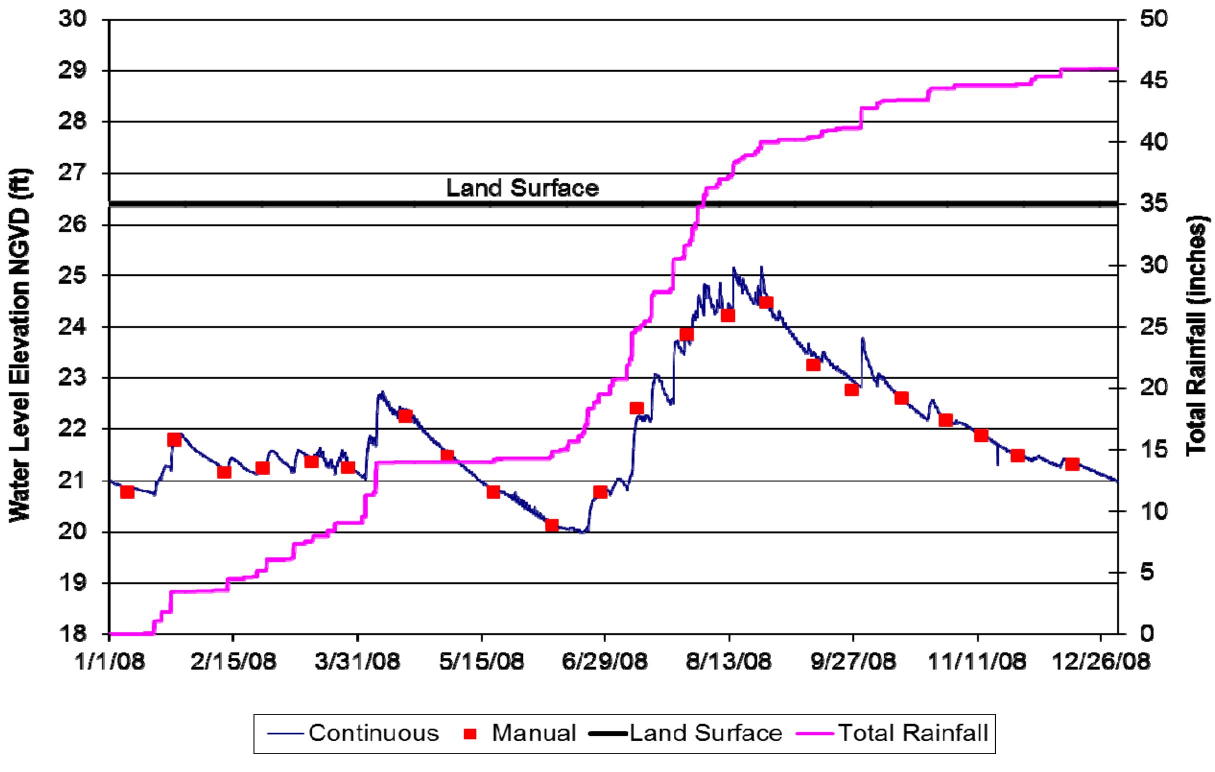

Figure 91. Continuous water-table measurements at ECO-5 with manual measurements and total rainfall for 2008.

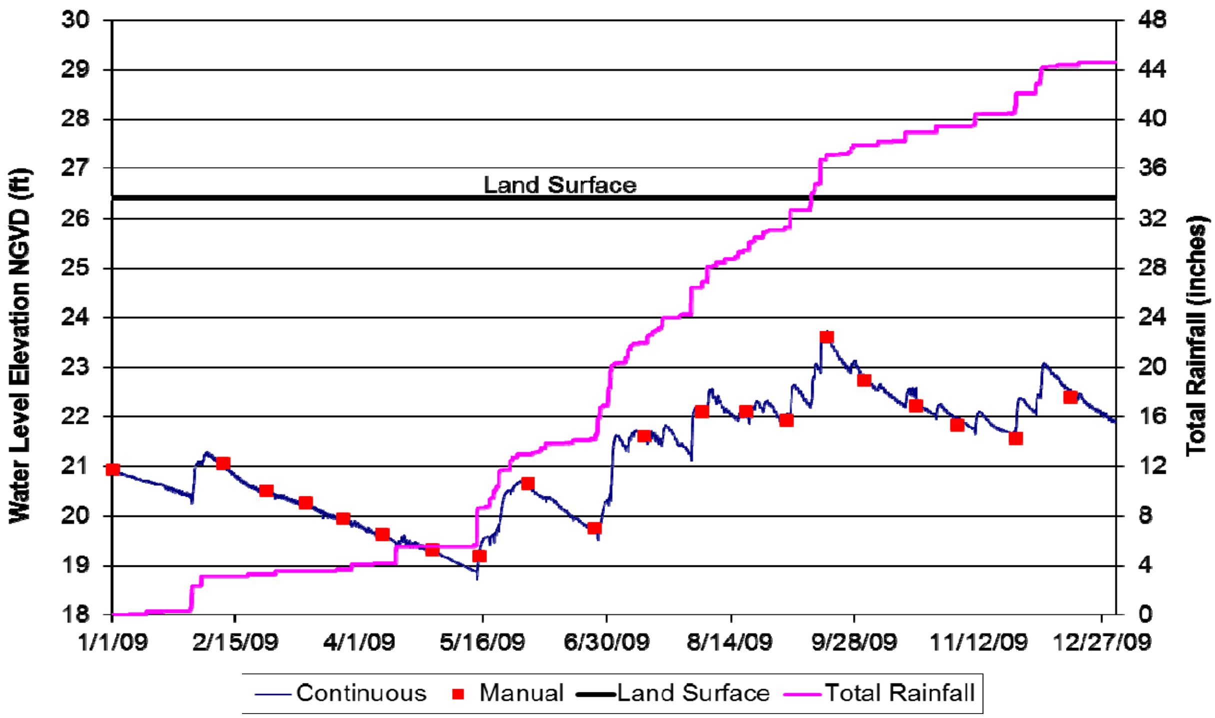

Figure 92. Continuous water-table measurements at ECO-5 with manual measurements and total rainfall for 2009.

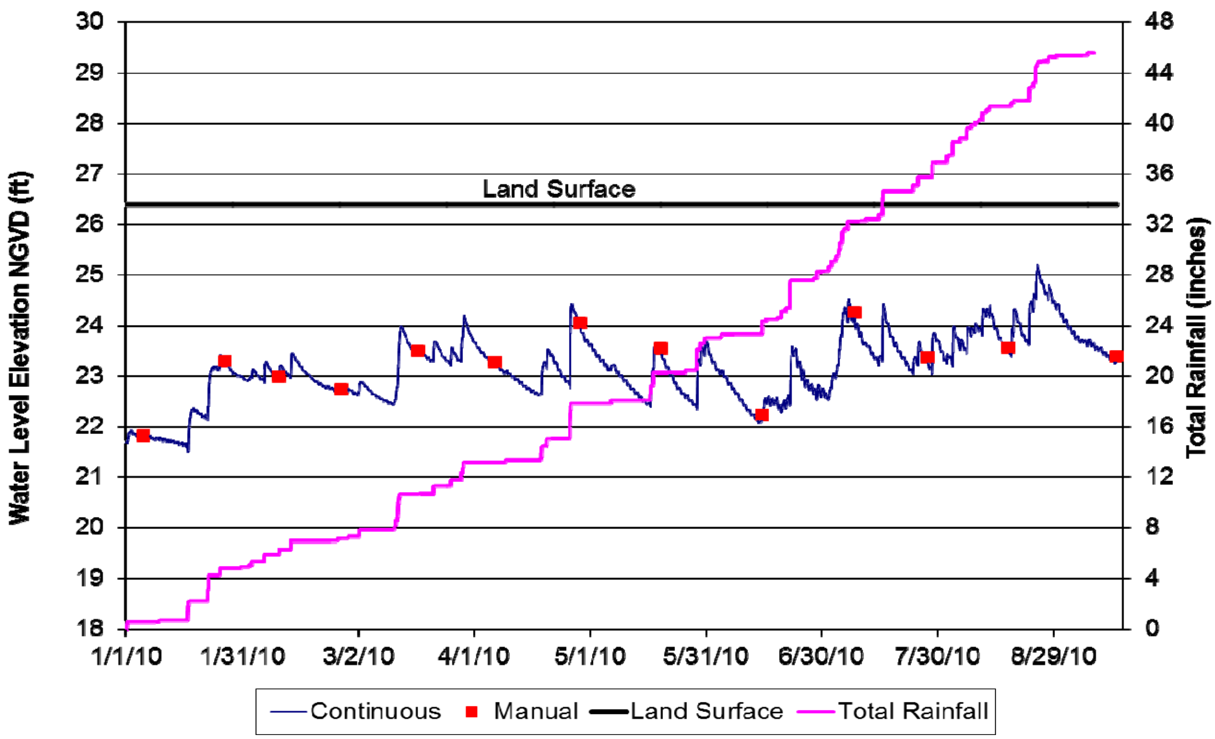

Figure 93. Continuous water-table measurements at ECO-5 with manual measurements and total rainfall for 2010.

ECO-6

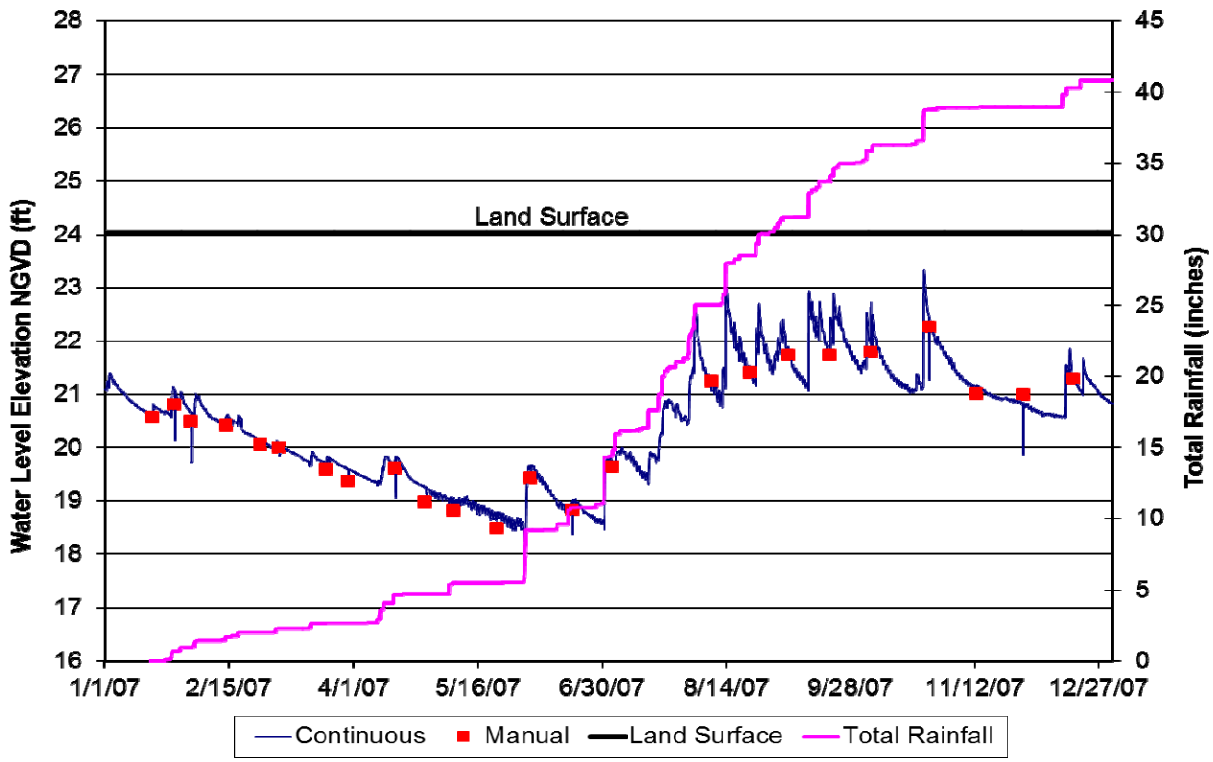

Figure 94. Continuous water-table measurements at ECO-6 with manual measurements and total rainfall for 2007.

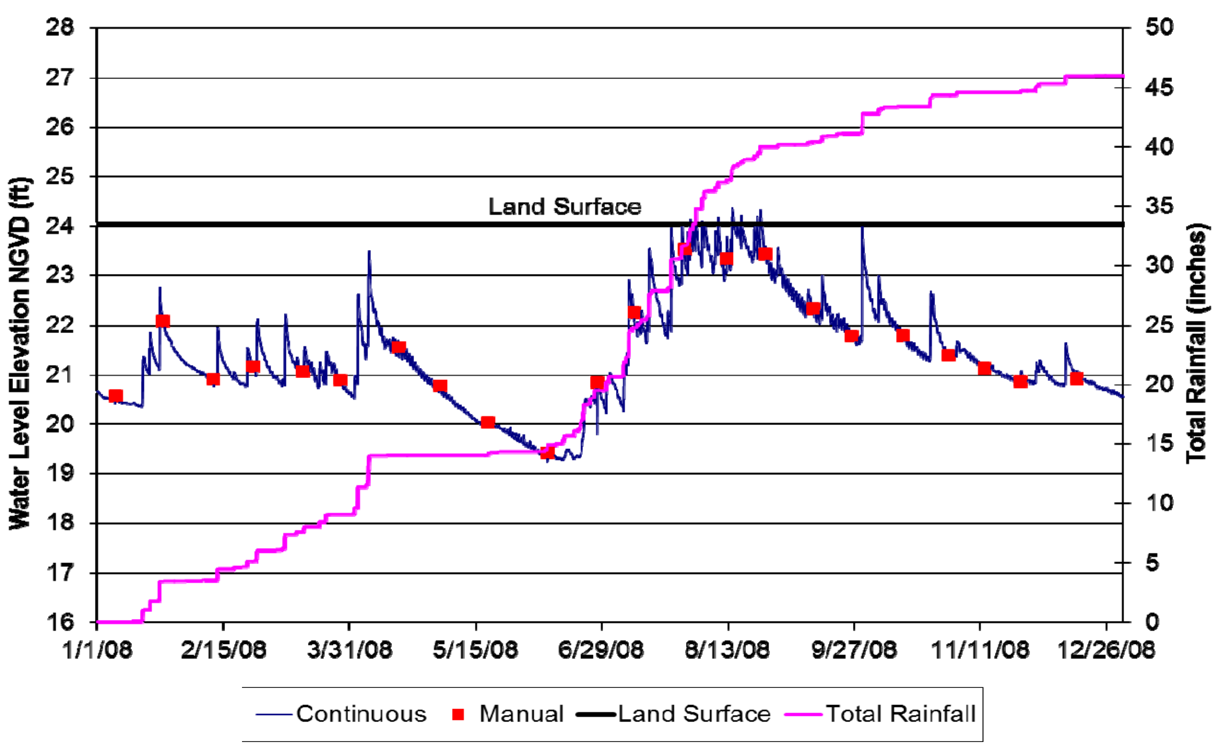

Figure 95. Continuous water-table measurements at ECO-6 with manual measurements and total rainfall for 2008.

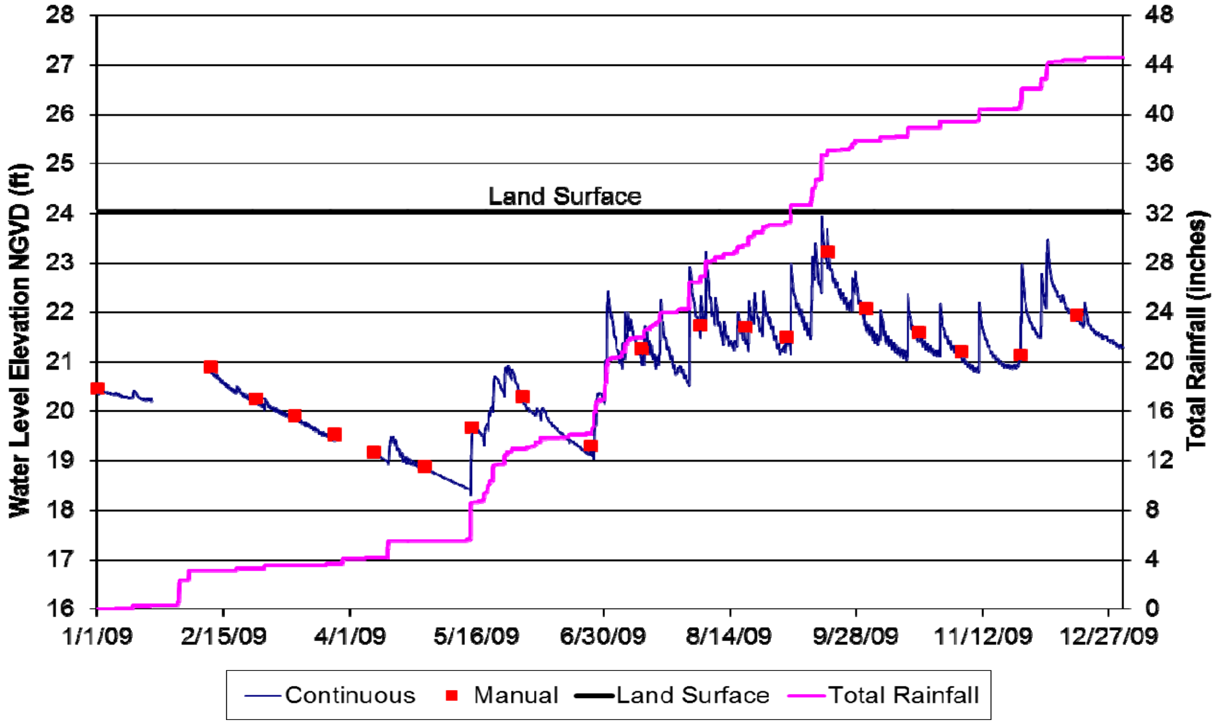

Figure 96. Continuous water-table measurements at ECO-6 with manual measurements and total rainfall for 2009.

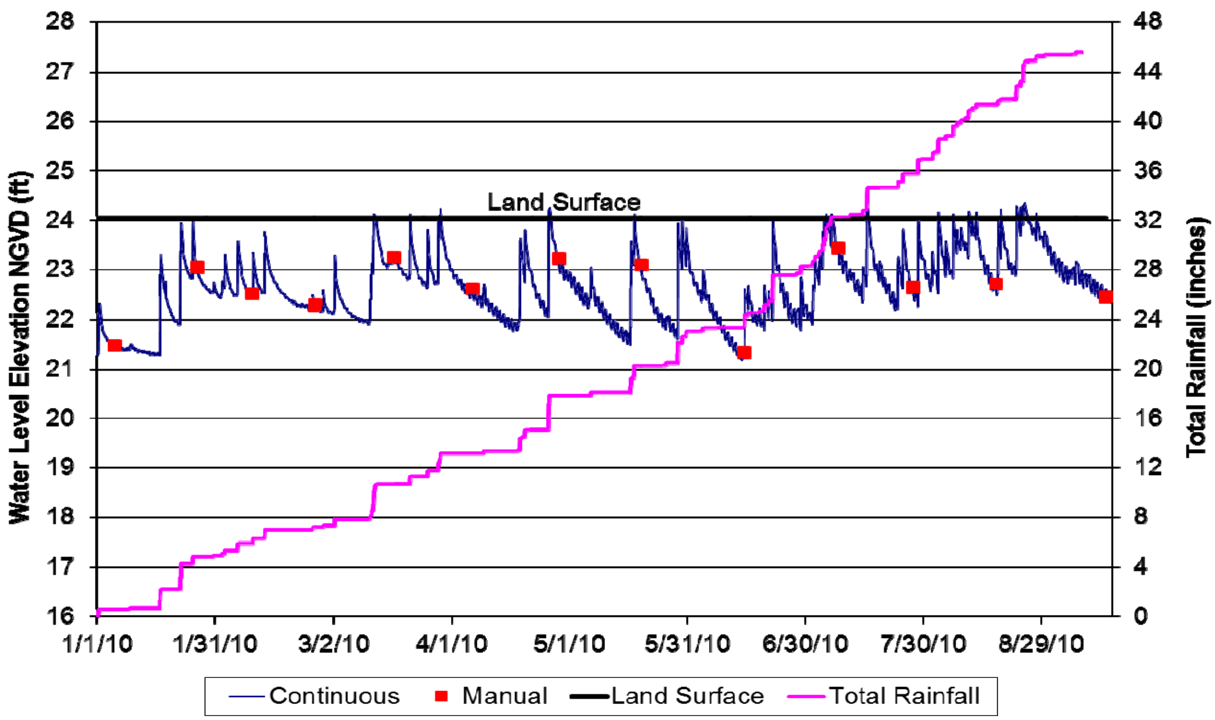

Figure 97. Continuous water-table measurements at ECO-6 with manual measurements and total rainfall for 2010.

FL-01

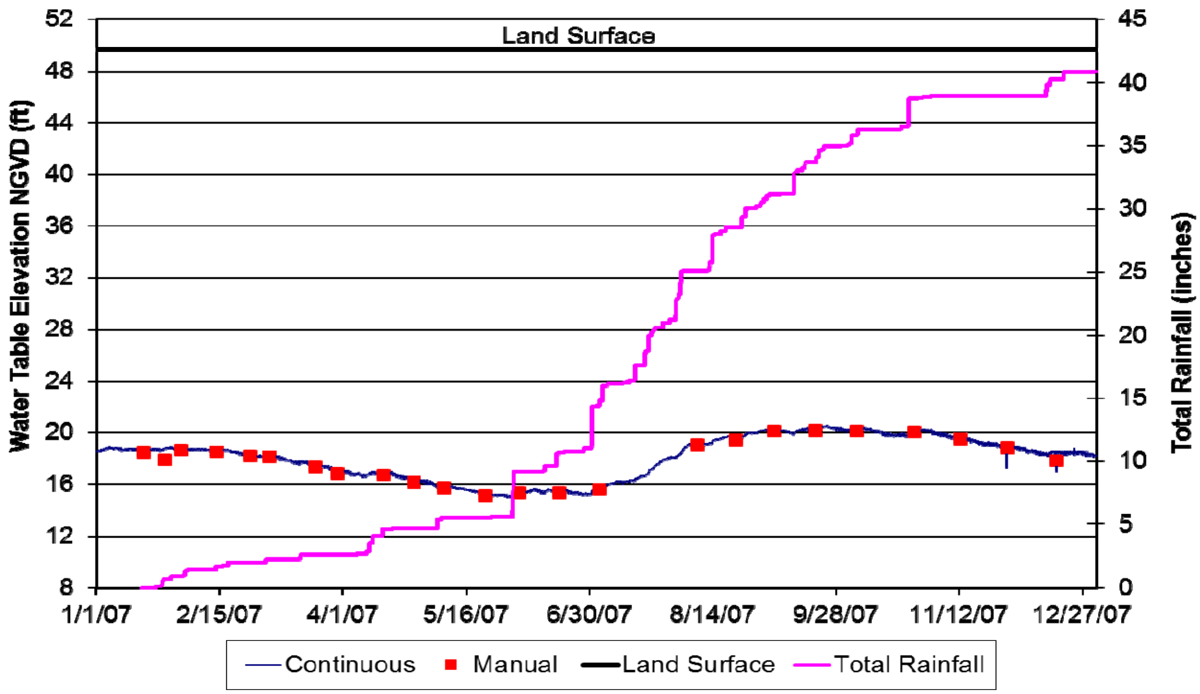

Figure 98. Continuous approximate Floridan Aquifer water levels at FL-01 with manual measurements and total rainfall for 2007.

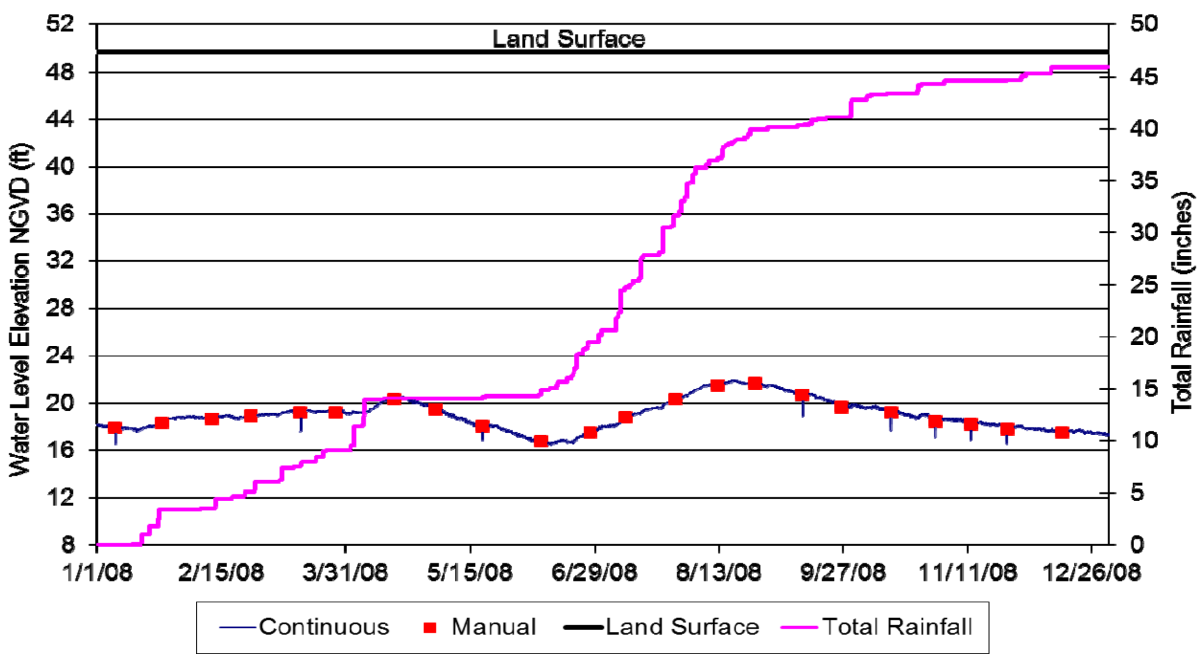

Figure 99. Continuous approximate Floridan Aquifer water levels at FL-01 with manual measurements and total rainfall for 2008.

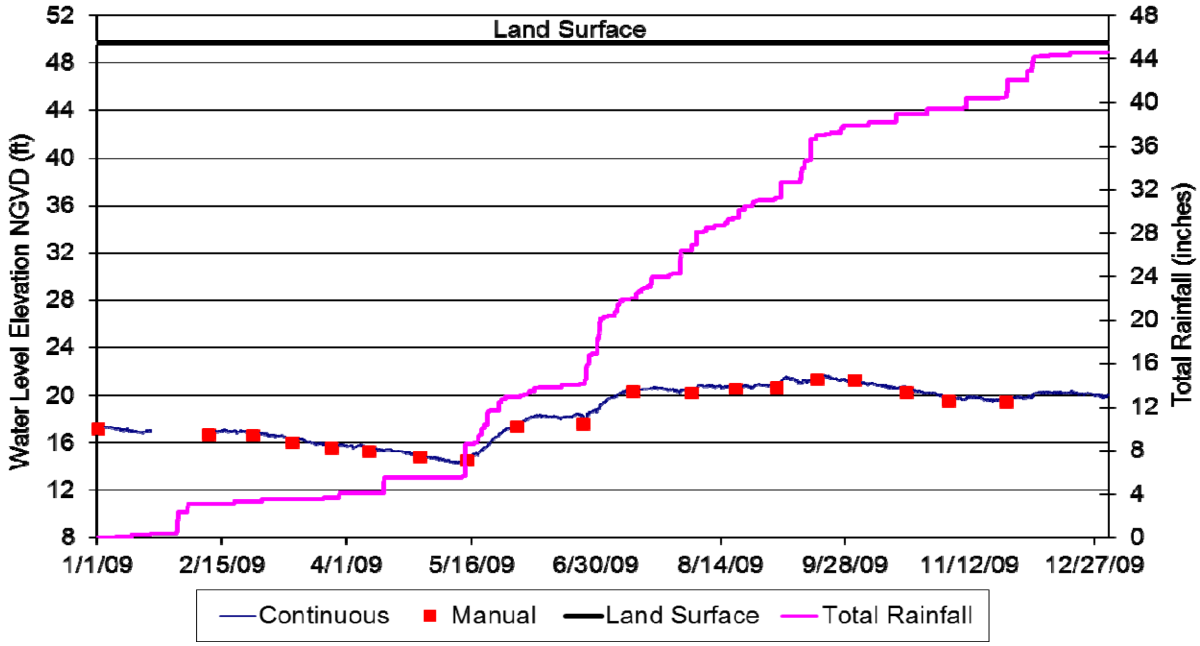

Figure 100. Continuous approximate Floridan Aquifer water levels at FL-01 with manual measurements and total rainfall for 2009.

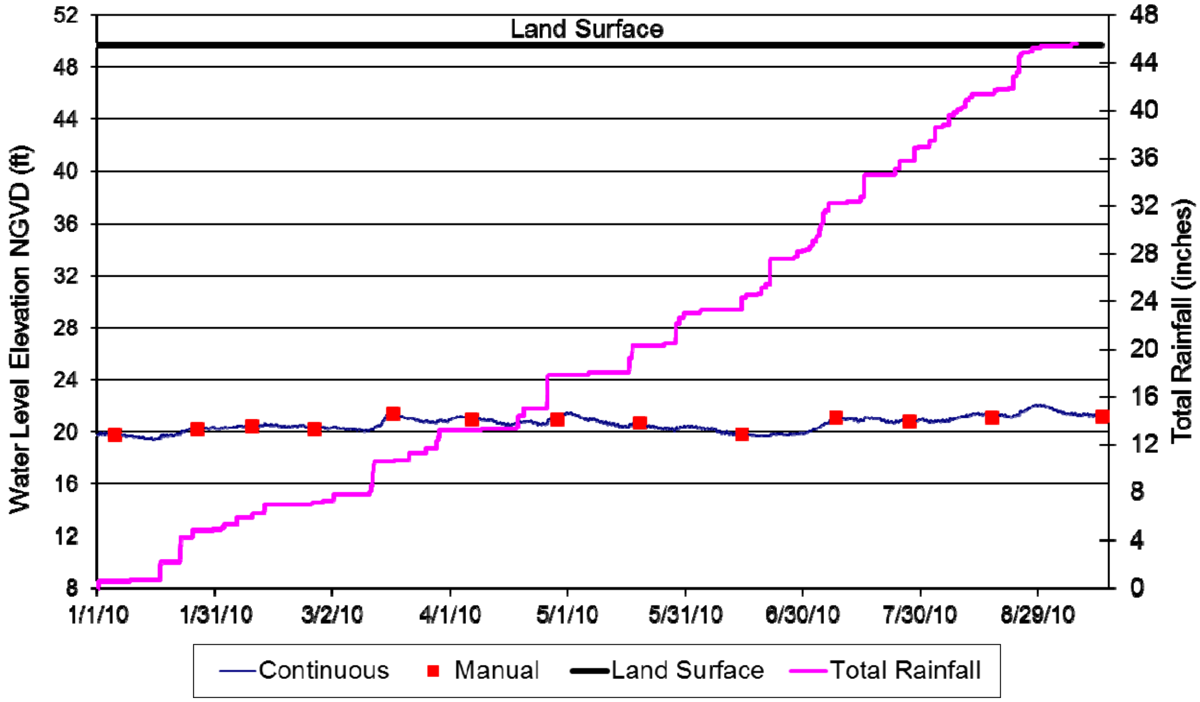

Figure 101. Continuous approximate Floridan Aquifer water levels at FL-01 with manual measurements and total rainfall for 2010.

FL-02

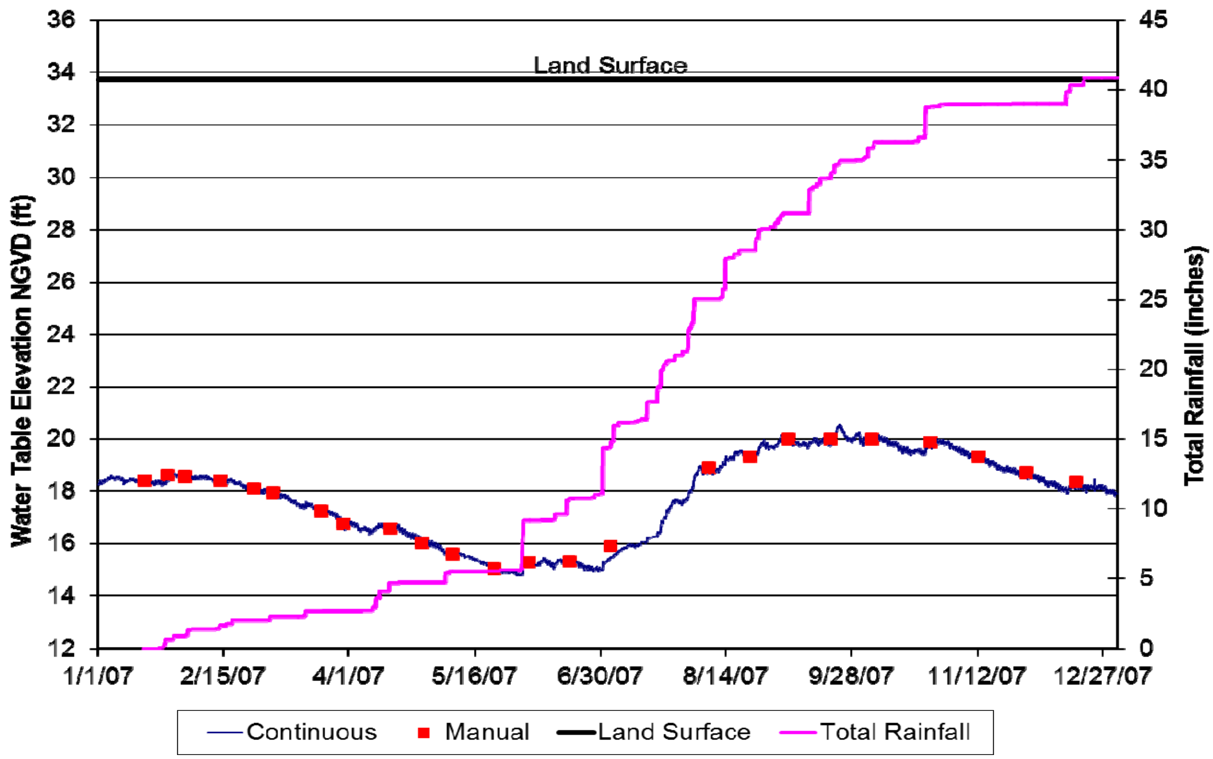

Figure 102. Continuous water-table measurements at FL-02 with manual measurements and total rainfall for 2007.

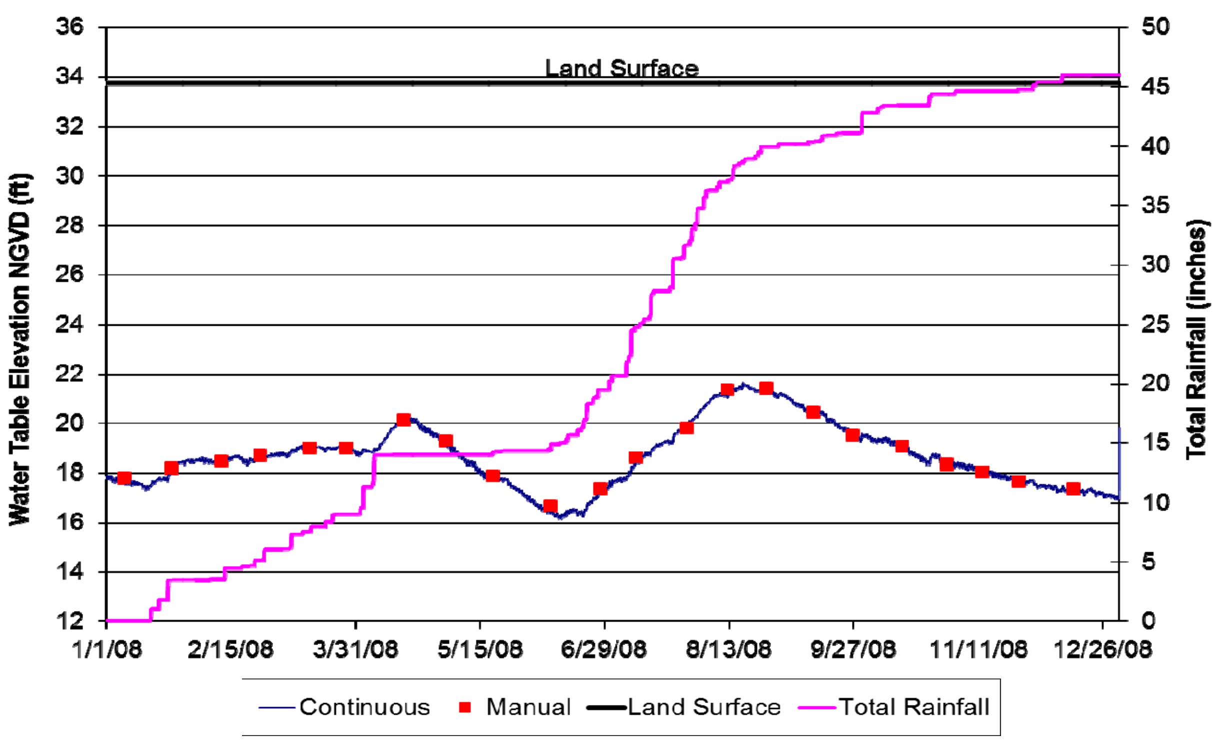

Figure 103. Continuous water-table measurements at FL-02 with manual measurements and total rainfall for 2008.

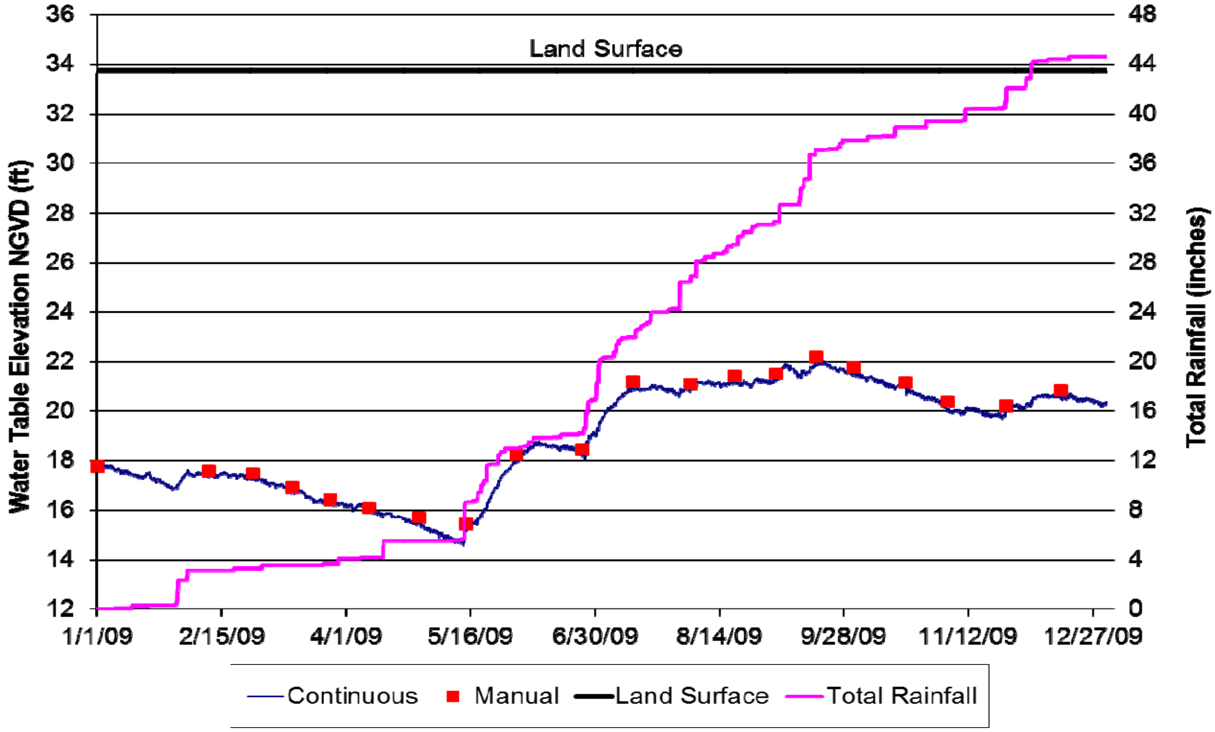

Figure 104. Continuous water-table measurements at FL-02 with manual measurements and total rainfall for 2009.

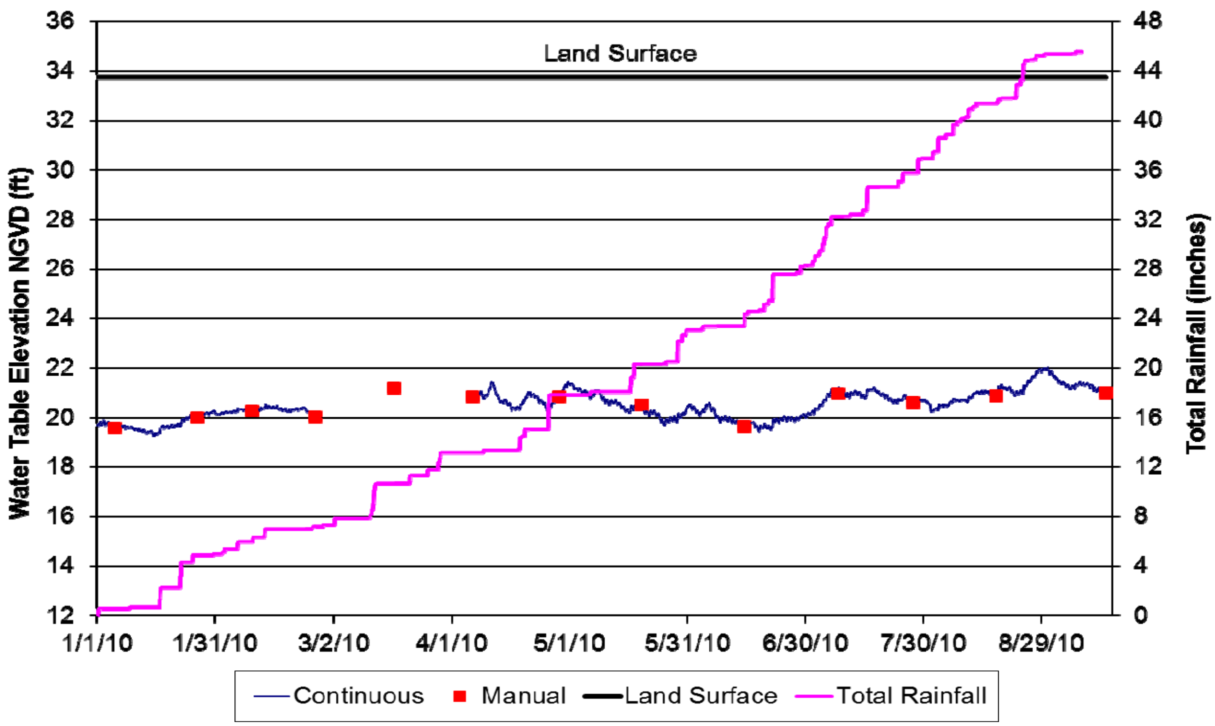

Figure 105. Continuous water-table measurements at FL-02 with manual measurements and total rainfall for 2010.

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 respectively and finished in limestone, the water elevations in all three wells match. Figure 106 illustrates the correspondence between the water elevations in the three wells. It is therefore believed that all three wells reflect water elevations in the Floridan Aquifer.

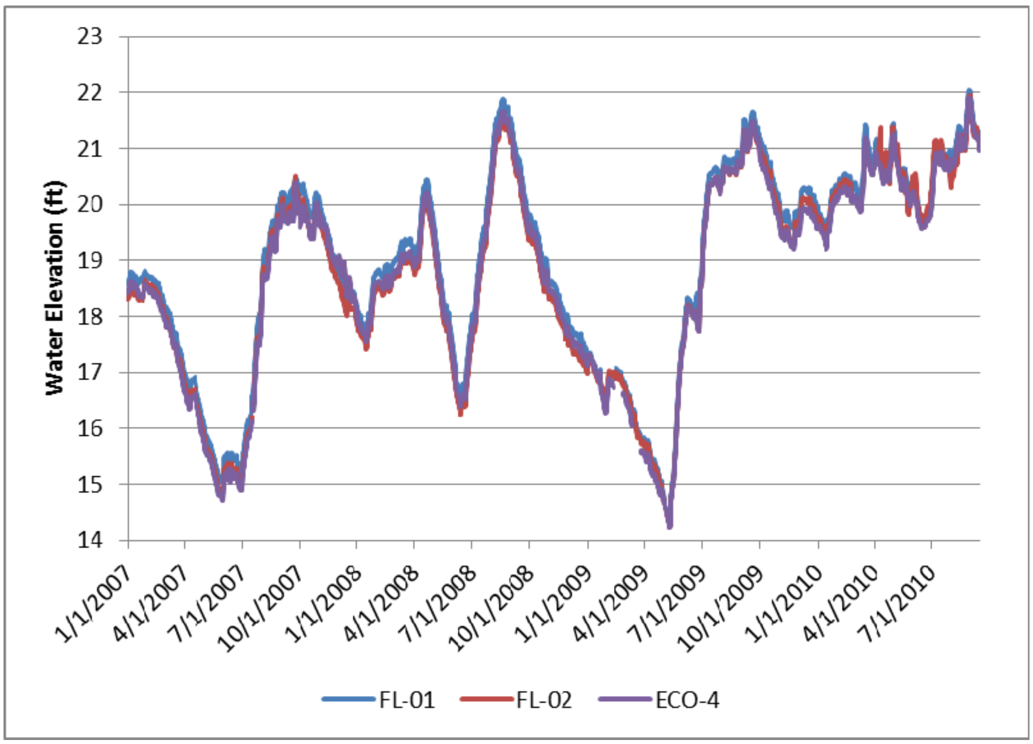

Figure 106. Water elevation comparison between FL-1, FL-2 and ECO-4.

A second well was manually installed at the ECO-6 location to a depth of approximately four feet. This well was 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. Figures 107-109 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 2008 and 2009, there were numerous possible air-pressurization events, visible where the pink line exceeds the blue line in response to rainfall events. During 2010, the water table was closer to the land surface resulting in fewer opportunities for pressurization.

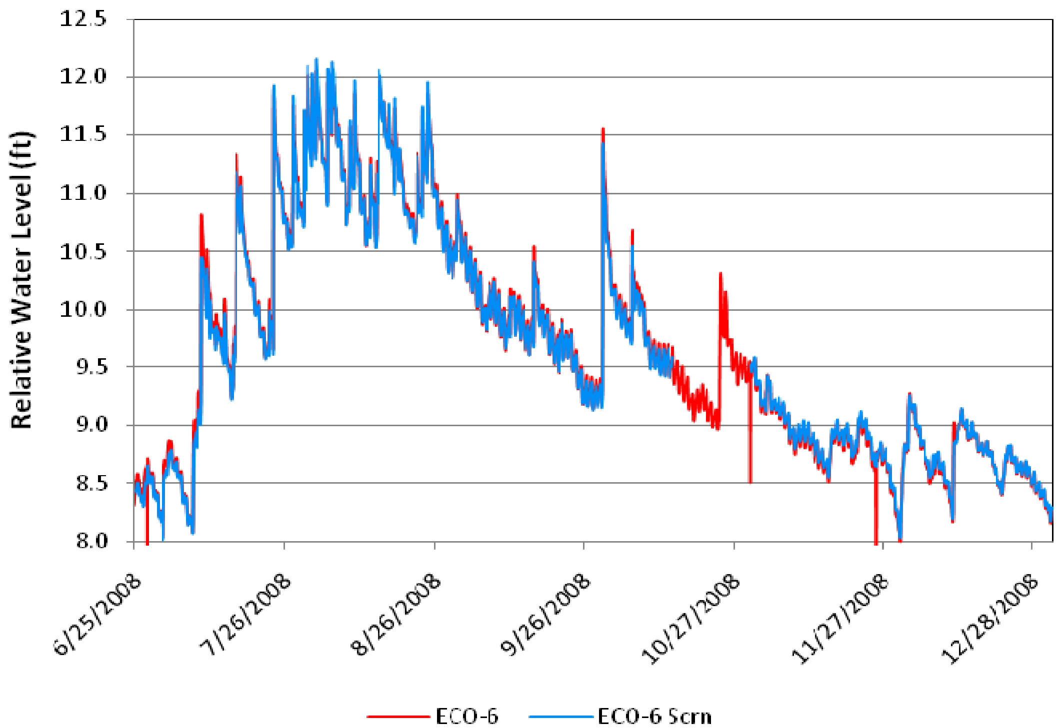

Figure 107. Water elevations at the ECO-6 wells illustrating possible air pressurization events for 2008.

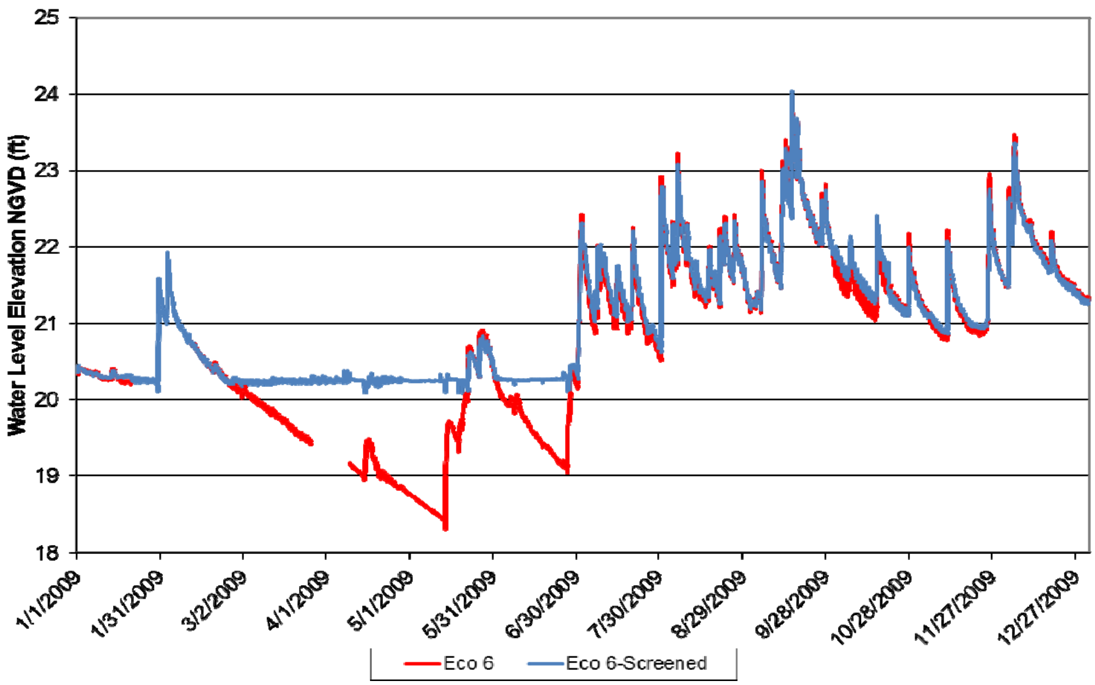

Figure 108. Water elevations at the ECO-6 wells illustrating possible air pressurization events for 2009.

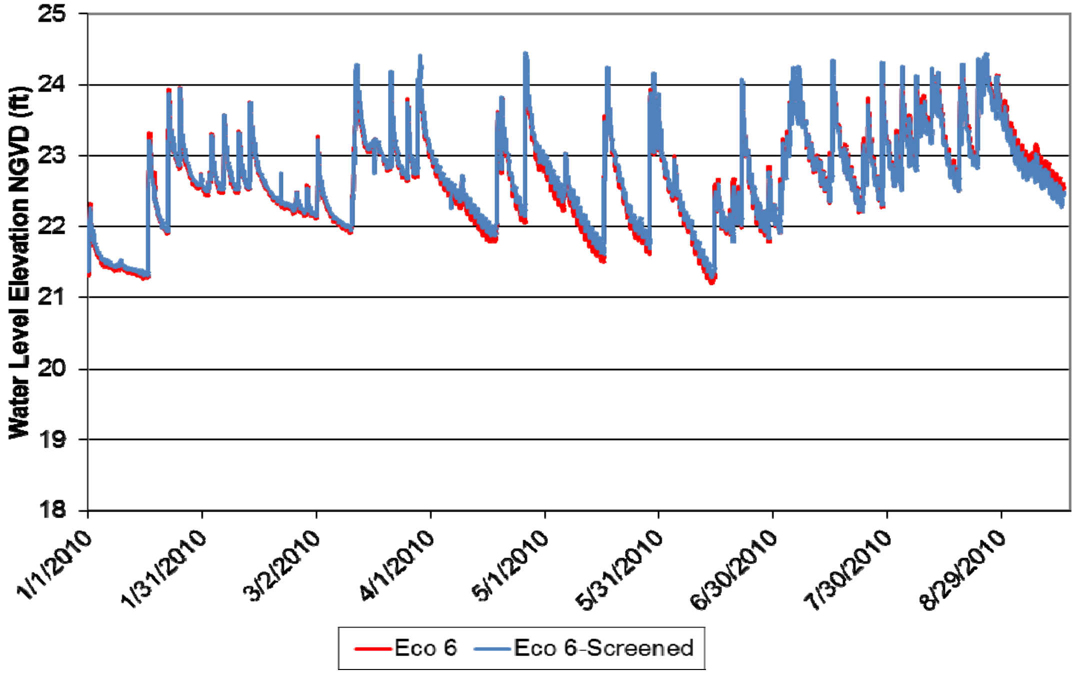

Figure 109. Water elevations at the ECO-6 wells illustrating possible air pressurization events for 2010.

Recharge

Antecedent soil moisture conditions, depth to the water table, root zone depth and post-event rainfall/ET deficit all play a role in aquifer recharge. Figure 110 displays the position of the water table and timing of rainfall events during the first quarter of 2008 at ECO-3, a deep water-table environment (depth to the water table varied between 12 and 16 feet). The water table is seen to make a gradual decline through most of the period despite several rainfall events. For example, the largest event, on January 23, of 1.65 inches had almost no effect on the rate of decline of the water table (Figure 110). In fact, none of the rainfall events, including six of approximately one inch, 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. This increased the water content of the vadose zone while preventing recharge from reaching the water table. The phenomenon is known as vadose zone recharge (Shah and Ross, 2007). The total rainfall recorded during this quarter was 9.06 inches and the net decline in the water table was 0.45 feet.

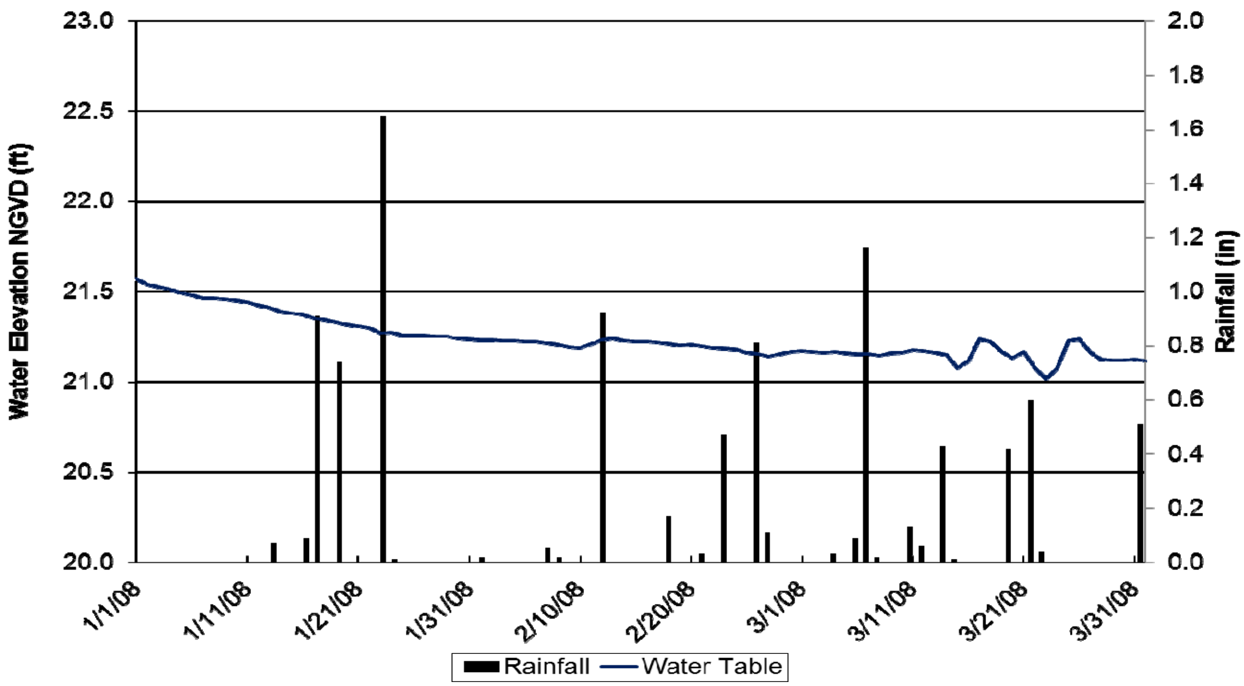

Figure 110. Water-table elevation at ECO-3 and rainfall events during quarter 1 2008.

Figure 111 displays the position of the water table and timing of rainfall events during the first quarter of 2009 at ECO-3. 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. None of the rainfall events made any appreciable change to the rate of the water-table decline. The soil in the vadose zone was again sufficiently dry to prevent 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.

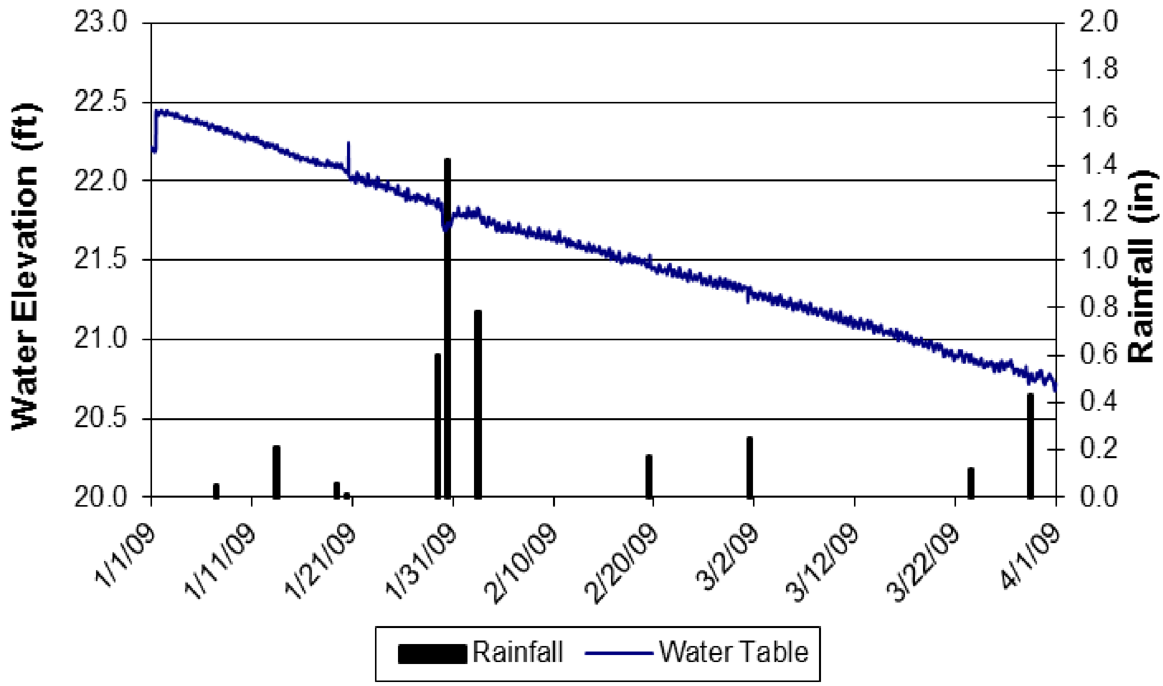

Figure 111. Water-table elevation at ECO-3 and rainfall events during quarter 1 2009.

During the summer period from June 1st through August 31st 2008, the water table slope transitioned from declining to increasing (Figure 112). The decline of the water table ceased on July 8th following a 2.20 inch rainfall event. Following several smaller rainfall events, the soil moisture in the vadose zone became sufficient to permit recharge to the water table. On July 11th the first increase in water table occurred (0.02 feet) following a 0.25 inch rainfall. From June 1st through July 10th, a total of 10.48 inches of rainfall were recorded at the site and the water table experienced a net decline of 0.83 feet. From July 11th through August 31st, 15.40 inches of rainfall were recorded and the water table experienced a net increase of 4.29 feet. The entire rise in the water table during this period took place in the second half of the period.

During the wetter summer quarter of 2009 (June 1st through August 31st), following an exceptionally wet May, the water table slope also transitioned from declining to increasing (Figure 113). The larger June events beginning June 29 resulted in recharge over the month of July. Between June 1st and June 22nd, 1.08 inches of total rainfall fell recharging the upper vadose zone but not affecting the lower soil moisture sensors. The water table increase observed by the end of June of 0.6 feet was mostly due to the rainfall received in May. The total rainfall from June 1st to September 1st was 18.07 inches and the water table ultimately rose 3.47 feet. The increase in the elevation of the water table in 2009 occurred over the entire quarter 3 period.

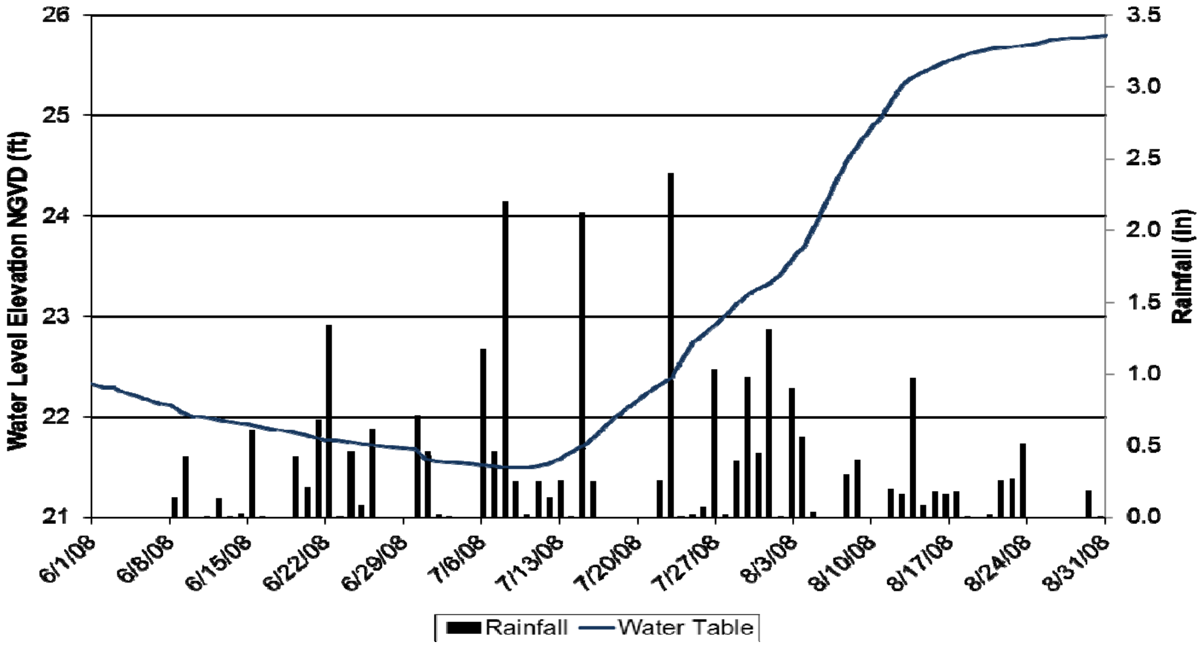

Figure 112. Water-table elevation at ECO-3 and rainfall events during quarter 3 2008. Land surface at ECO-3 is 37 feet.

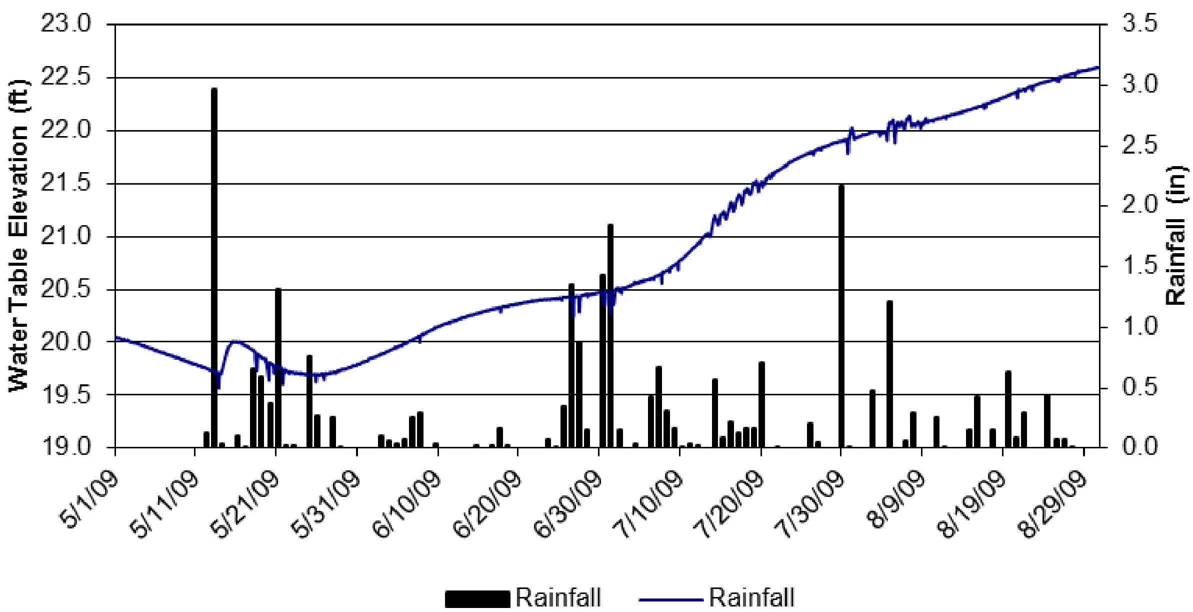

Figure 113. Water-table elevation at ECO-3 and rainfall events during quarter 3 2009.

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 July 16th to July 22nd 2008 and from June 10th through June 15th 2009 in the absence of almost any rainfall. There is a delay between the time rainfall strikes the land surface and the time recharge arrives at the water table. The deeper the water table, the longer the delay; and, the deeper the root zone the more opportunity there is to intercept a percolating wetting front by plant ET demand.

Figure 114 illustrates this effect for May to September of 2009. The figure is similar to Figure 113 but replaces rainfall with percent soil moisture content at a depth of 6.25 feet. Land surface elevation at ECO-3 is 37 feet. The decline of the water table in May ceased briefly following a 3 inch event on May 13th. While the bottom soil moisture sensor (see Figure 114) showed responses on May 14th indicating percolation to that depth, the immediate rise in the water table which began prior to the response of the bottom sensor indicates that air entrapment was a significant and possibly the only factor that caused the water table to rise. The 3" event was sufficient to recharge the vadose zone to a moisture condition that allowed subsequent rainfall events to recharge the water table. The rainfall events starting on May 18th have been shown through soil moisture observations at the lowest sensors and modeling analysis to produce the recharge that occurs during the entire month of June. The larger June events commencing on June 29 resulted in recharge over the month of July. There appears to be a 1-week to 1-month delay for infiltration to reach the (4m) 15-foot deep water table depending on antecedent moisture and post-event rainfall/ET deficit.

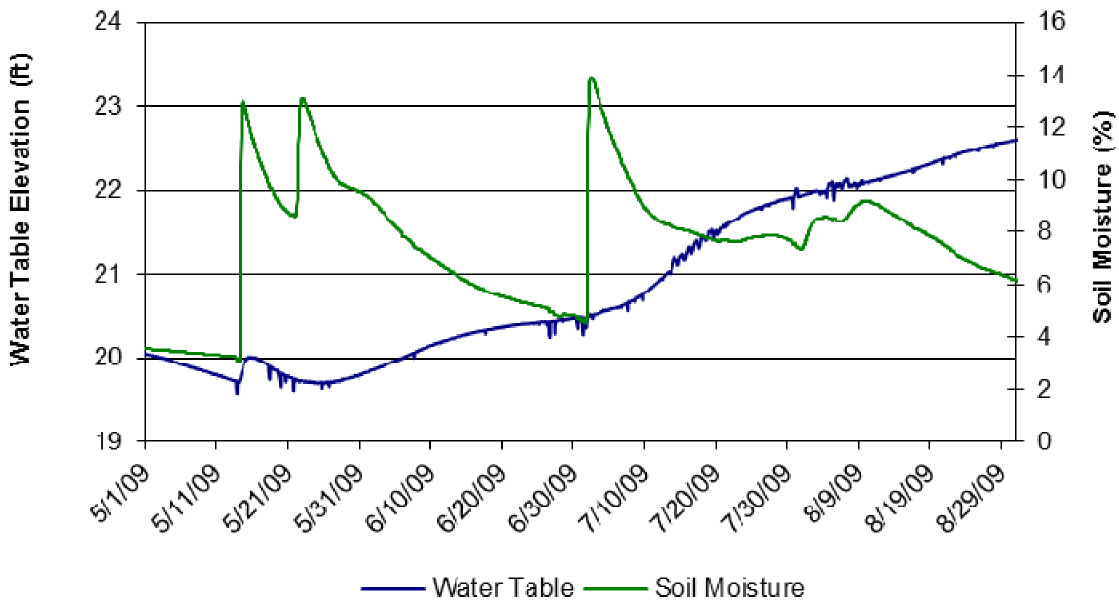

Figure 114. Water-table elevation at ECO-3, and percent soil moisture content at 6.25 feet during quarter 3. Land surface is 37 feet.

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 of 2008 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 115). 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 derive water from the vadose (root uptake) zone; plants at ECO-6, with the help of the capillary fringe, can derive water directly from the water table (phreatophytes). 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.

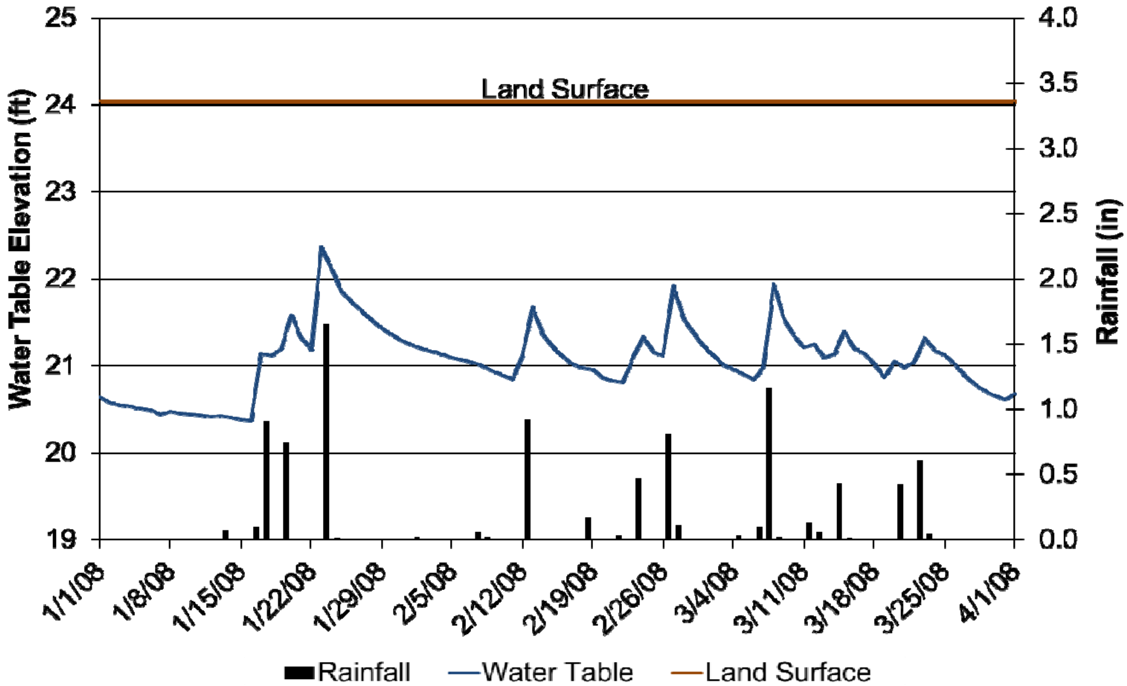

Figure 115. Water-table elevation at ECO-6 and rainfall events during quarter 1 2008.

In the first quarter of 2009, the water table responded in a similar manner (Figure 116). There was less rainfall during this quarter than there was in 2008 and the water table ended the quarter at a lower elevation than it began. Unfortunately, water-table elevation data is missing for the largest rainfall events; however, measurable water-table elevation increases are evident for rainfall events as low as 0.2 to 0.3 inches.

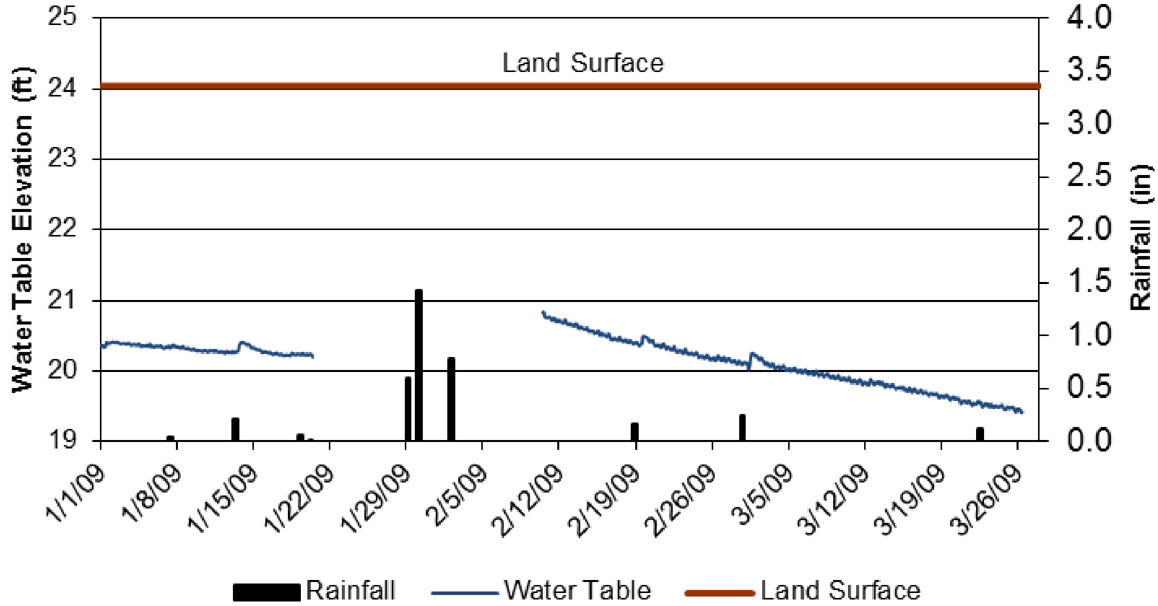

Figure 116. Water-table elevation at ECO-6 and rainfall events during quarter 1 2009.

Figures 117 and 118 illustrate the water-table response to rainfall at ECO-6 during the wet summer quarters of 2008 and 2009. As was evident for previous periods, the water table is seen to respond quickly to rainfall events followed by rapid declines due to ET. During the summer, due to the frequency and intensity of rainfall events, recharge to the water table exceeds ET and the water table rises until it reaches land surface.

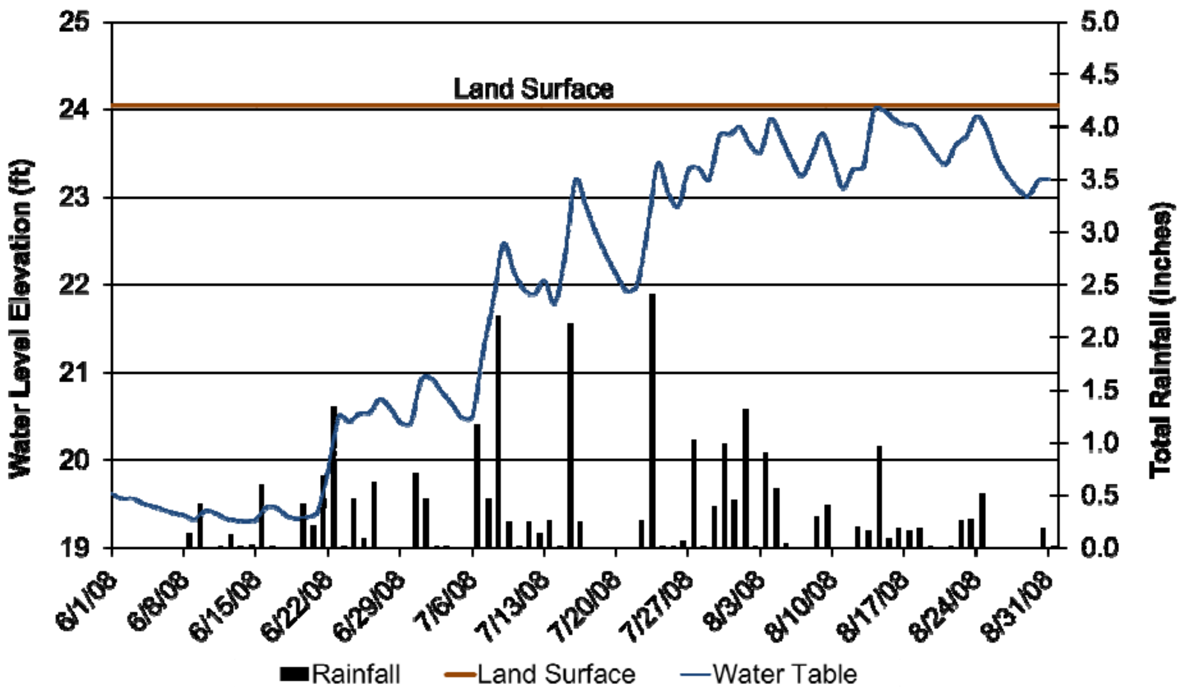

Figure 117. Water-table elevation at ECO-6 and rainfall events during Summer 2008

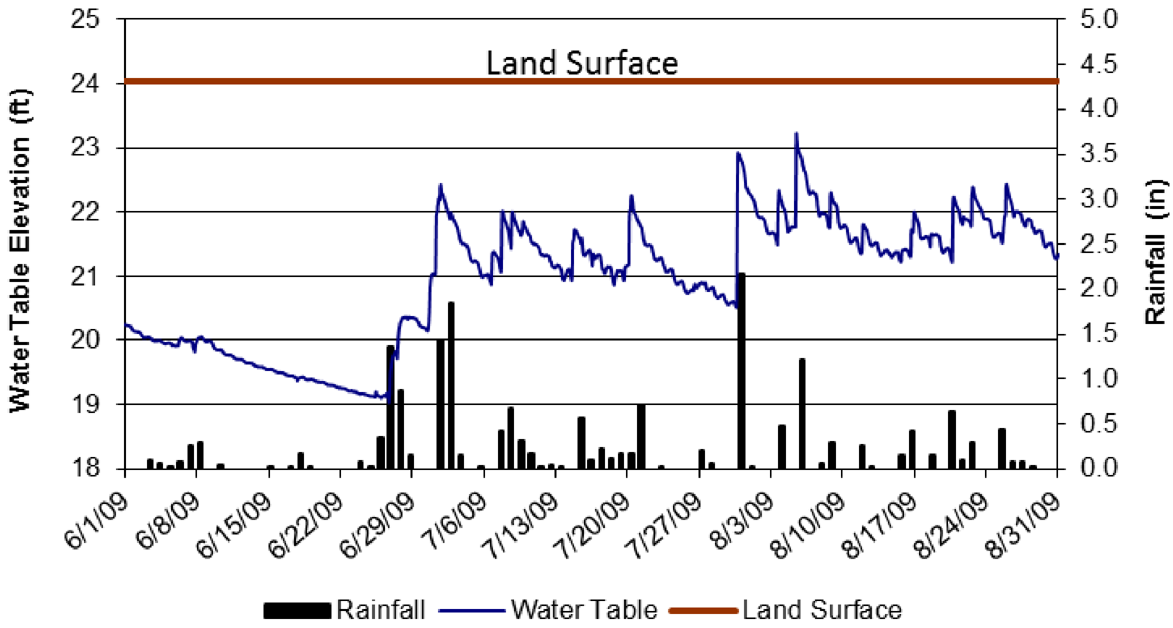

Figure 118. Water-table elevation at ECO-6 and rainfall events during Summer 2009.

Wave Front Propagation

The time of propagation for wetting front movement down through the soil column for two rainfall events was calculated from ECO-3 soil moisture data, water table elevation and rainfall recorded at 10-minute intervals. ECO-3 had eight soil-moisture sensors located at 10, 20, 30, 50, 80, 110, 150, and 190 cm below land surface for monitoring a 2-m deep soil column. The following analyses were made for two events considering the initial and centroid of fluxes:

1. Event A: Dry Antecedent Moisture Condition (5/13/2009)
    a. Propagation of the head of wetting front
    b. Propagation of the centroid of wetting front

2. Event B: Wet Antecedent Moisture Condition (5/21/2009)
    a. Propagation of the head of wetting front
    b. Propagation of the centroid of wetting front

The 10-minute resolution soil-moisture data were observed for two rainfall events to determine the time of propagation of the wetting front and the corresponding rise in the water table signifying a recharge event. The two rainfall events were selected based on antecedent moisture conditions (AMC). During the first event, on 5/13/2009, the soil moisture conditions were considered relatively dry because no significant rainfall events took place during the previous four weeks. The second rainfall event (5/21/2009) occurred one week later when the antecedent moisture conditions were relatively wet.

The wetting front propagation and the soil moisture distribution for a 2.9 inch rainfall event at ECO-3 following a relatively dry period are shown in Figure. 119. Figure 120 shows the wetting front propagation and the moisture distribution for a 1.3 inch rainfall event during a relatively wet period at the same location.

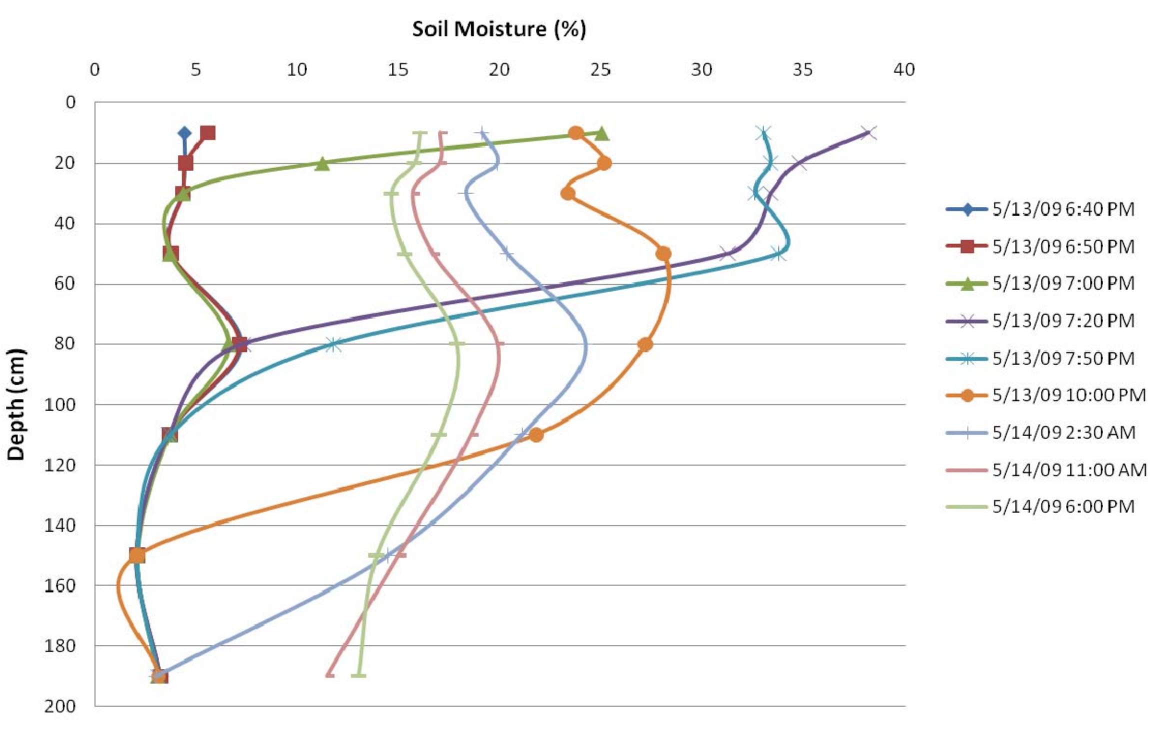

Figure 119. Soil Moisture profiles showing wetting front propagation through a 2 meter soil column before and after a 2.9 inch rainfall at ECO-3 (event A: Dry AMC).

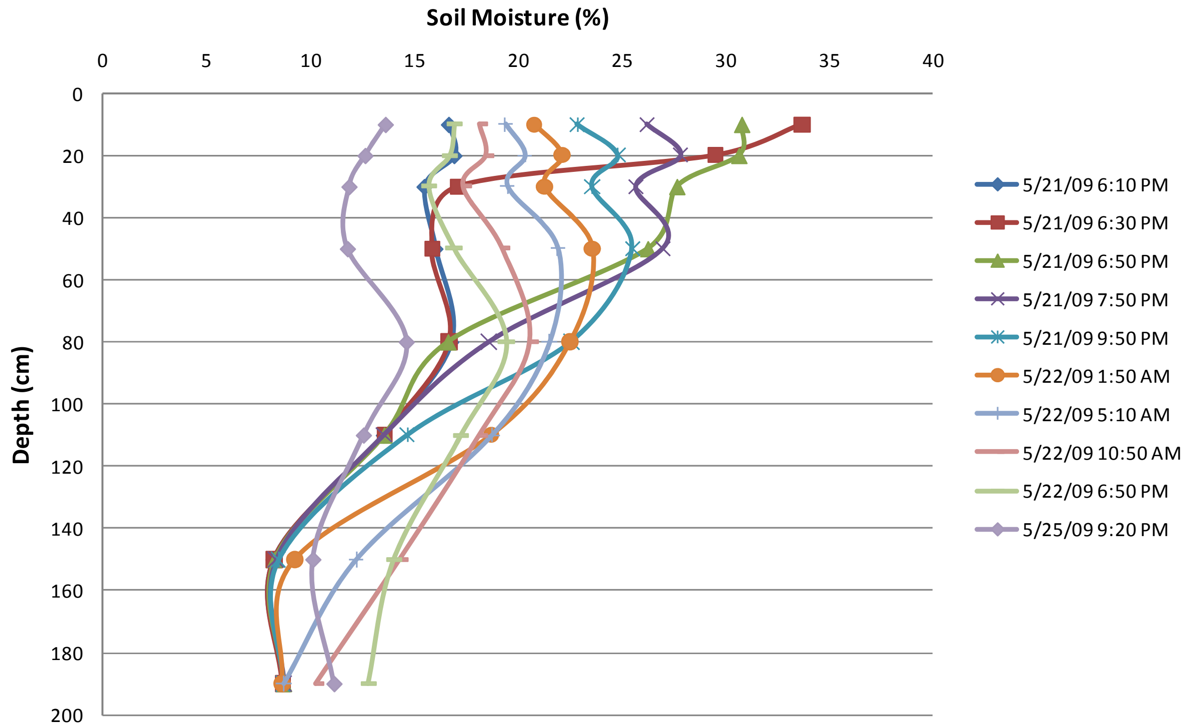

Figure 120. Soil Moisture profiles showing wetting front propagation through a 2 meter soil column before and after a 1.3 inch rainfall at ECO-3 (event B: Wet AMC).

The time of propagation of the centroid of the wetting front and the approaching head of the wetting front for event A (dry AMC) and event B (wet AMC) is summarized in Table 3 and illustrated in Figure 121. It took more than 12 hours for the leading edge of the wetting front to travel 2 m into the soil for event A and, for event B, approximately 17 hours. Event A (dry AMC) was much larger than event B (wet AMC), possibly contributing to the increased time needed for the wetting front of event B to penetrate 2 m. However, as noted previously, it took many days to several weeks for the bulk of the recharge to fully reach the water table for both events.

Table 3. Summary of Wetting Front Propagation Time.

	Wetting Front (Dry AMC, Event A)		Wetting Front (Wet AMC, Event B)	
Depth below land surface	Centroid timing (hr)	Approaching-front timing (hr)	Centroid timing (hr)	Approaching-front timing (hr)
10	0.70	0.33	1.00	0.33
20	0.75	0.50	1.00	0.83
30	0.83	0.67	1.17	1.00
50	1.00	0.83	1.50	1.00
80	2.00	1.33	5.00	1.83
110	4.17	2.50	10.33	3.33
150	10.67	5.67	18.17	8.33
190	23.83	12.17	32.33	17.00
526.5[a]	998.50	70	807.33	50

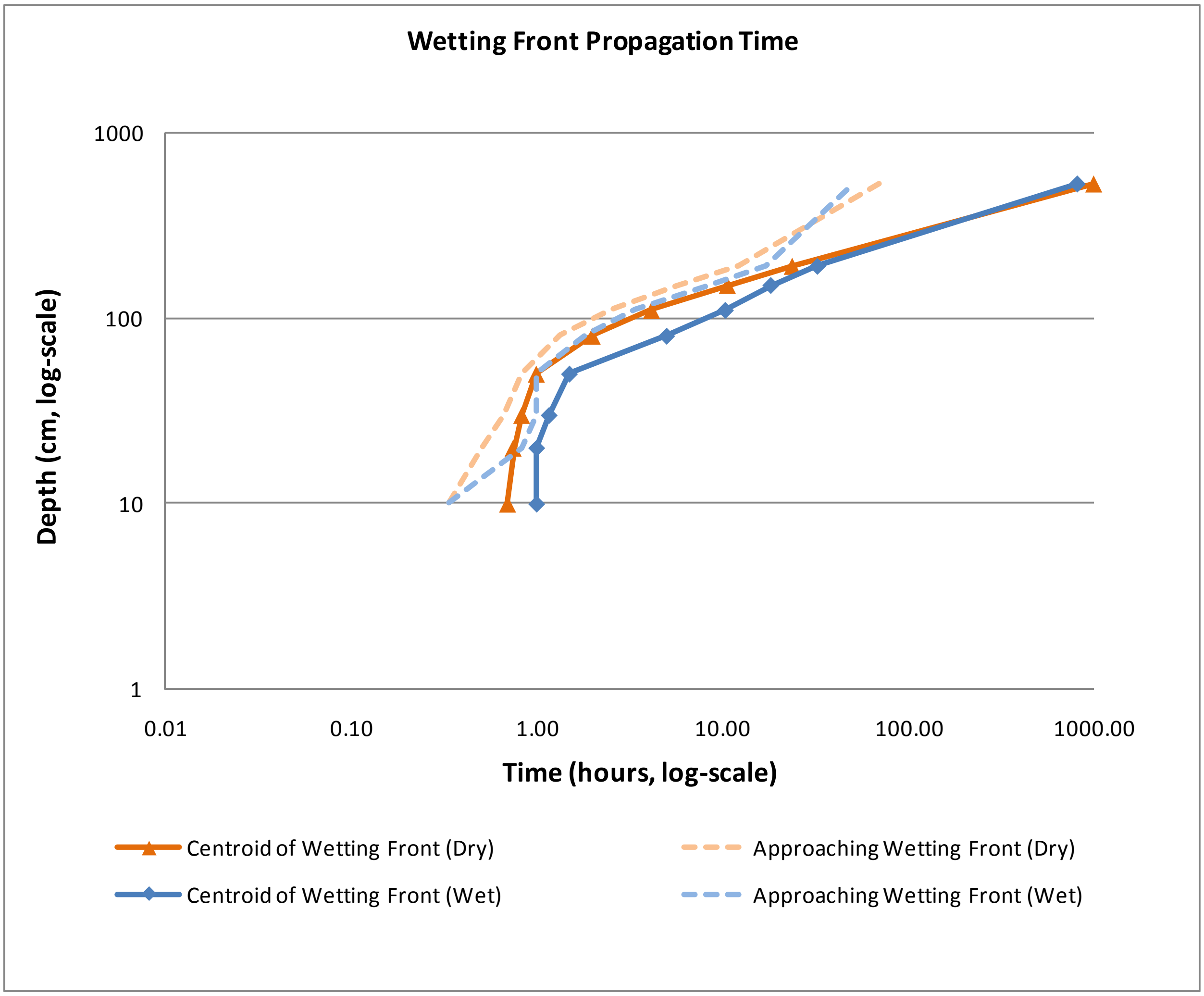

Figure 121. Log-log plot of the time of propagation of wetting front for dry and wet Antecedent Moisture Conditions at ECO-3.

Eco-Area Water Budget Analyses

Water budgets were derived for each measurement station (ECO 1-6) based on rainfall, soil moisture and water table measurements. Soil moisture was 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 (decreases). 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 (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.

Integrated Soil Moisture Water Budget Methodology

Soil moisture sensors were generally placed at 10, 20, 30, 50, 80, 110, 150, and 190 cm depth at each station. Each of the eight sensors determined the soil water content present in the surrounding soil over a range +/- 5 cm. The sensor's observed values were taken every ten minutes and then averaged over every hour. This averaged water content was then converted to inches of water present within the surrounding soil. From this total soil moisture (TSM) value, the differences between successive hourly values were 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 for a rain event to infiltrate through the soil column, it was determined that large increases in TSM are observed on average four hours following small rain events (less than 0.4 inches) and up to 12 hours following larger events. Because of this apparent delay in developing a smooth moisture profile, the 4 and 12 hour periods were used, based on the 0.4" event magnitude threshold, as time intervals following rain events to calculate net event infiltration. Following these periods, hourly changes were used to calculate vertical and ET fluxes in the method described herein.

The first step in determining the water budget was establishing an estimate of the rate at which continuous (very slowly changing) vertical processes occur. This excludes the more rapidly changing daytime ET and any 4- or 12-hour post-event infiltration period. Thus, for net groundwater flux, only the changes in TSM between 12 am and 6 am were used because the ET values are negligible during this period. If a rainfall event occurred during or around this time frame, the change in TSM observed was ignored. The net change over these six hours is averaged and smoothed to arrive at a rate which is applied over the entire day. In order to account for days in which the rate could not be determined due to a rainfall event, the average of the previous day's and the following day's rates was used. Furthermore, in order to ensure a smooth transition in these rates, a 24-hour smoothing of the data was performed. This final smoothed vertical (or groundwater flow) estimates were used for each hour of every day from which daytime ET fluxes and net infiltration fluxes are derived.

In the absence of a rainfall event, ET and groundwater support values were calculated by taking the difference of the hourly change in TSM and the smoothed vertical flow rate calculated for the time step. In the case in which the TSM increases, there was assumed to be groundwater support either by lateral flow, depression storage percolation or a rising 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. Finally, on rare occasions (several times each quarter), random spikes in changes in TSM occur. In order to eliminate erroneous large changes in TSM outside of a rainfall events that are occasionally observed, a maximum negative change of 0.06 inches and maximum positive change of 0.1 inches were used as filter thresholds.

As mentioned previously, a period of 4 or 12 hours, respectively, is used to determine the net increase in TSM due to rainfall infiltration. During a rainfall event, the TSM at both the beginning and end of the 4 (for events < 0.4") or 12 hour period is observed. The differences in TSM over these gaps are used to arrive at the total infiltration for the event. Moreover, in order to calculate the interception evaporation at each site, an average of the differences between an event's total rain amount and the observed infiltration is determined. This difference is the interception capture rate. This rate is then applied to all rainfall events. For those rainfall events which are less than this rate, the total amount of rainfall is considered (and observed for most events) to be completely intercepted. Conversely, for those rainfall events larger than this rate, the calculated interception is set to this maximum rate and net rainfall is the found from the difference.

Surface runoff is also estimated by the comparing the infiltration fluxes and the net rainfall. Potential runoff (rainfall excess) is derived from the difference in net rainfall and infiltration. In order to derive runoff both flowing into and out of a site, a difference between rainfall, calculated interception rate, and the corresponding sensor flux is taken. For cases in which net rainfall exceeds the positive soil moisture change, net runoff leaving the site is calculated. Conversely, for an event where the infiltration flux to the soil exceeds net rainfall, a net inflow of runoff (also probably contributed to by depression storage seepage) entering the site is determined. From these results, a comparison the runoff leaving and entering nearby sites can be made. Net *run-in* occurs when the infiltration flux exceeds the net rainfall overall for the event as is most prevalent in convergent and decreasing slope environments.

For periods in which there are data gaps (equipment or battery failures), a net difference between the TSM for the last collected value and that for the next collected value is taken. This net difference is taken as either infiltration, if positive, or GWET, if negative. Also summed (for overall water balance for the year) are any erroneous changes in TSM that were filtered while calculating groundwater support and GWET. For those rare periods when changes in TSM exceed the maximum or minimum thresholds, values are set to the threshold and the differences are accumulated for overall mass balance budgeting and to assess the magnitude of this error. In arriving at an overall annual water balance, the difference in TSM at both the beginning and end of the year is derived. These changes in storage for the entire year are used to verify either the positive or negative net fluxes for a particular site. The steps used for this analysis are further summarized in Appendix 1.

Figures 122 to 145 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. Rainfall for the period was consistently below average (accumulated rainfall for each year is shown as a blue line in the figures) averaging below 45” for the four year period. Instrument failure and other data gaps are indicated as discontinuous periods in the lines.

Tabulated results for water budgets are included in Tables 4 to 10 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 were filtered and, for complete mass balance closure, were accumulated. The results are tabulated to evaluate their magnitude. Note, there was some missing data in the record for stations ECO 1, ECO-2, and ECO-5 which should be considered when discussing results for these stations.

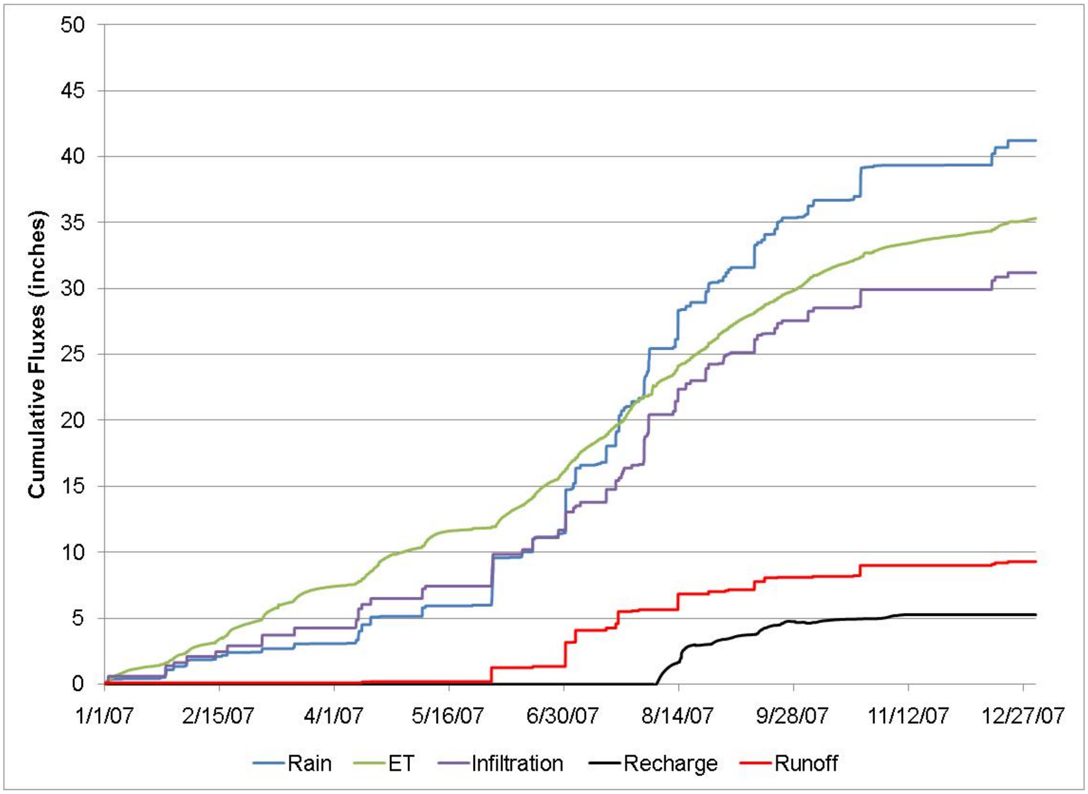

Figure 122. Eco 1 Observed Water Balance for 2007.

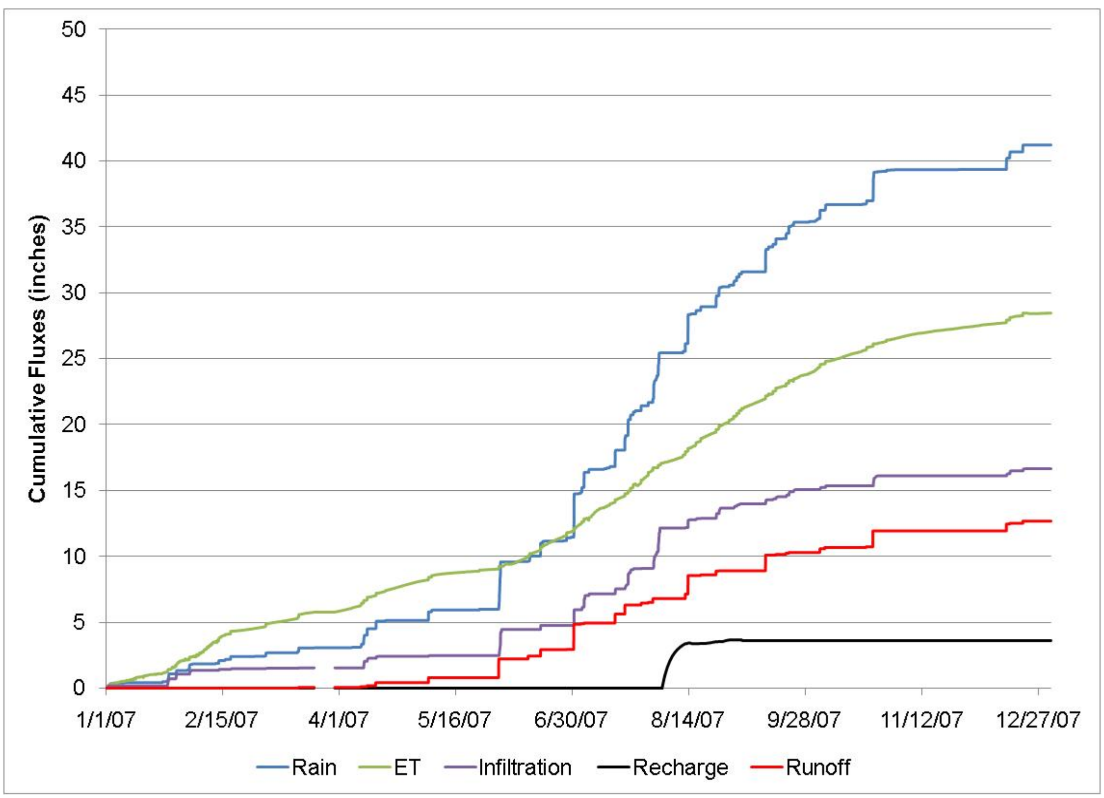

Figure 123. Eco 2 Observed Water Balance for 2007.

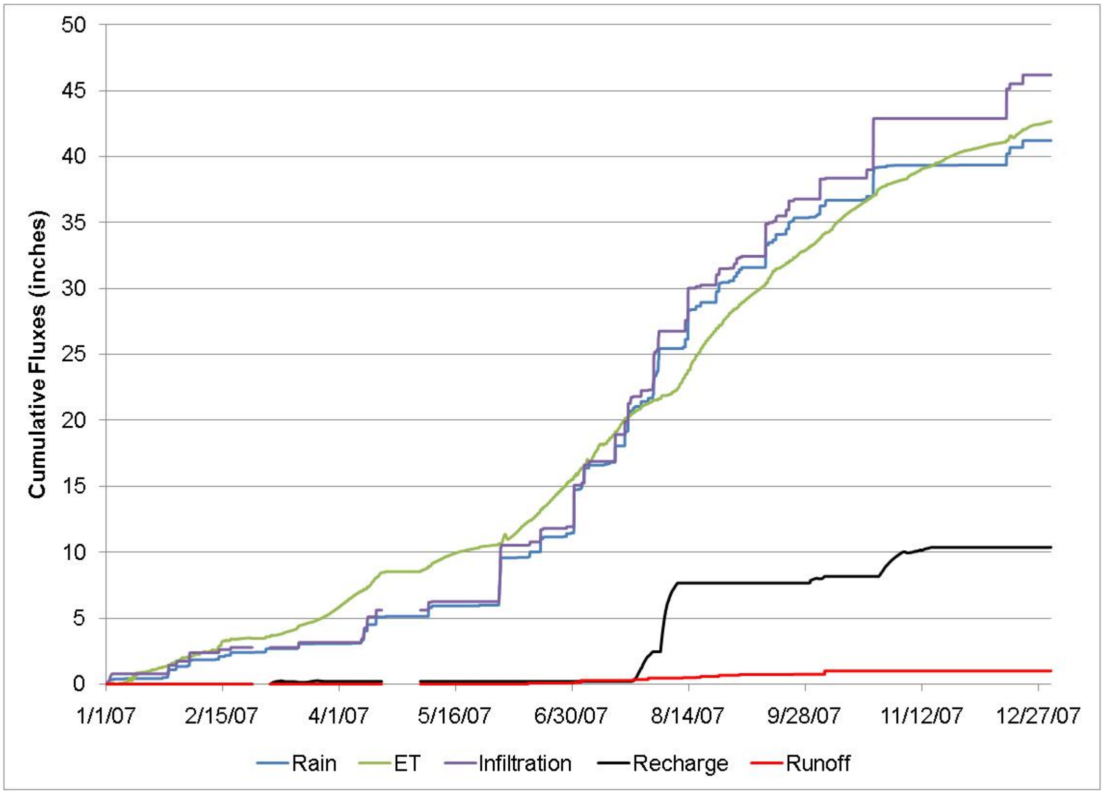

Figure 124. Eco 3 Observed Water Balance for 2007.

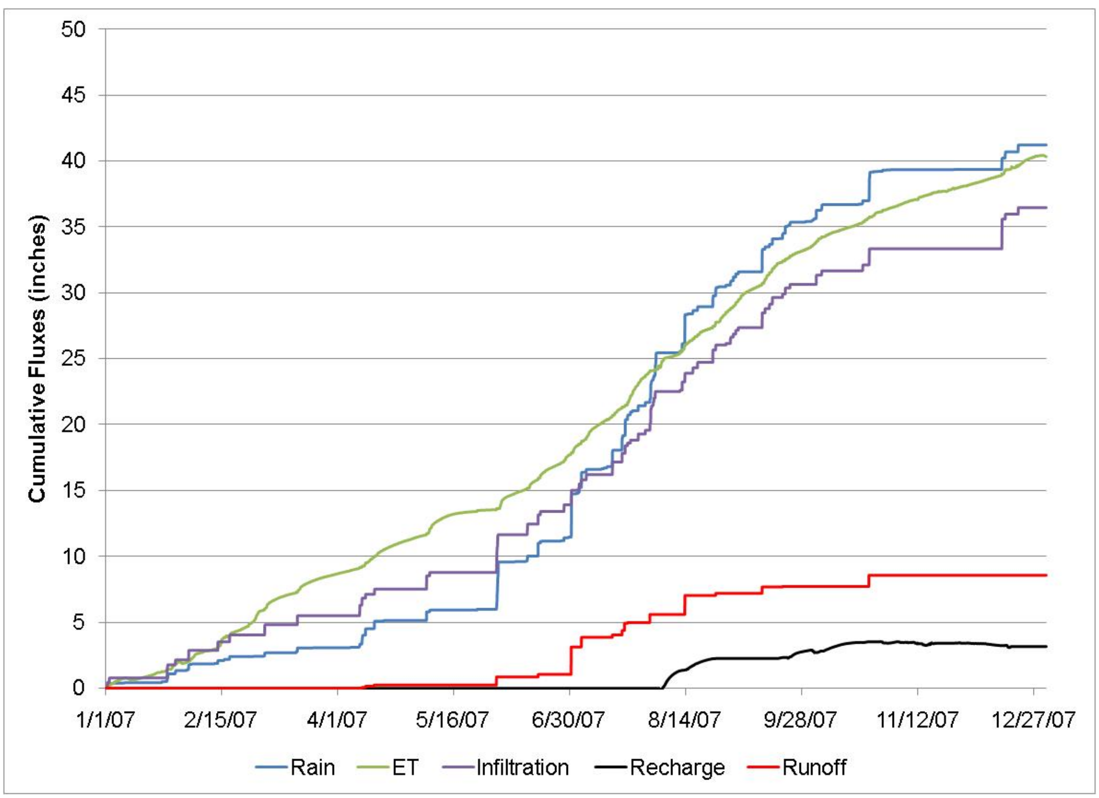

Figure 125. Eco 4 Observed Water Balance for 2007.

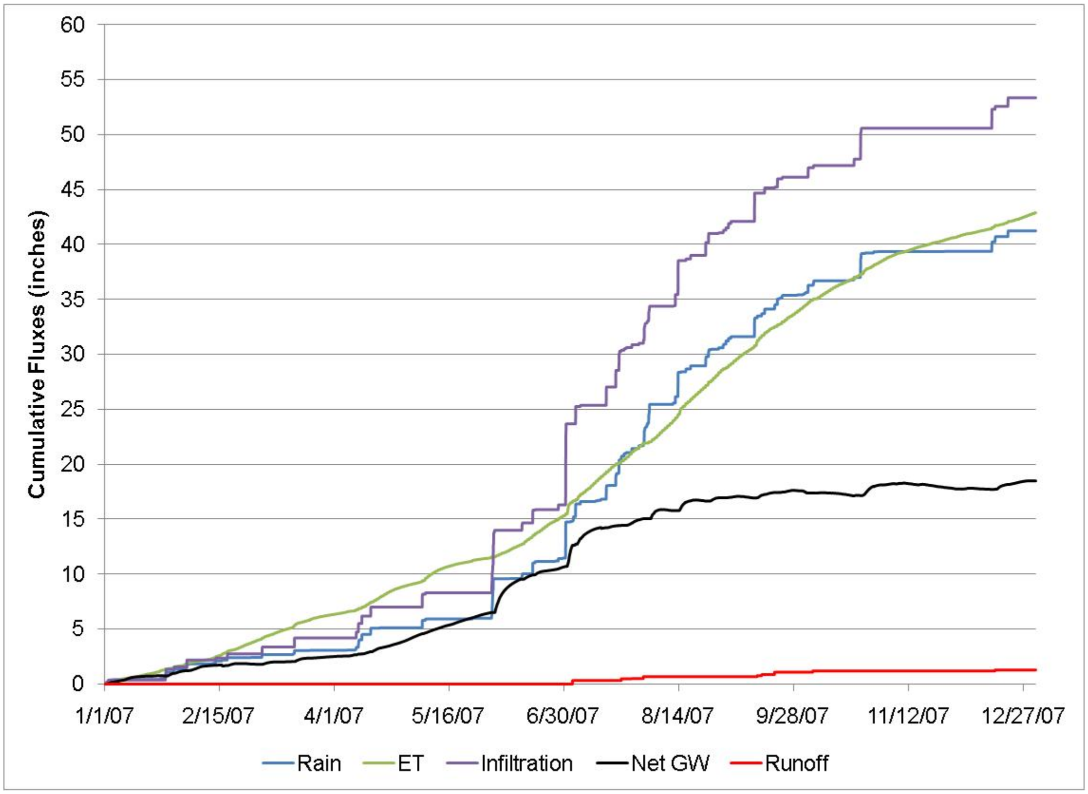

Figure 126. Eco 5 Observed Water Balance for 2007.

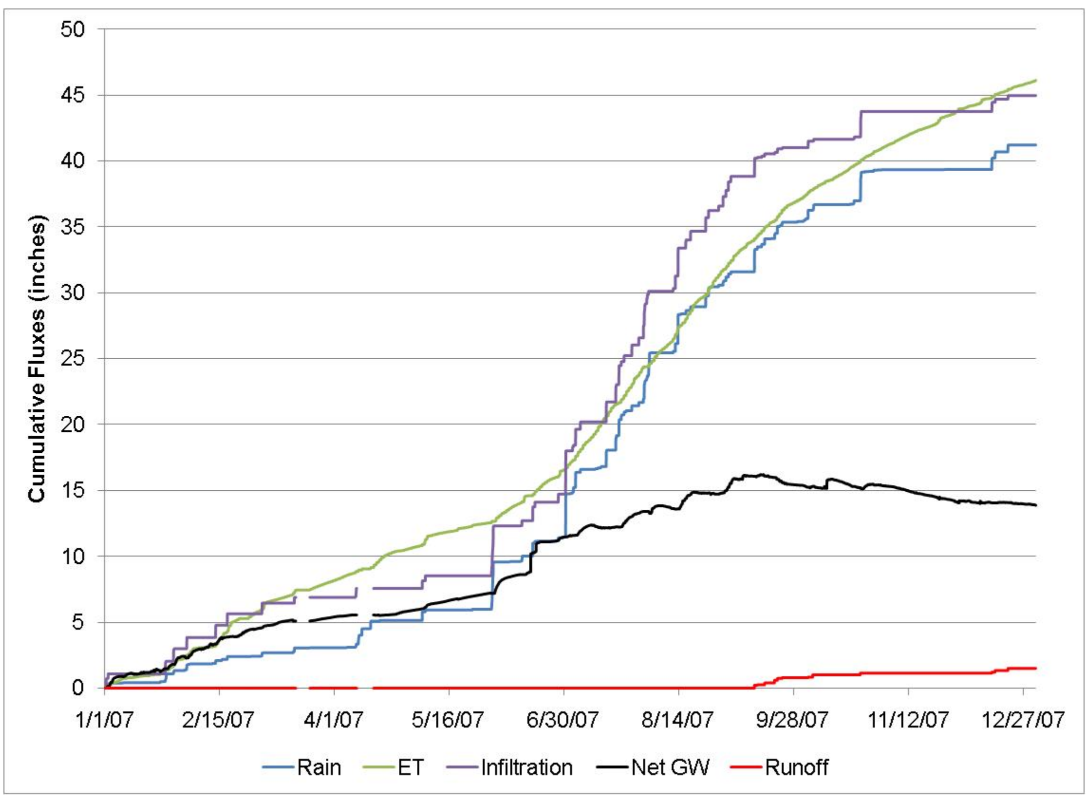

Figure 127. Eco 6 Observed Water Balance for 2007.

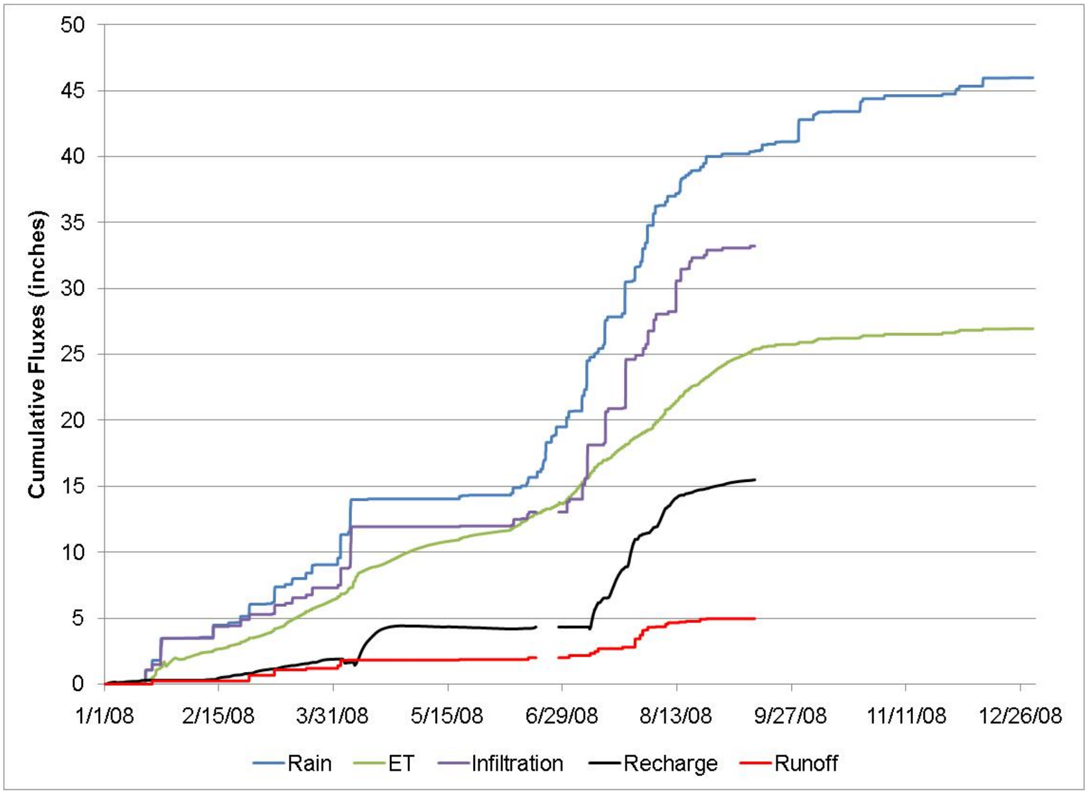

Figure 128. Eco 1 Observed Water Balance for 2008.

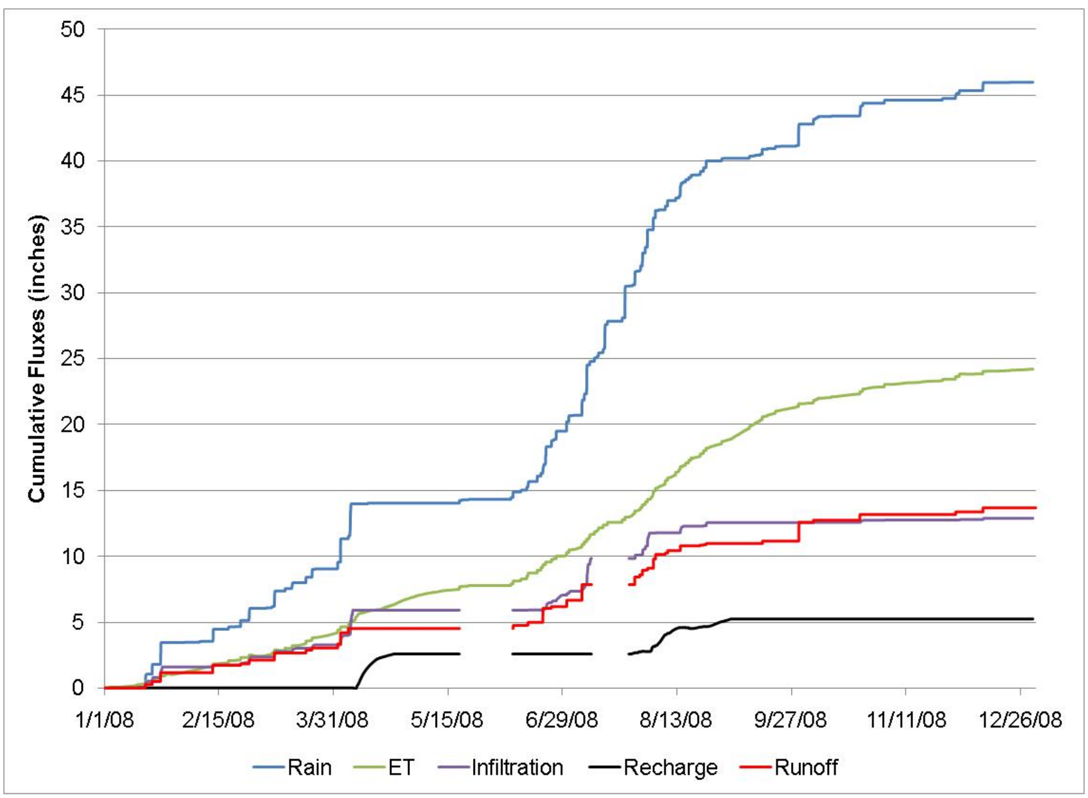

Figure 129. Eco 2 Observed Water Balance for 2008.

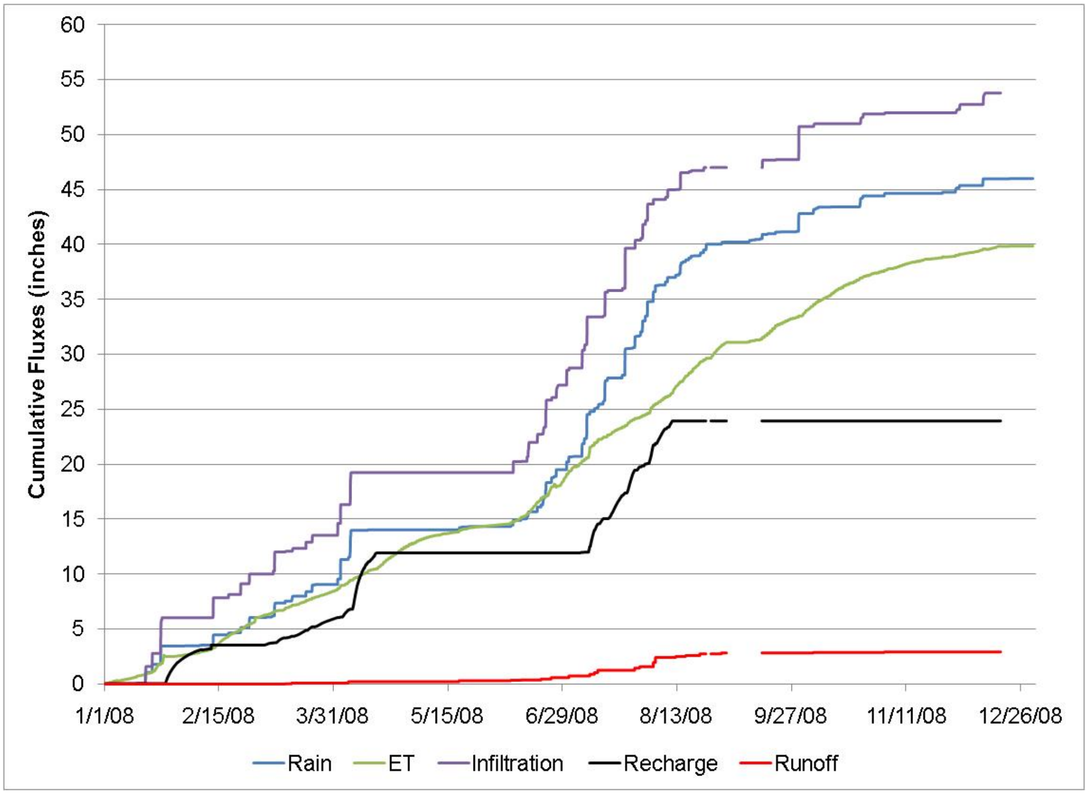

Figure 130. Eco 3 Observed Water Balance for 2008.

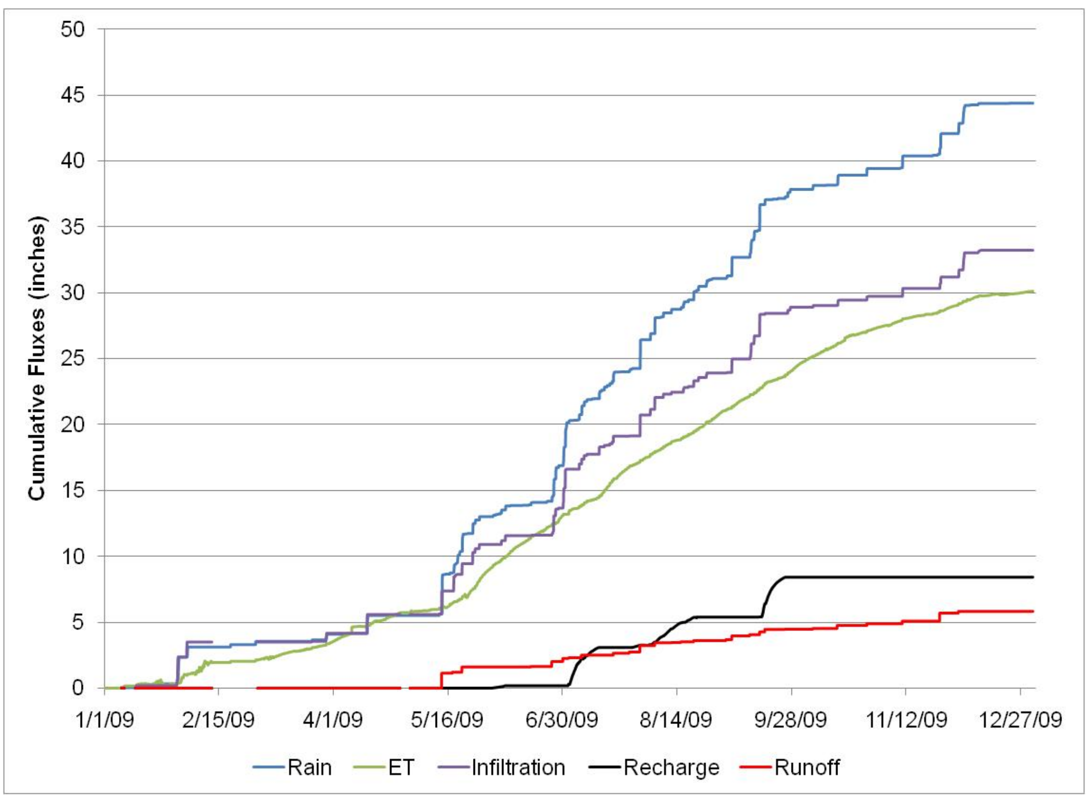

Figure 131. Eco 4 Observed Water Balanced for 2008.

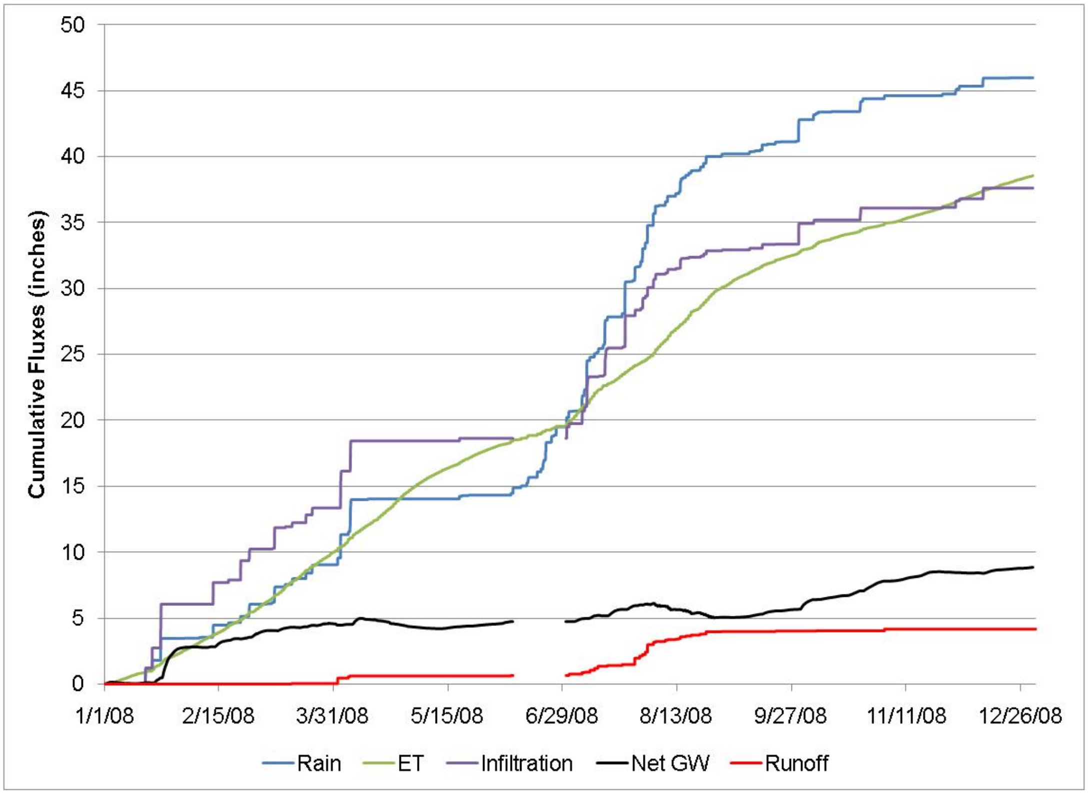

Figure 132. Eco 5 Observed Water Balance for 2008.

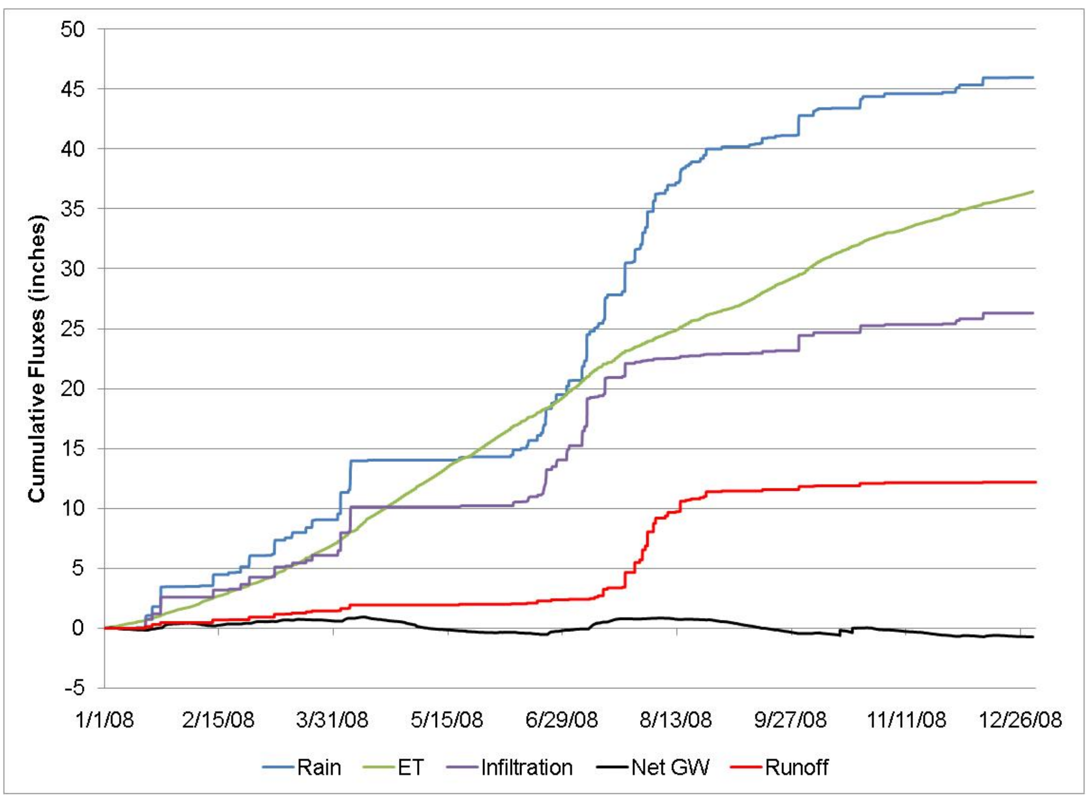

Figure 133. Eco 6 Observed Water Balance for 2008.

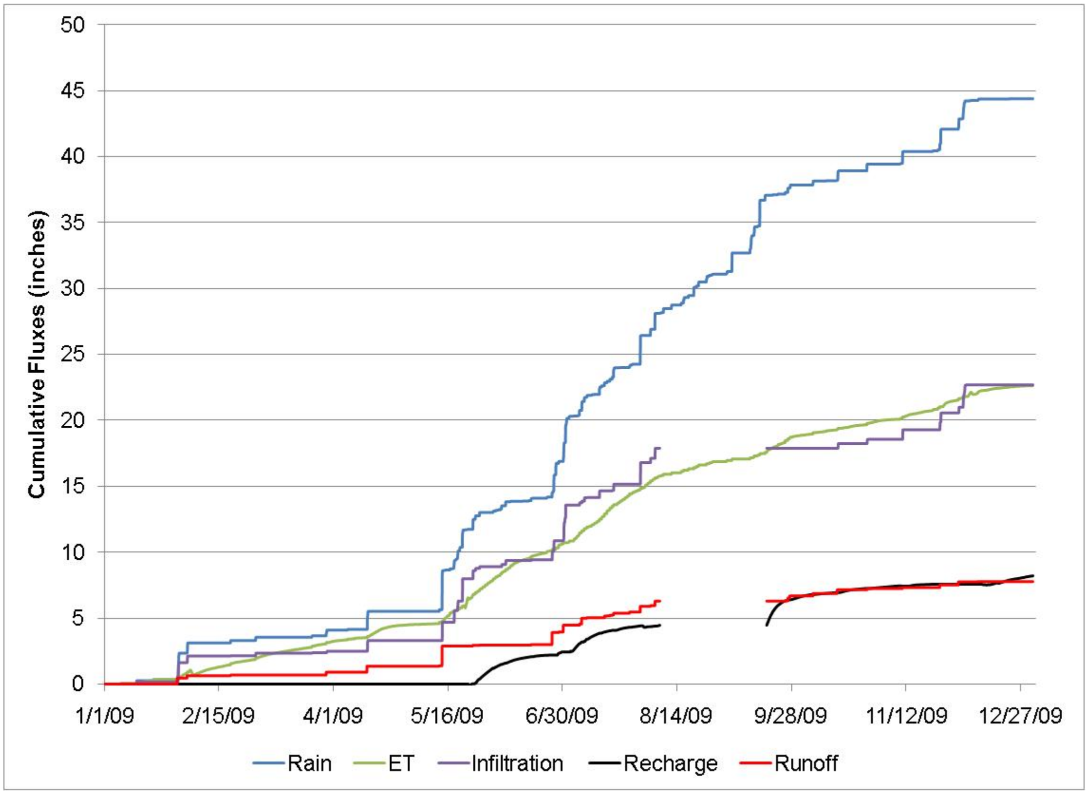

Figure 134. Eco 1 Observed Water Balance for 2009.

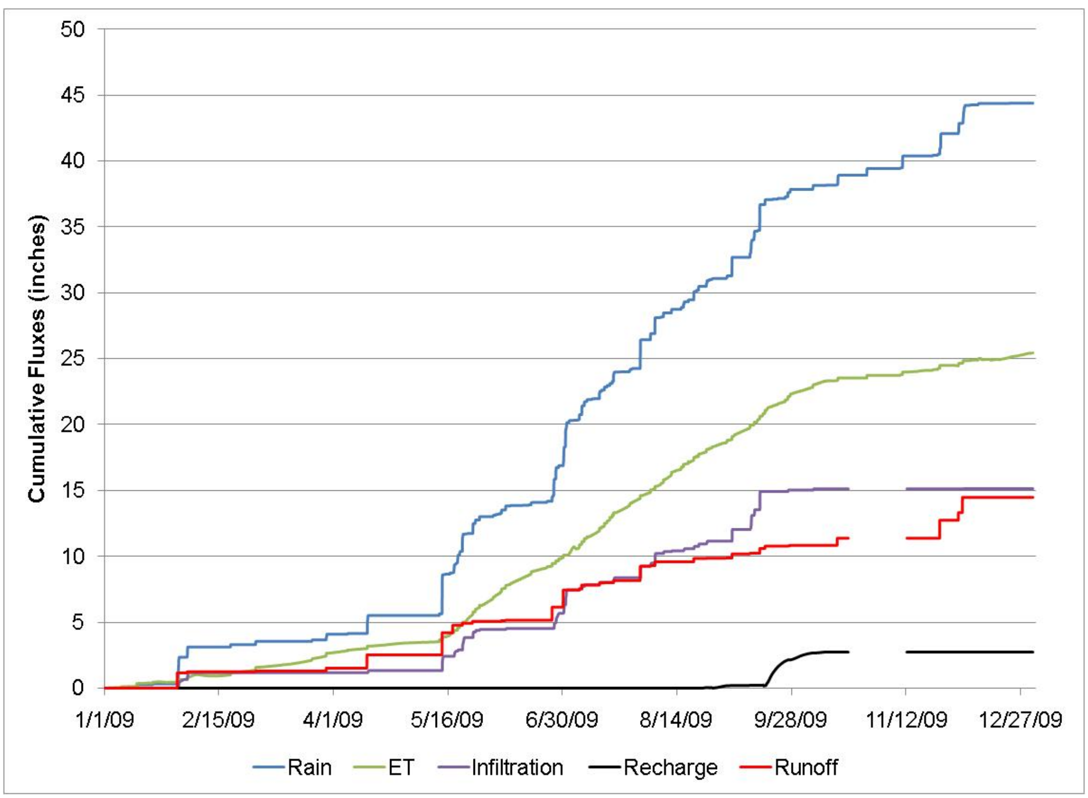

Figure 135. Eco 2 Observed Water Balance for 2009.

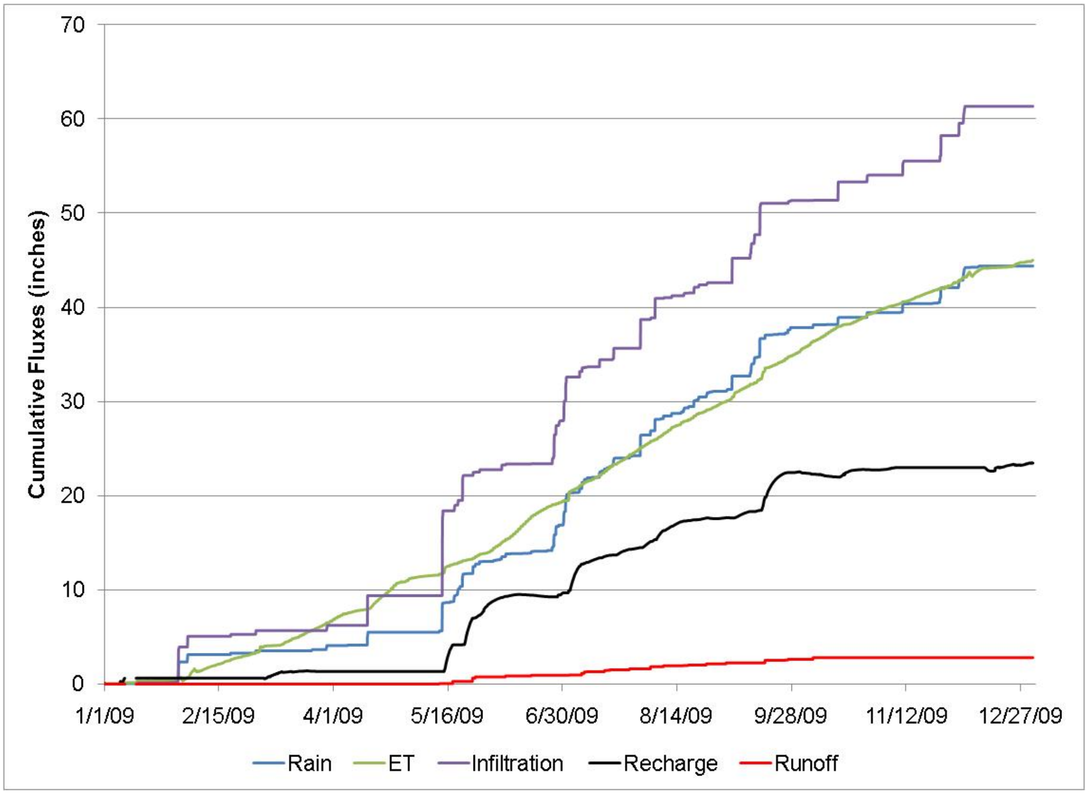

Figure 136. Eco 3 Observed Water Balance for 2009.

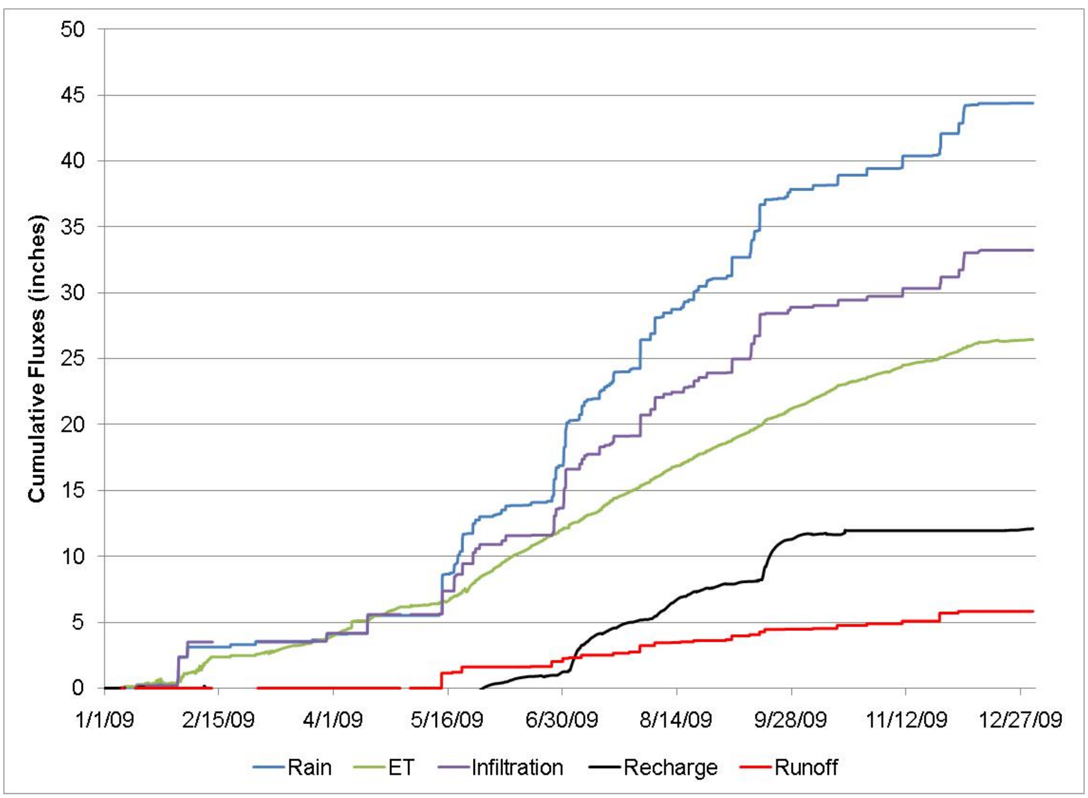

Figure 137. Eco 4 Observed Water Balance for 2009.

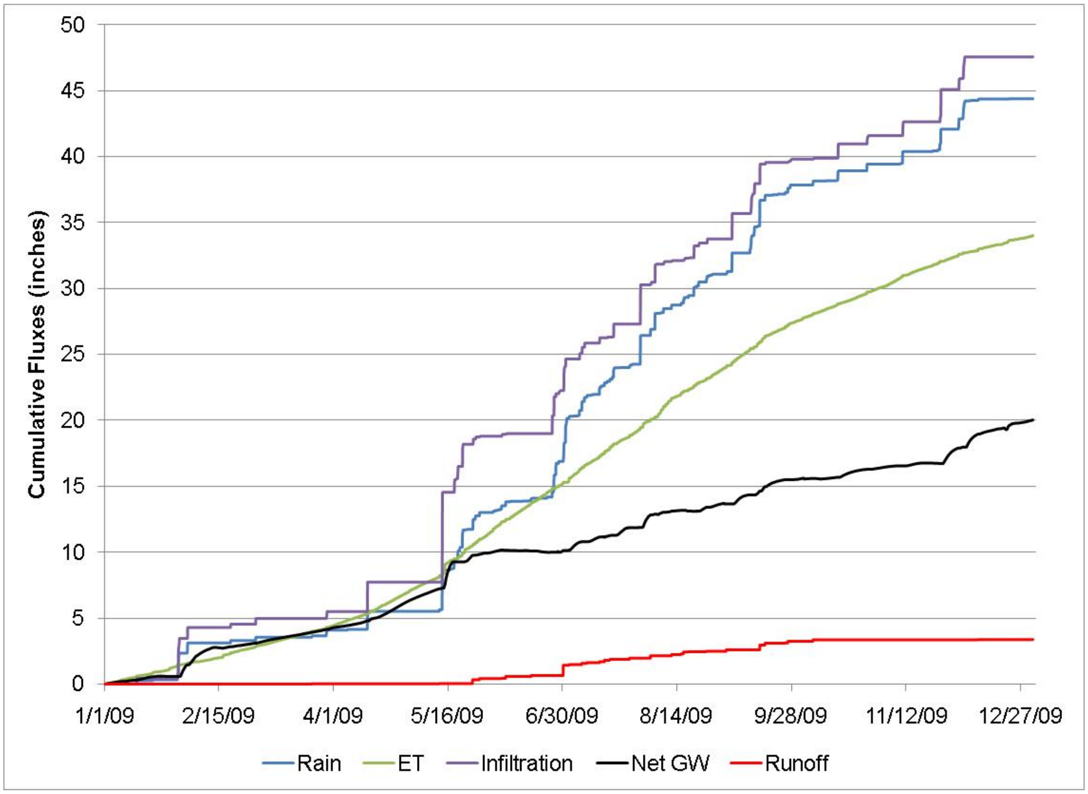

Figure 138. Eco 5 Observed Water Balance for 2009.

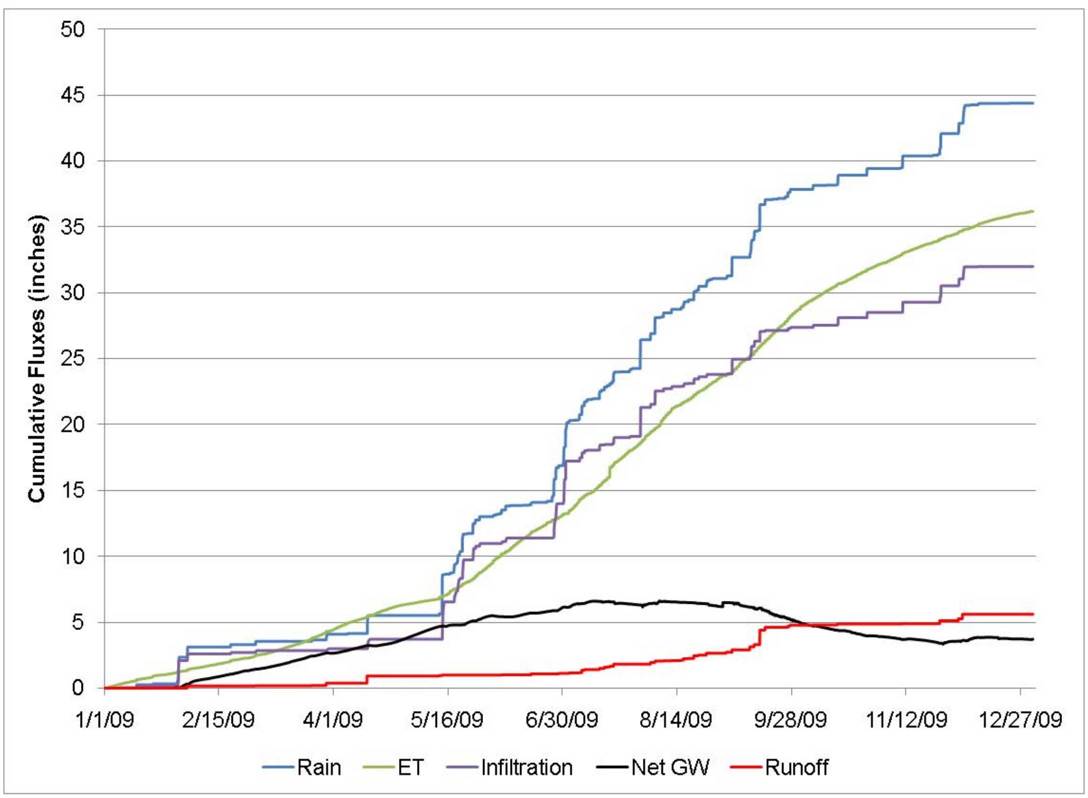

Figure 139. Eco 6 Observed Water Balance for 2009.

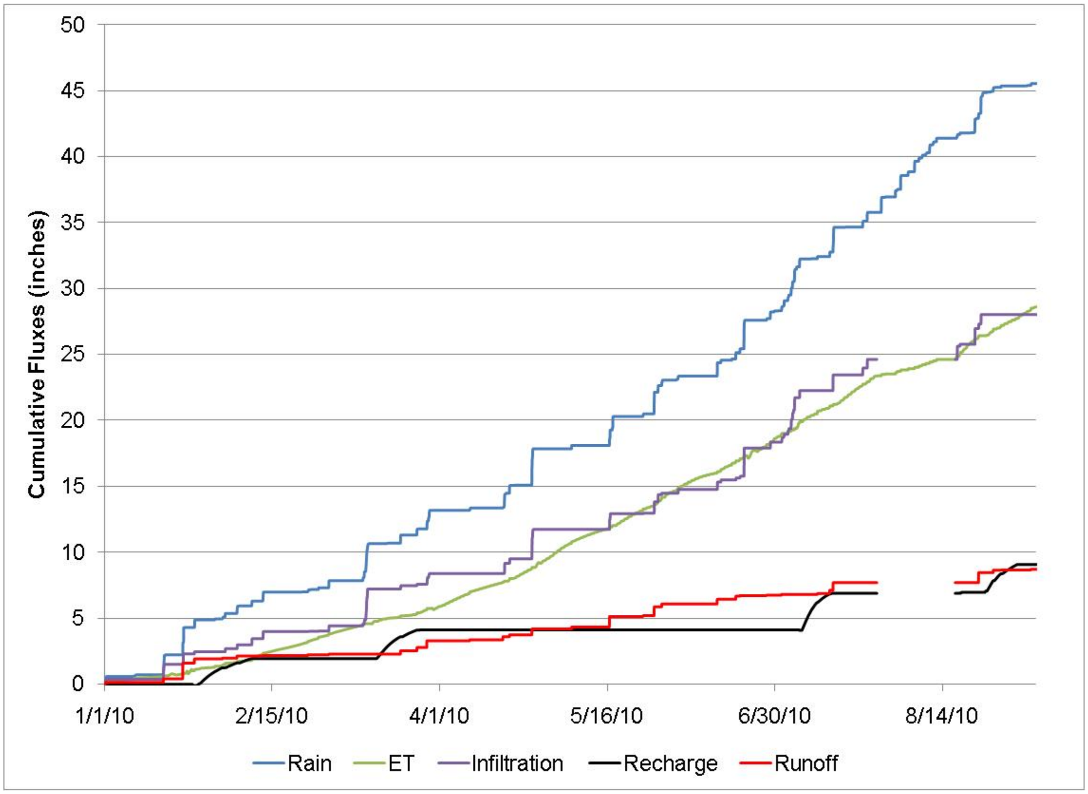

Figure 140. Eco 1 Observed Water Balance for 2010.

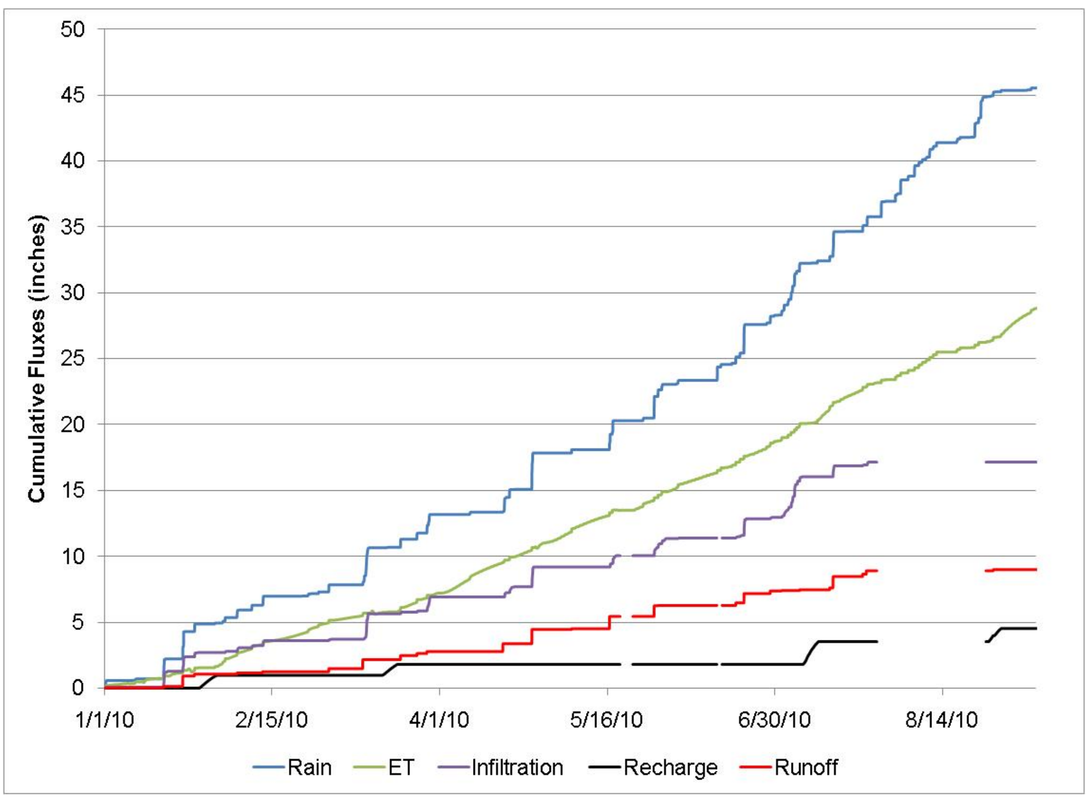

Figure 141. Eco 2 Observed Water Balance for 2010.

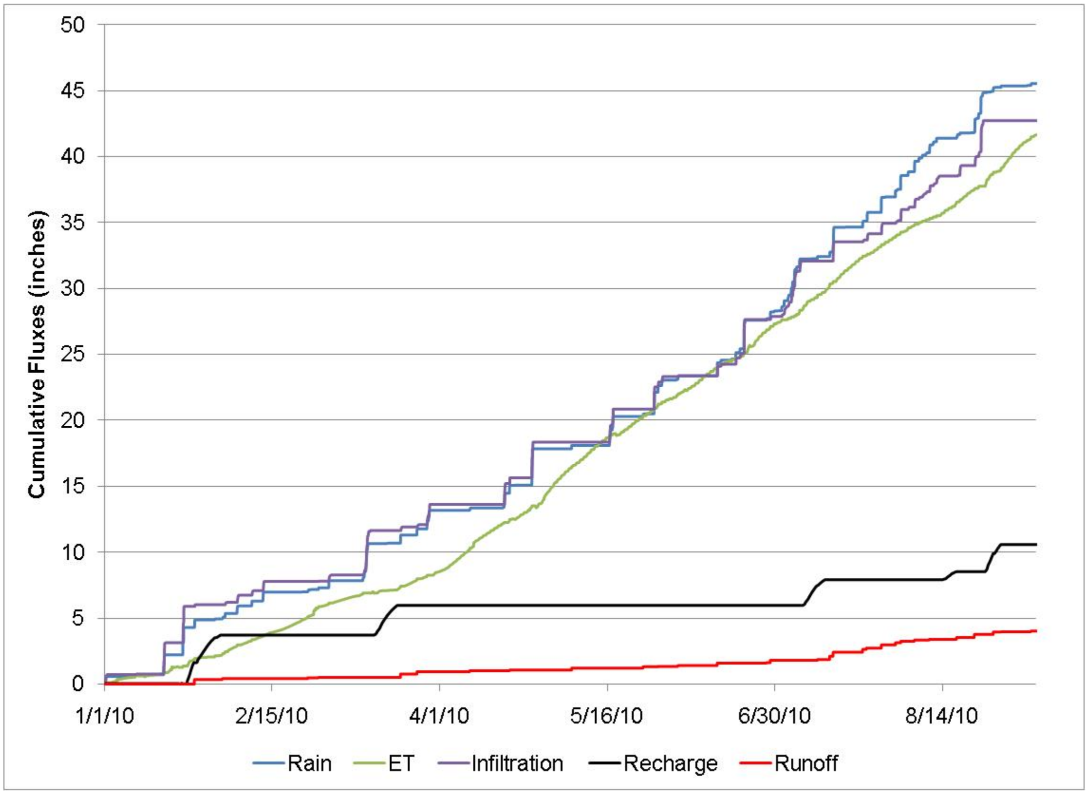

Figure 142. Eco 3 Observed Water Balance for 2010.

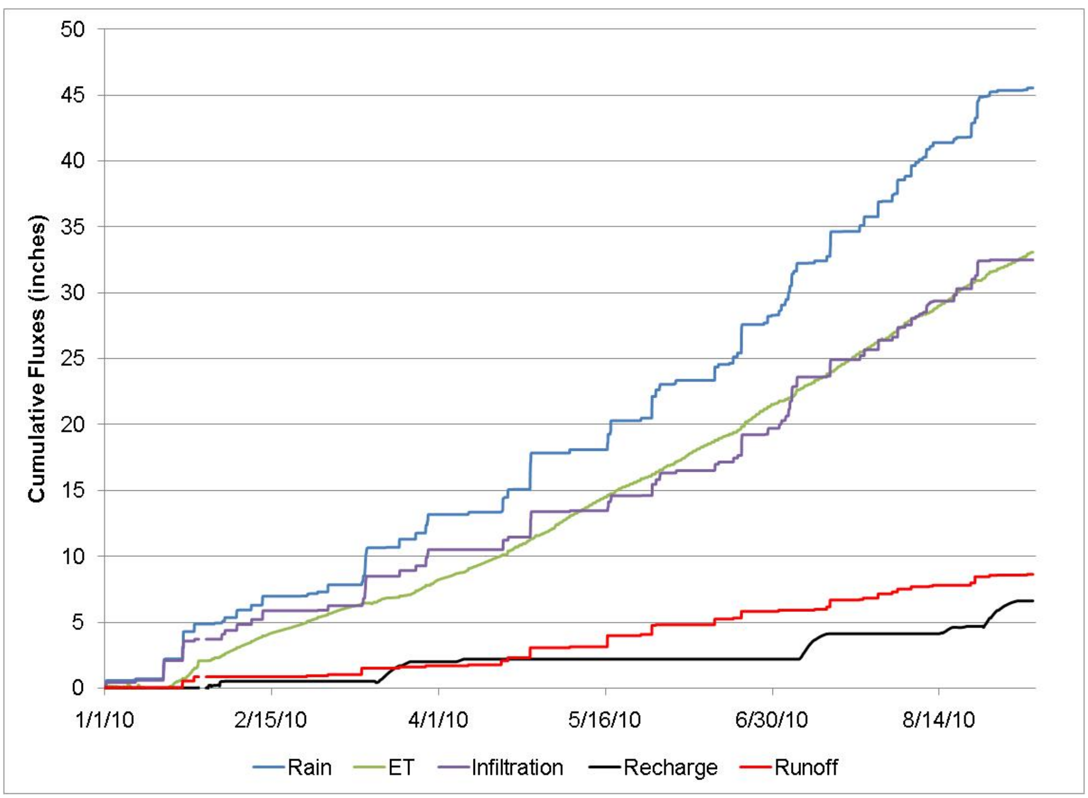

Figure 143. Eco 4 Observed Water Balance for 2010.

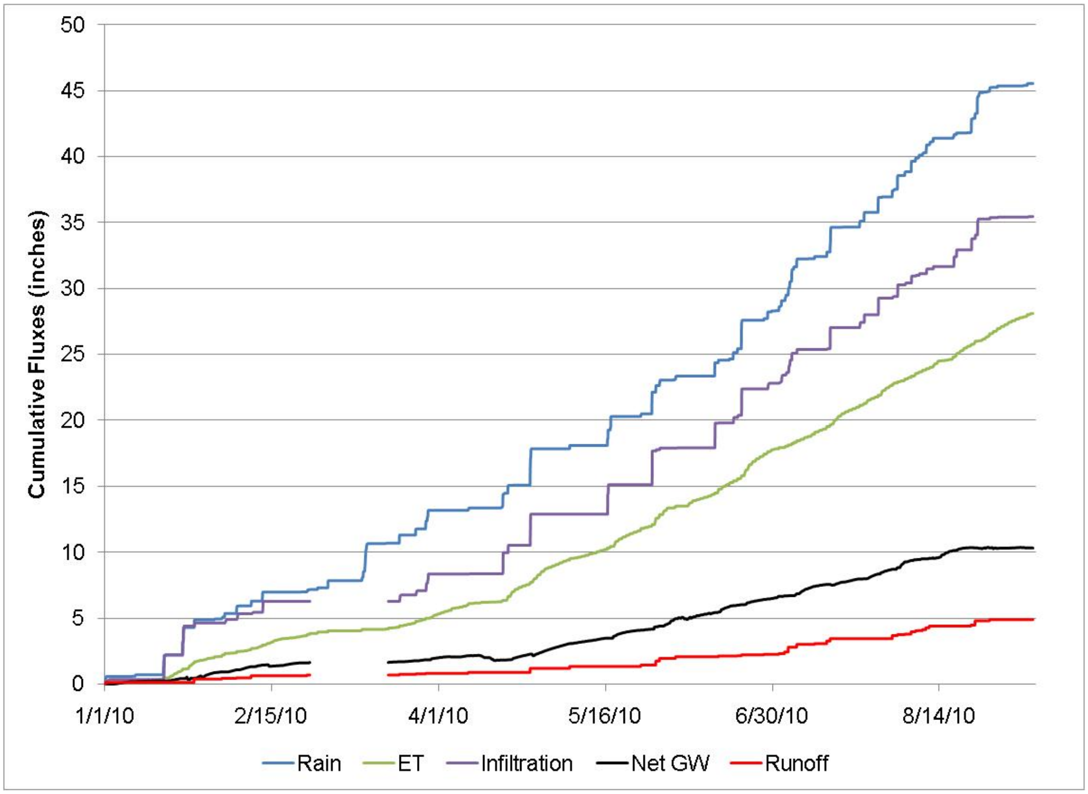

Figure 144. Eco 5 Observed Water Balance for 2010.

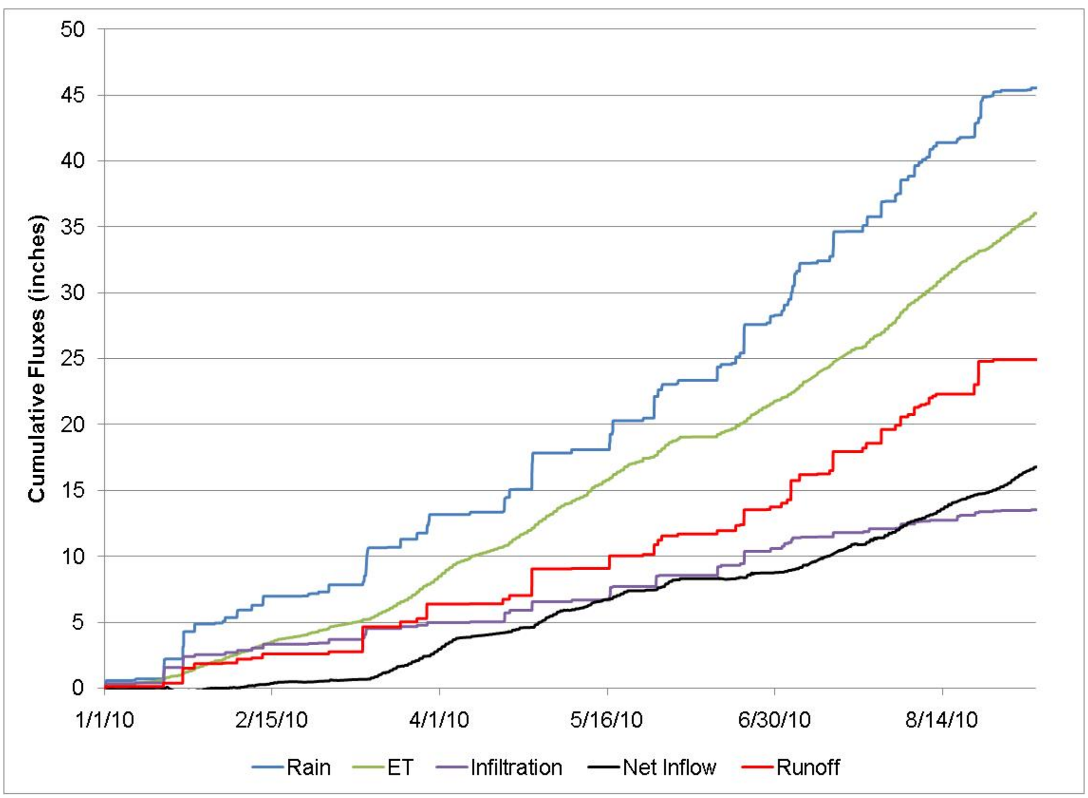

Figure 145. Eco 6 Observed Water Balance for 2010.

Table 4. Water Budget at ECO-1 (2007-2010).

2007 Eco Area 1 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table FL 1 (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	7.8	Infiltration	31.2	Soil ET	27.4	-1.4	3.1	1/1/2007	18.5	1/1/2007	4.5
Surface RO (in)	6.9	Surface RO (out)	9.2			Int. ET	7.8			12/31/2007	18.1	12/31/2007	4.7
		Infiltration	31.1			Recharge	5.3						
Total In	48.1	Total Out	48.1	Total In	31.2	Total Out	31.0			Difference	-0.4	Difference (ΔS)	0.2
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		0.2		Net Difference =	1.7	Residual ΔS-I+O (in) =		0.0	

2008 Eco Area 1 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table FL 1 (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	6.4	Infiltration	33.2	Soil ET	18.1	-2.7	1.0	1/1/2008	18.1	1/1/2008	4.7
Surface RO (in)	8.0	Surface RO (out)	4.9	Chg Over Data Gap	2.5	Int. ET	8.7			12/31/2008	17.2	9/12/2008	5.1
Rain During Gap	-9.5	Infiltration	33.2			Recharge	15.5						
Total In	44.5	Total Out	44.5	Total In	35.7	Total Out	35.3			Difference	-0.9	Difference (ΔS)	0.4
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		0.4		Net Difference =	-1.7	Residual ΔS-I+O (in) =		0.0	

2009 Eco Area 1 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table FL 1 (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	6.5	Infiltration	22.7	Soil ET	12.0	-0.2	1.2	1/1/2009	17.3	1/12/2009	1.6
Surface RO (in)	1.6	Surface RO (out)	7.8	Chg Over Data Gap	1.0	Int. ET	8.3			12/31/2009	20.0	12/31/2009	3.8
Rain During Gap	-9.0	Infiltration	22.7			Recharge	10.5						
Total In	37.0	Total Out	37.0	Total In	23.7	Total Out	21.5			Difference	2.7	Difference (ΔS)	2.2
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		2.2		Net Difference =	1.0	Residual ΔS-I+O (in) =		0.0	

2010 Eco Area 1 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table FL 1 (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	6.0	Infiltration	28.1	Soil ET	21.3	0.0	1.5	1/1/2010	19.8	1/1/2010	3.8
Surface RO (in)	2.9	Surface RO (out)	8.7	Chg Over Data Gap	0.4	Int. ET	7.3			9/8/2010	21.1	9/8/2010	3.4
Rain During Gap	-5.6	Infiltration	28.1			Recharge	9.1						
Total In	42.8	Total Out	42.8	Total In	28.5	Total Out	28.9			Difference	1.3	Difference (ΔS)	-0.4
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-0.4		Net Difference =	1.5	Residual ΔS-I+O (in) =		0.0	

Table 5. Water Budget at ECO-2 (2007-2010).

2007 Eco Area 2 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	13.3	Infiltration	16.7	Soil ET	15.1	-1.7	3.3	1/1/2007	N/A	1/1/2007	5.5
Surface RO (in)	1.4	Surface RO (out)	12.6	Chg Over Data Gap	-0.3	Int. ET	13.3			12/31/2007	N/A	12/31/2007	4.8
		Infiltration	16.7			Recharge	3.6						
Total In	42.6	Total Out	42.6	Total In	18.0	Total Out	18.7			Difference		Difference (ΔS)	-0.7
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-0.7		Net Difference =	1.6	Residual ΔS-I+O (in) =		0.0	

2008 Eco Area 2 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	13.8	Infiltration	12.9	Soil ET	8.9	-7.6	9.7	1/1/2008	N/A	1/1/2008	4.8
Surface RO (in)	0.4	Surface RO (out)	13.7	Chg Over Data Gap	-1.8	Int. ET	15.4			12/31/2008	N/A	12/31/2008	3.8
Rain During Gap	-6.0	Infiltration	12.9			Recharge	5.3						
Total In	40.4	Total Out	40.4	Total In	13.2	Total Out	14.2			Difference		Difference (ΔS)	-1.0
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-1.0		Net Difference =	2.1	Residual ΔS-I+O (in) =		0.0	

2009 Eco Area 2 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	13.5	Infiltration	15.1	Soil ET	11.5	0.0	1.3	1/1/2009	N/A	1/1/2009	3.8
Surface RO (in)	0.2	Surface RO (out)	14.5	Chg Over Data Gap	-1.2	Int. ET	13.9			12/31/2009	N/A	12/31/2009	4.8
Rain During Gap	-1.5	Infiltration	15.1			Recharge	2.7						
Total In	43.1	Total Out	43.1	Total In	15.2	Total Out	14.2			Difference		Difference (ΔS)	1.0
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		1.0		Net Difference =	1.3	Residual ΔS-I+O (in) =		0.0	

2010 Eco Area 2 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	9.8	Infiltration	17.1	Soil ET	15.6	0.0	0.2	1/1/2010	N/A	1/1/2010	4.8
Surface RO (in)	0.7	Surface RO (out)	9.0	Chg Over Data Gap	2.3	Int. ET	13.2			9/8/2010	N/A	9/8/2010	4.3
Rain During Gap	-10.3	Infiltration	17.1			Recharge	4.5						
Total In	35.9	Total Out	35.9	Total In	19.6	Total Out	20.1			Difference		Difference (ΔS)	-0.5
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-0.5		Net Difference =	0.2	Residual ΔS-I+O (in) =		0.0	

Table 6. Water Budget at ECO-3 (2007-2010).

2007 Eco Area 3 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	7.6	Infiltration	46.1	Soil ET	34.8	-1.9	2.4	1/1/2007	21.4	1/1/2007	7.5
Surface RO (in)	13.8	Surface RO (out)	1.0	Chg Over Data Gap	-1.7	Int. ET	7.8			12/31/2007	21.5	12/31/2007	7.3
Rain During Gap	-0.3	Infiltration	46.1			Recharge	10.3						
Total In	54.7	Total Out	54.7	Total In	44.4	Total Out	44.6			Difference	0.1	Difference (ΔS)	-0.2
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-0.2		Net Difference =	0.5	Residual ΔS-I+O (in) =		0.0	

2008 Eco Area 3 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	8.3	Infiltration	53.8	Soil ET	31.1	-5.8	7.0	1/1/2008	21.6	1/1/2008	7.3
Surface RO (in)	19.9	Surface RO (out)	2.9	Chg Over Data Gap	-2.3	Int. ET	8.7			12/31/2008	23.0	12/18/2008	4.9
Rain During Gap	-0.9	Infiltration	53.8			Recharge	24.0						
Total In	65.0	Total Out	65.0	Total In	51.5	Total Out	53.9			Difference	1.4	Difference (ΔS)	-2.4
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-2.4		Net Difference =	1.2	Residual ΔS-I+O (in) =		0.0	

2009 Eco Area 3 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	8.3	Infiltration	61.4	Soil ET	36.7	-5.6	8.8	1/1/2009	22.2	1/1/2009	18.6
Surface RO (in)	28.1	Surface RO (out)	2.8	Chg Over Data Gap	-15.7	Int. ET	8.3			12/31/2009	22.4	12/31/2009	7.3
		Infiltration	61.4			Recharge	23.5						
Total In	72.5	Total Out	72.5	Total In	45.7	Total Out	57.0			Difference	0.2	Difference (ΔS)	-11.3
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-11.3		Net Difference =	3.2	Residual ΔS-I+O (in) =		0.0	

2010 Eco Area 3 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	7.3	Infiltration	42.7	Soil ET	34.4	-1.2	2.5	1/1/2010	22.3	1/1/2010	7.3
Surface RO (in)	8.5	Surface RO (out)	4.0			Int. ET	7.3			9/8/2010	25.5	9/8/2010	6.3
		Infiltration	42.7			Recharge	10.6						
Total In	54.0	Total Out	54.0	Total In	42.7	Total Out	43.7			Difference	3.2	Difference (ΔS)	-1.0
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-1.0		Net Difference =	1.3	Residual ΔS-I+O (in) =		0.0	

Table 7. Water Budget at ECO-4 (2007-2010).

2007 Eco Area 4 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	7.8	Infiltration	36.4	Soil ET	32.4	-2.5	1.9	1/1/2007	18.3	1/1/2007	4.8
Surface RO (in)	11.6	Surface RO (out)	8.6			Int. ET	7.8			12/31/2007	18.1	12/31/2007	5.0
		Infiltration	36.4			Recharge	3.2						
Total In	52.8	Total Out	52.8	Total In	36.4	Total Out	36.2			Difference	-0.2	Difference (ΔS)	0.2
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		0.2		Net Difference =	-0.6	Residual ΔS-I+O (in) =		0.0	

2008 Eco Area 4 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	8.7	Infiltration	41.6	Soil ET	35.0	-0.7	1.4	1/1/2008	18.0	1/1/2008	5.0
Surface RO (in)	9.5	Surface RO (out)	5.2			Int. ET	8.7			12/31/2008	17.0	12/31/2008	4.4
		Infiltration	41.6			Recharge	7.9						
Total In	55.5	Total Out	55.5	Total In	41.6	Total Out	42.2			Difference	-1.0	Difference (ΔS)	-0.6
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-0.6		Net Difference =	0.7	Residual ΔS-I+O (in) =		0.0	

2009 Eco Area 4 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	8.0	Infiltration	33.2	Soil ET	18.1	-2.9	5.7	1/1/2009	17.0	1/8/2009	5.7
Surface RO (in)	3.1	Surface RO (out)	5.8	Chg Over Data Gap	-7.2	Int. ET	8.3			12/31/2009	19.6	12/31/2009	4.3
Rain During Gap	0.5	Infiltration	33.2			Recharge	12.1						
Total In	47.0	Total Out	47.0	Total In	26.0	Total Out	27.4			Difference	2.6	Difference (ΔS)	-1.4
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-1.4		Net Difference =	2.8	Residual ΔS-I+O (in) =		0.0	

2010 Eco Area 4 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	7.3	Infiltration	32.4	Soil ET	25.8	-1.1	3.5	1/1/2010	19.5	1/1/2010	4.3
Surface RO (in)	2.8	Surface RO (out)	8.6	Chg Over Data Gap	-2.7	Int. ET	7.3			9/8/2010	20.9	9/8/2010	4.0
		Infiltration	32.4			Recharge	6.6						
Total In	48.3	Total Out	48.3	Total In	29.7	Total Out	30.0			Difference	1.4	Difference (ΔS)	-0.3
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-0.3		Net Difference =	2.4	Residual ΔS-I+O (in) =		0.0	

Table 8. Water Budget at ECO-5 (2007-2010).

2007 Eco Area 5 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	7.8	Infiltration	53.4	Soil ET	35.0	-0.5	0.0	1/1/2007	21.4	1/1/2007	19.0
Surface RO (in)	21.3	Surface RO (out)	1.3			Int. ET	7.8			12/31/2007	21.0	12/31/2007	18.4
		Infiltration	53.4			Net GW	18.5						
Total In	62.5	Total Out	62.5	Total In	53.4	Total Out	54.0			Difference	-0.4	Difference (ΔS)	-0.6
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		-0.6		Net Difference =	-0.5	Residual ΔS-I+O (in) =		0.0	

2008 Eco Area 5 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	7.6	Infiltration	37.6	Soil ET	29.8	-0.9	0.9	1/1/2008	21.0	1/1/2008	18.4
Surface RO (in)	8.4	Surface RO (out)	4.2	Chg Over Data Gap	2.2	Int. ET	8.7			12/31/2008	20.9	12/31/2008	19.5
Rain During Gap	-5.0	Infiltration	37.6			Net GW	8.9						
Total In	49.4	Total Out	49.4	Total In	39.8	Total Out	38.7			Difference	-0.1	Difference (ΔS)	1.1
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		1.1		Net Difference =	0.0	Residual ΔS-I+O (in) =		0.0	

2009 Eco Area 5 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	8.3	Infiltration	47.6	Soil ET	25.7	-0.6	0.4	1/1/2009	20.9	1/1/209	19.5
Surface RO (in)	14.7	Surface RO (out)	3.3			Int. ET	8.3			12/31/2009	21.9	12/31/2009	21.1
		Infiltration	47.5			Net GW	20.1						
Total In	59.1	Total Out	59.1	Total In	47.6	Total Out	46.0			Difference	1.0	Difference (ΔS)	1.6
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		1.6		Net Difference =	-0.2	Residual ΔS-I+O (in) =		0.0	

2010 Eco Area 5 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	7.0	Infiltration	35.4	Soil ET	20.8	-0.4	0.2	1/1/2010	21.7	1/1/2010	21.1
Surface RO (in)	5.3	Surface RO (out)	5.0	Chg Over Data Gap	0.3	Int. ET	7.3			9/8/2010	23.6	9/8/2010	25.5
Rain During Gap	-3.5	Infiltration	35.3			Net GW	10.3						
Total In	47.3	Total Out	47.3	Total In	35.7	Total Out	31.3			Difference	1.9	Difference (ΔS)	4.4
Net Inflows I-O (in) =		0.0		Net Inflows I-O (in) =		4.4		Net Difference =	-0.2	Residual ΔS-I+O (in) =		0.0	

Table 9. Water Budget at ECO-6 (2007-2010).

2007 Eco Area 6 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	41.2	Int. ET	7.5	Infiltration	44.9	Soil ET	38.2	-49.6	57.2	1/1/2007	21.0	1/1/2007	16.2
Surface RO (in)	14.5	Surface RO (out)	1.5	Chg Over Data Gap	-0.3	Int. ET	7.8			12/31/2007	20.8	12/31/2007	16.4
Rain During Gap	-1.8	Infiltration	44.9			Net GW	13.8						
Total In	53.9	Total Out	53.9	Total In	52.2	Total Out	52.0			Difference	-0.2	Difference (?S)	0.2
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		0.2		Net Difference =	7.6	Residual ?S-I+O (in) =		0.0	

2008 Eco Area 6 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	46.0	Int. ET	8.7	Infiltration	26.3	Soil ET	35.9	-71.3	72.4	1/1/2008	20.6	1/1/2008	16.4
Surface RO (in)	1.1	Surface RO (out)	12.1			Int. ET	8.7			12/31/2008	20.5	12/31/2008	16.3
		Infiltration	26.3			Net GW	-8.4						
Total In	47.1	Total Out	47.1	Total In	27.4	Total Out	27.5			Difference	-0.1	Difference (?S)	-0.1
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		-0.1		Net Difference =	1.1	Residual ?S-I+O (in) =		0.0	

2009 Eco Area 6 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	44.4	Int. ET	8.3	Infiltration	31.9	Soil ET	27.8	-2.3	3.3	1/1/2009	20.3	1/1/2009	16.3
Surface RO (in)	1.4	Surface RO (out)	5.6			Int. ET	8.3			12/31/2009	21.3	12/31/2009	17.6
		Infiltration	31.9			Net GW	3.7						
Total In	45.8	Total Out	45.8	Total In	32.9	Total Out	31.5			Difference	1.0	Difference (?S)	1.3
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		1.4		Net Difference =	1.0	Residual ?S-I+O (in) =		0.0	

2010 Eco Area 6 Results													
Land Surface Fluxes				Soil Moisture Sensor Fluxes				Major Changes in TSM w/o Rain		Storage Change			
Positive Changes (Inflow)		Negative Changes (outflow)		Positive Changes (Inflow)		Negative Changes (outflow)		Neg Chgs <-.06	Pos Chgs >.03	Water Table (ft)		2m Soil Moisture Storage (in)	
Rain	45.5	Int. ET	7.3	Infiltration	13.6	Soil ET	28.7	-4.0	3.7	1/1/2010	21.3	1/1/2010	17.7
Surface RO (in)	0.3	Surface RO (out)	24.9			Int. ET	7.3			9/8/2010	22.9	9/8/2010	18.8
		Infiltration	13.6			Net GW	-16.8						
Total In	45.8	Total Out	45.8	Total In	13.4	Total Out	12.3			Difference	1.6	Difference (?S)	1.1
Net Inflows I-O (in) =			0.0	Net Inflows I-O (in) =		1.1		Net Difference =	-0.3	Residual ?S-I+O (in) =		0.0	

Table 10. Summary of fluxes at the ECO sites.

Eco 1					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	35.2	33.7	21.3	33.1	30.8
Infiltration	31.2	40.3	29.2	31.3	33.0
Runoff	9.2	4.9	8.4	8.7	7.8
Run In	6.9	8	1.6	2.9	4.9
Recharge	5.3	16.5	12.8	9.8	11.1

Eco 2					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	28.4	25.2	25.7	30.3	27.4
Infiltration	16.7	14	16	19.7	16.6
Runoff	12.6	17	14.7	12.4	14.2
Run In	1.4	0.4	0.2	0.7	0.7
Recharge	3.6	5.5	2.7	4.7	4.1

Eco 3					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	43.8	46.3	45	41.7	44.2
Infiltration	46.2	54.2	61.4	42.7	51.1
Runoff	1	2.9	2.8	4	2.7
Run In	13.8	19.9	28.1	8.5	17.6
Recharge	10.3	24.2	23.5	10.6	17.2

Eco 4					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	40.2	43.7	28.3	33.1	36.3
Infiltration	36.4	41.6	35	32.4	36.4
Runoff	8.6	5.2	5.8	8.6	7.1
Run In	11.6	9.5	3.1	2.8	6.8
Recharge	3.2	7.9	12.3	6.6	7.5

Eco 5					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	42.8	45.5	34	40.1	40.6
Infiltration	53.4	41.5	47.6	38.9	45.4
Runoff	1.3	4.2	3.3	5	3.5
Run In	21.3	8.4	14.7	5.3	12.4
Net Groundwater	18.5	8.9	20.1	10.3	14.5

Eco 6					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46	44.4	45.5	44.3
ET (soil + interceptive	48.1	44.6	36.1	36	41.2
Infiltration	46.2	26.3	31.9	13.6	29.5
Runoff	2.3	12.1	5.6	24.9	11.2
Run In	14.5	1.1	1.4	0.3	4.3
Net Groundwater	13.8	-8.4	3.7	-16.8	-1.9

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

Expectedly, vegetative areas on a ridge with a deep water table exhibit lower ET (e.g., 30.8” and 27.4” average ET for ECO 1 and 2, respectively) compared to mid-hill, topographic convergent regions (44.2” and 36.3” for ECO 3 and 4, respectively) and further downhill, hill-slope discharge high water table environments (40.6” and 41.2” ET from ECO 5 and 6, respectively). Total ET at ECO 2 appears to be anomalous (very low) at 27.4” 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 years experienced during the study.

Perhaps more inconsistent for the hillslope was the net groundwater recharge 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 11.11” at ECO 1 (note this should be higher but the missing final quarter is missing) to -1.9” (net discharge) at ECO 6. However, there was considerable variation in the values in between from 4.1” at ECO 2 to 17.2” at ECO 3, 7.5” at 4, and 14.5” at Eco 5, respectively. Again, ECO 2 should be considered in the context of high slope and ECO 3 and 5 where low slope (topographic convergence zones exhibiting high runin and high net groundwater recharge. The high recharge rates at the down slope stations 3 and 5 appears to the result of high runoff from uphill (i.e., ECO 2 and 4) areas with repeatedly higher than rainfall infiltration values observed at these stations for larger (>1”) rain events. Note that total infiltration at ECO 3 was 51.1” (7” greater than annual rainfall).

Concerning the anomalous behavior exhibited at ECO-2 for infiltration, vertical flow and ET, the lower values for fluxes observed at this station appear to be a result of the placement of this station 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 ECO-3 both support the hypothesis that this high slope (>10%) environment exhibits considerable locally generated runoff at the expense of infiltration (only 16.6”, with some data gaps). The milder slopes at stations ECO-3 and ECO-5 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 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.

IHM Testing

From the current Eco Site study, there appears to be a significant relationship between the time-scale of recharge and the antecedent soil moisture and the depth to the water table. Most hydrologic models, other than those that solve the Richard's Equation, which is impractical on a regional basis, assume a direct and fixed timestep relationship between rainfall and recharge. In fact, there can be a substantial delay between rainfall and recharge to the water table (weeks and perhaps months), if recharge occurs at all. During dry conditions with a deep water table, a large wetting front moving downward through the unsaturated zone may be partially or completely removed by plant transpiration and evaporation. Additionally, if the soil column is drier than equilibrium, moisture from the wetting front will be used to restore equilibrium moisture to the soil (vadose zone recharge) which reduces the moisture that would otherwise recharge the water table. In the dry season, many rainfall events may be necessary to sufficiently wet the soli column to allow recharge to reach the water table but in deep settings that can take weeks.

The IHM model was tested using the new deep water-table data now available to ensure that the current formulation of vadose-zone moisture movement is consistent with field data. The IHM model was developed with a three-layer unsaturated zone concept that considers antecedent soil moisture conditions. However, prior to this study there was no deep water-table data available to fully test the applicability of the model. The IHM testing phase of this proposal compares the observed recharge data during deep water-table and dry soil moisture conditions to the IHM predicted water-table response and provides suggestions for code improvements to the model.

Model Parameters

Soil Moisture Conditions, Capillary and Root Zone Thickness

Soil moisture conditions used for the IHM model were developed from observed soil moisture data. Because of the marked similarities of the soil samples taken from the individual site locations, it was determined that a single set of soil moisture property values would adequately represent the site’s soil characteristics. Average observed maximum and minimum soil moisture values were used for porosity and wilt point values respectively. Capillary fringe moisture content and capillary zone thickness were determined from an analysis of the soil moisture curve characteristics of ECO-5 and ECO-6. An upper zone nominal storage value of 0.5” was derived from the site. Upper zone nominal storage is defined as the “A” horizon (top 10-15cm of soil) equilibrium retention plus the depression volume. Capillary fringe and capillary zone thickness were determined from an analysis of the soil moisture curve characteristics of ECO-5 and ECO-6. For ECO-1, ECO-2, and ECO-4, which do not have a surficial water table, the root zone thickness was set at 48 inches (yielding an extinction depth of approximately 7’. For ECO-3, with its moderately deep water table, the root zone thickness of 48 inches was also used, while a value of 36 inches was used for the shallow water table sites ECO-5 and ECO-6. A listing of the above parameters values is presented in Table 11 below.

Table 11 Soil Moisture Conditions and Capillary and Root Zone Parameter Values

Eco 1,2, 3 and 4 Model Parameter Values			
Soil Moisture Conditions		**Capillary and Root Zone Thickness (in)**	
Porosity	37%	Root Zone	48.0
CapFringe	35%	Capillary Zone	44.0
Wilt Point	3%	Capillary Fringe	13.2
Specific Retention	8%	Upper Capillary Zone	29.0
SR-WP	5%	Plant ET Surface Zone	15.0
Wet Factor	1.5	Ground Water Extinction Depth	92.0
UZSN =	0.5		

Eco 5 and 6 Model Parameter Values			
Soil Moisture Conditions		**Capillary and Root Zone Thickness (in)**	
Porosity	37%	Root Zone	36.0
CapFringe	35%	Capillary Zone	44.0
Wilt Point	3%	Capillary Fringe	13.2
Specific Retention	8%	Upper Capillary Zone	29.0
SR-WP	5%	Plant ET Surface Zone	15.0
Wet Factor	1.5	Ground Water Extinction Depth	80.0
UZSN =	0.5		

Model Calibration and Parameter Values

The overall goal of the IHM model calibration exercise was to reproduce the evapotranspiration (ET) and infiltration responses demonstrated by the individual sites. To accomplish this task, the minimum and maximum plant ET coefficients and nominal infiltration index values of the individual site were utilized as calibration parameters. The minimum and maximum plant ET coefficients were adjusted to best replicate the overall observed ET response of the individual sites. The minimum plant ET coefficient value is the plant ET coefficient used during the winter and spring months while the maximum plant ET coefficient was used during the summer and fall. The Nominal Infiltration Index parameter was used to calibrate the model infiltration response and is defined as the mean infiltration rate of the soil at equilibrium moisture conditions. The individual site calibration parameters are presented in Table 12 below.

Table 12 Eco Site Model Calibration Parameter Values

Model Calibration Parameter Values			
Site Location	**Minimum ET Coefficient**	**Maximum ET Coefficient**	**Nominal Infiltration Index (in/hr)**
Eco 1	0.55	0.70	0.50
Eco 2	0.40	0.50	0.12
Eco 3	0.85	0.95	5.00
Eco 4	0.85	0.95	0.50
Eco 5	0.40	0.70	1.20
Eco 6	0.40	0.70	1.40

Model Input

Model inputs for the IHM model consist of net rainfall, net potential evapotranspiration (PET) and water table drawdown. For 2010, the ECO-6 site observed hourly net inflow volume was added to the hourly weather station rainfall data instead of the observed hourly inflow volume.

The model utilizes a single net potential evapotranspiration time series. The time series is derived by taking the hourly potential evapotranspiration rate time series calculated by the Eco Site weather station and setting the PET values to zero during rainfall events. An event specific hourly interception capture value is then subtracted from the rainfall adjusted hourly PET value to account for that portion of PET satisfied by the interception capture.

Water table drawdown is a fixed hourly withdrawal rate that is derived from the observed yearly groundwater rates for each of the individual site locations. A table of the yearly drawdowns is presented below in Table 13.

Table 13 Yearly Water Table Drawdown Rates

Water Table Drawdown Rates (in/yr)				
Site	**2007**	**2008**	**2009**	**2010**
ECO-1	18.71	17.00	10.13	16.93
ECO-2	5.07	6.75	4.15	13.59
ECO-3	18.70	32.75	28.80	24.05
ECO-4	12.88	20.86	11.31	16.93
ECO-5	18.51	8.90	20.06	1.03
ECO-6	13.86	-0.7	3.74	3.07

The following figures illustrate the comparisons between the calculated (observed) fluxes and the IHM derived fluxes (solid lines).

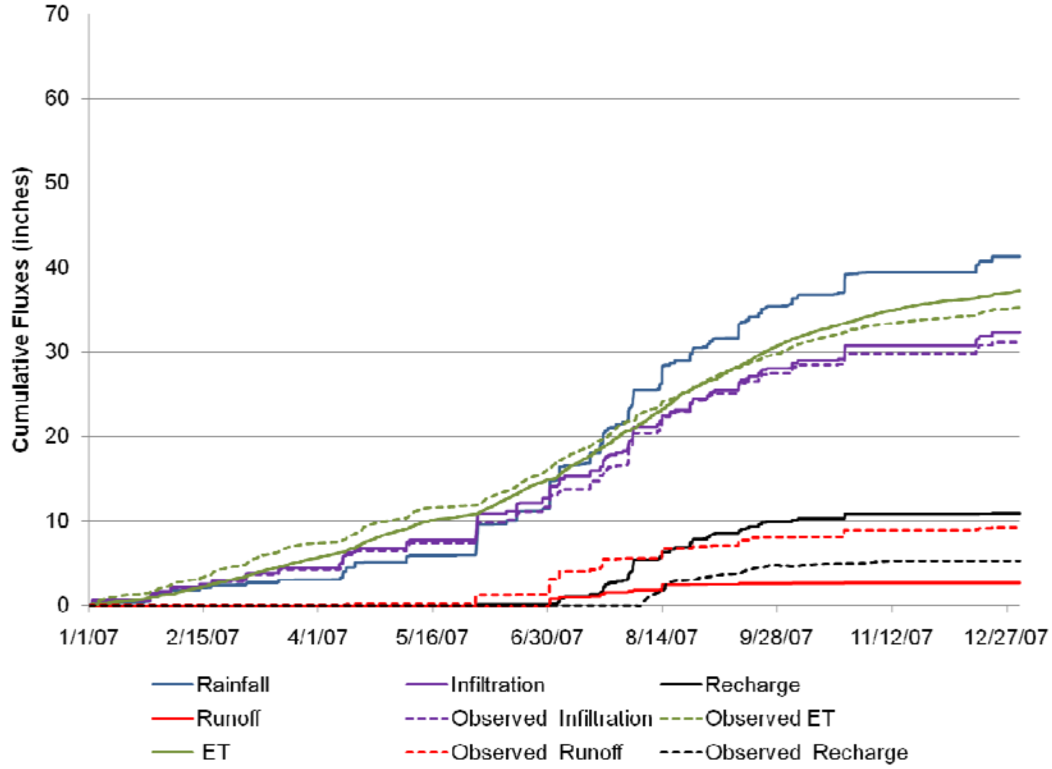

Figure 146 Eco 1 Simulated and Observed Water Balance for 2007

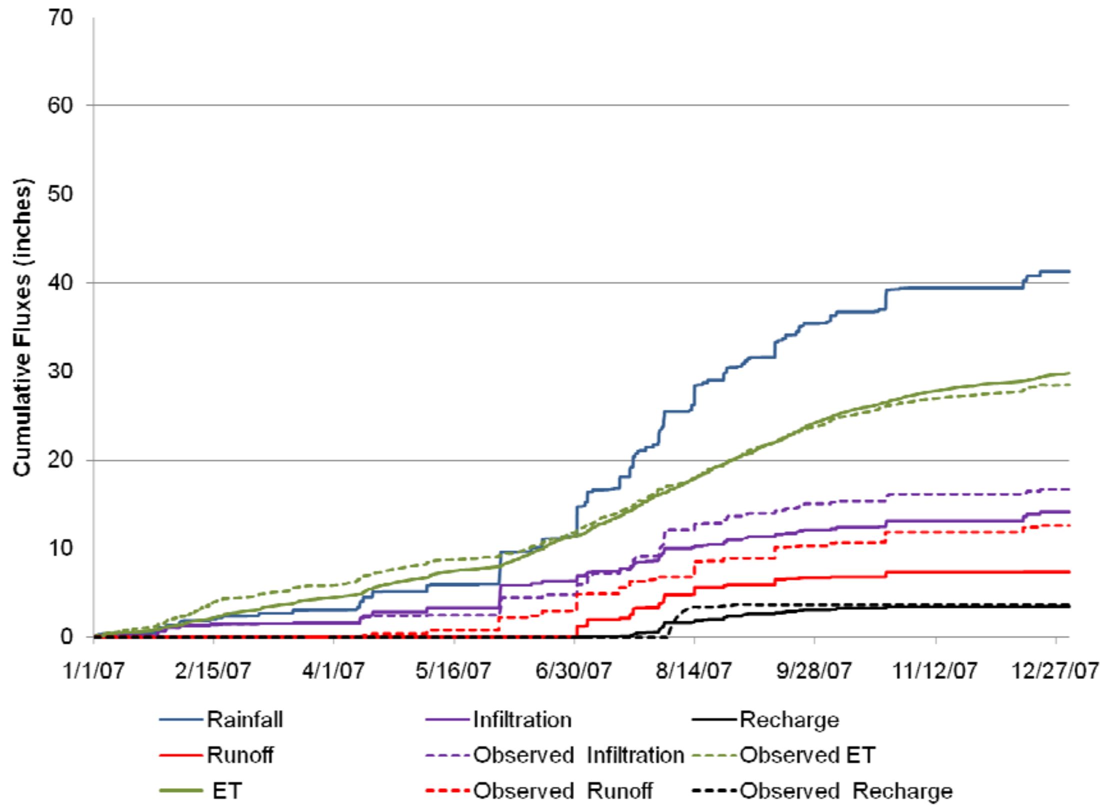

Figure 147 Eco 2 Simulated and Observed Water Balance for 2007

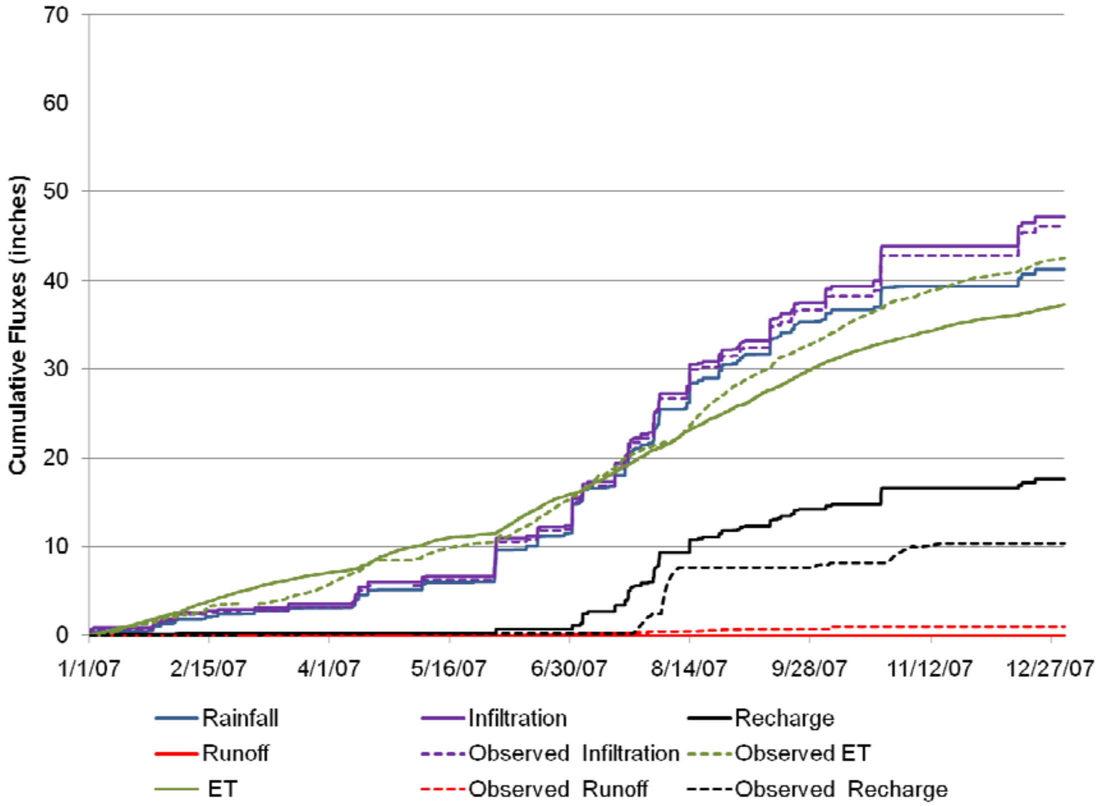

Figure 148 Eco 3 Simulated and Observed Water Balance for 2007

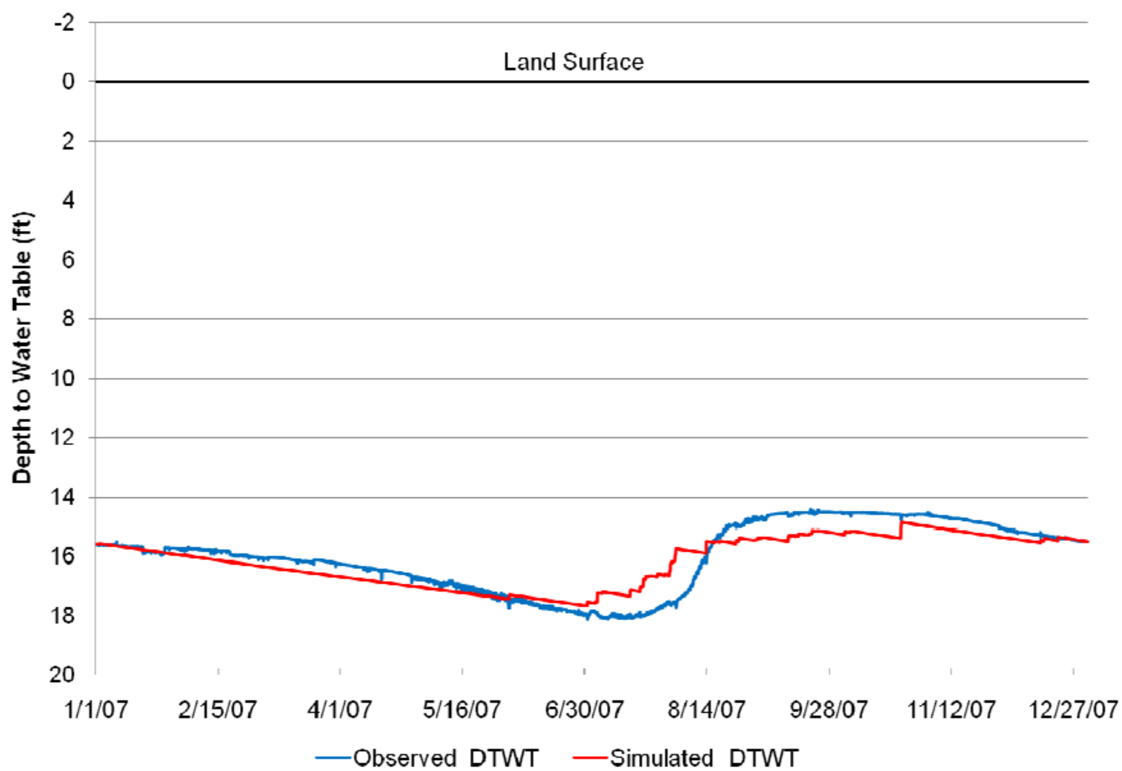

Figure 149 Eco 3 Simulated and Observed Water Table for 2007

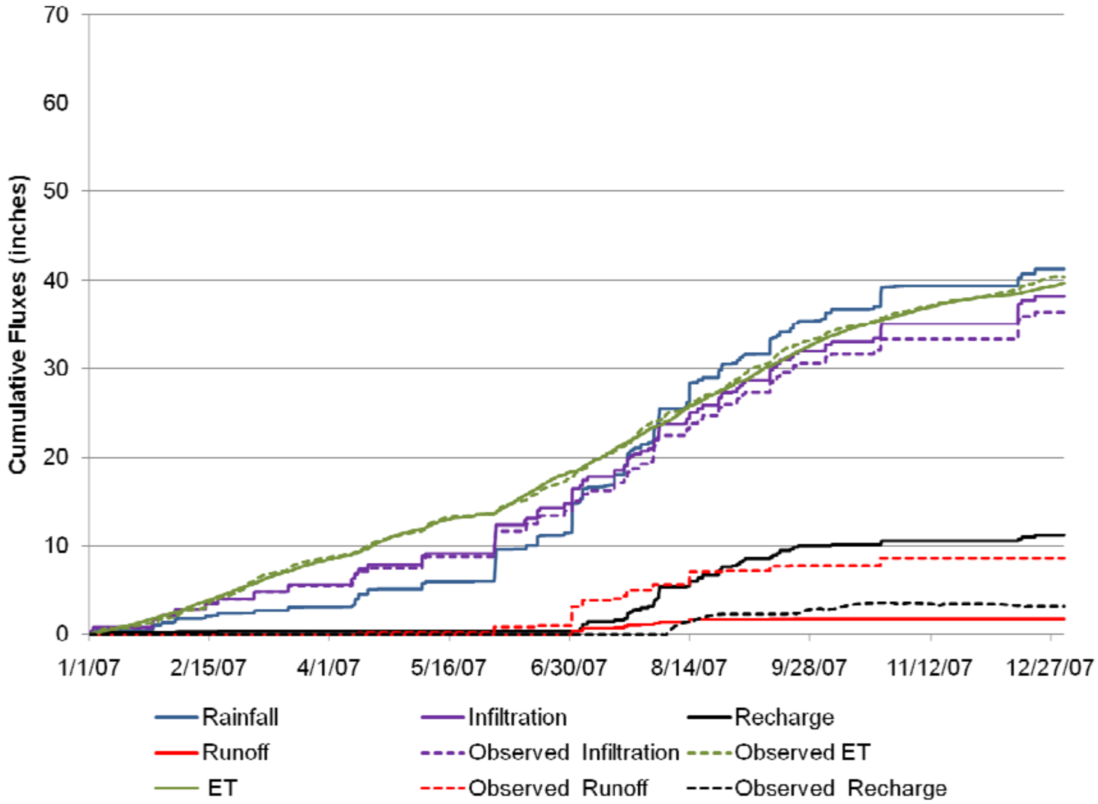

Figure 150 Eco 4 Simulated and Observed Water Balance for 2007

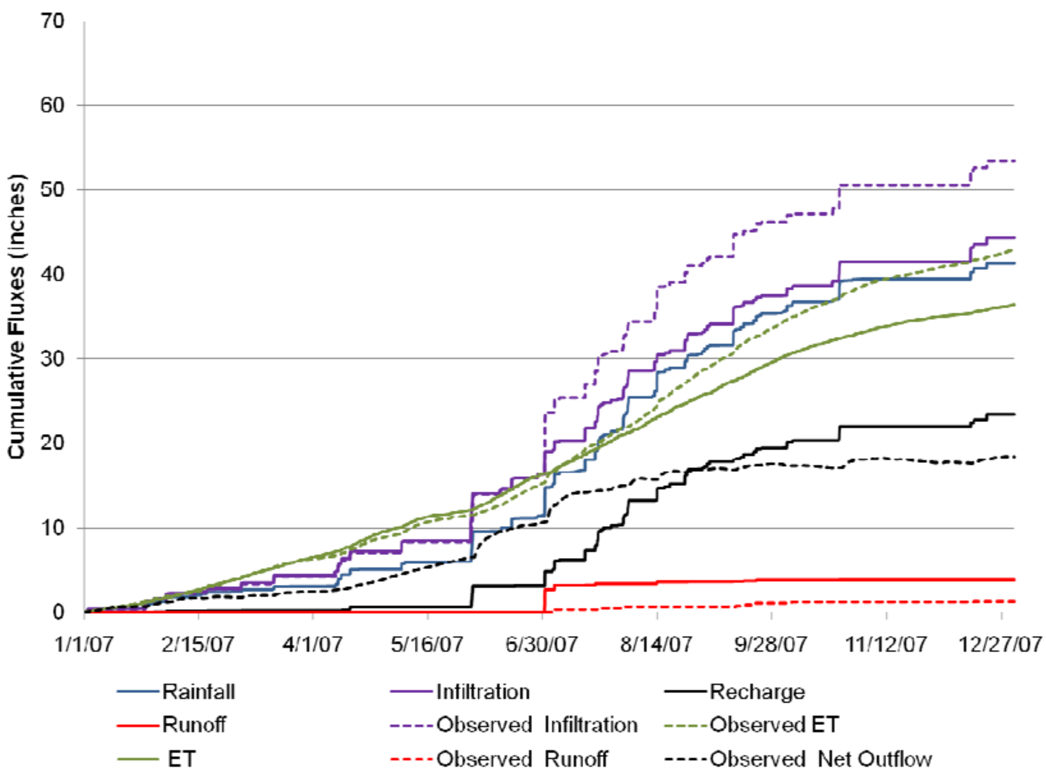

Figure 151 Eco 5 Simulated and Observed Water Balance for 2007

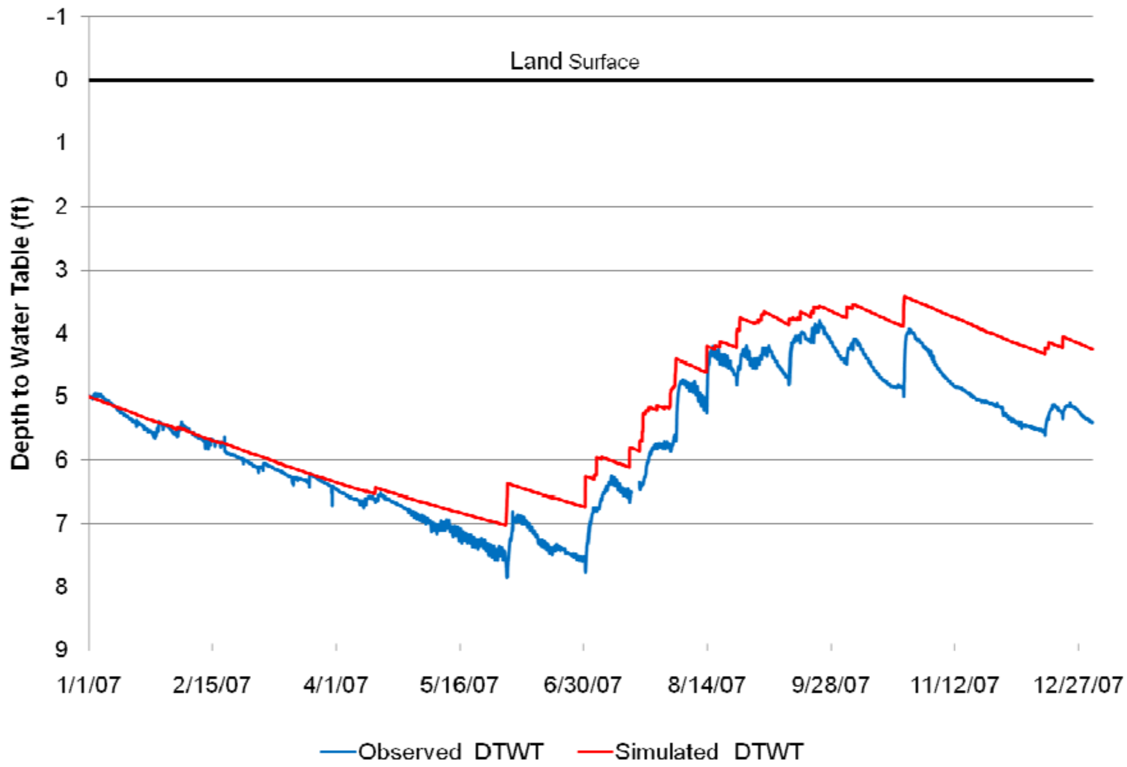

Figure 152 Eco 5 Simulated and Observed Water Table for 2007

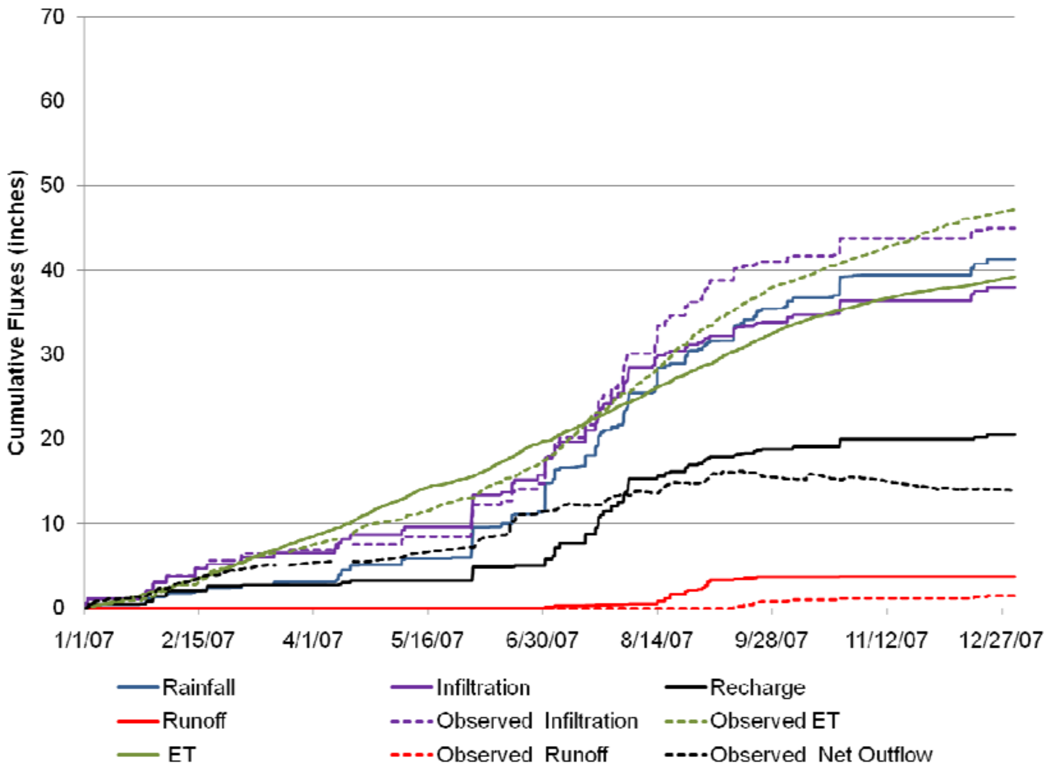

Figure 153 Eco 6 Simulated and Observed Water Balance for 2007

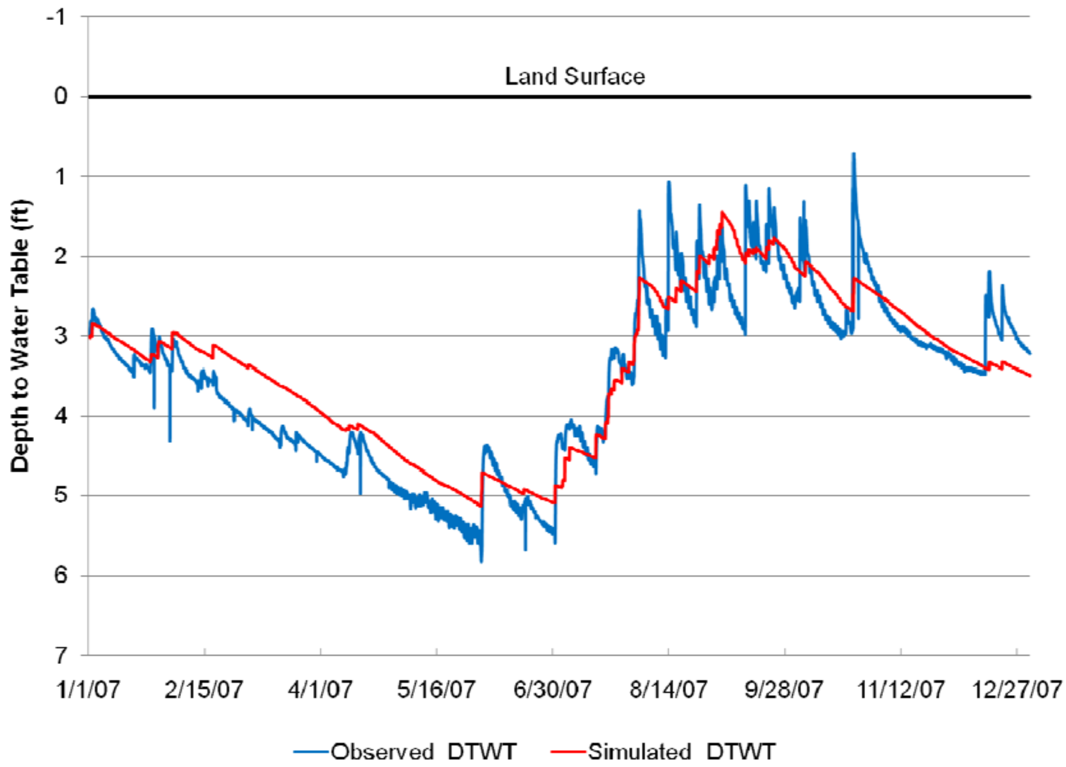

Figure 154 Eco 6 Simulated and Observed Water Table for 2007

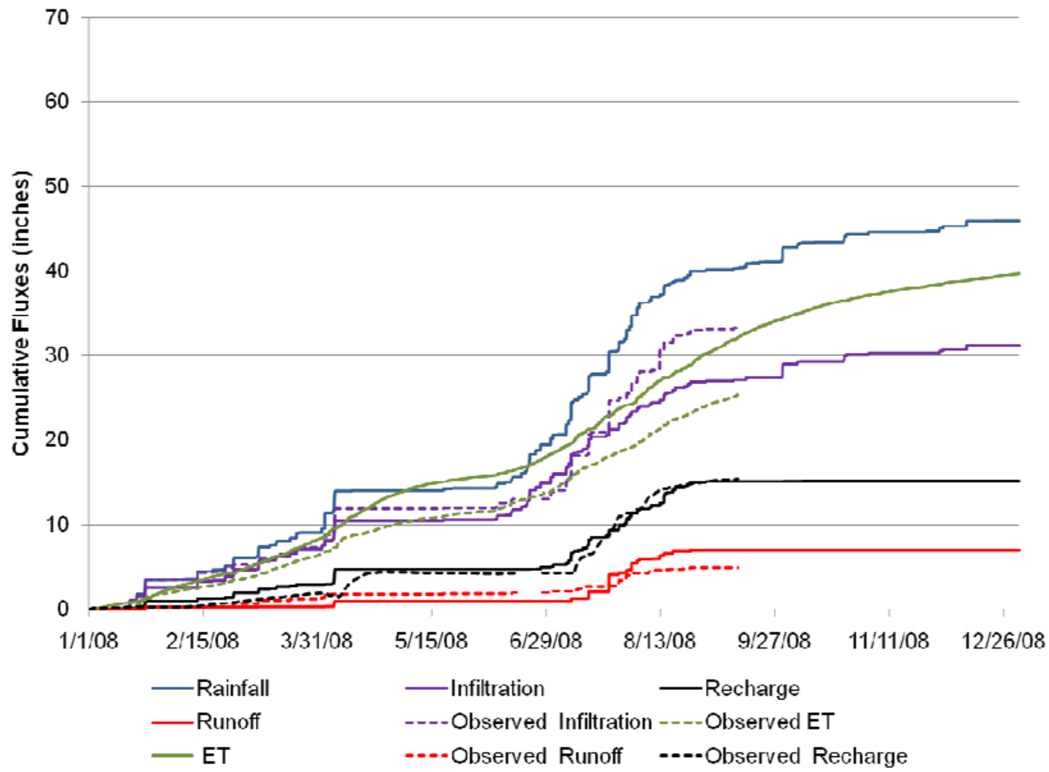

Figure 155 Eco 1 Simulated and Observed Water Balance for 2008

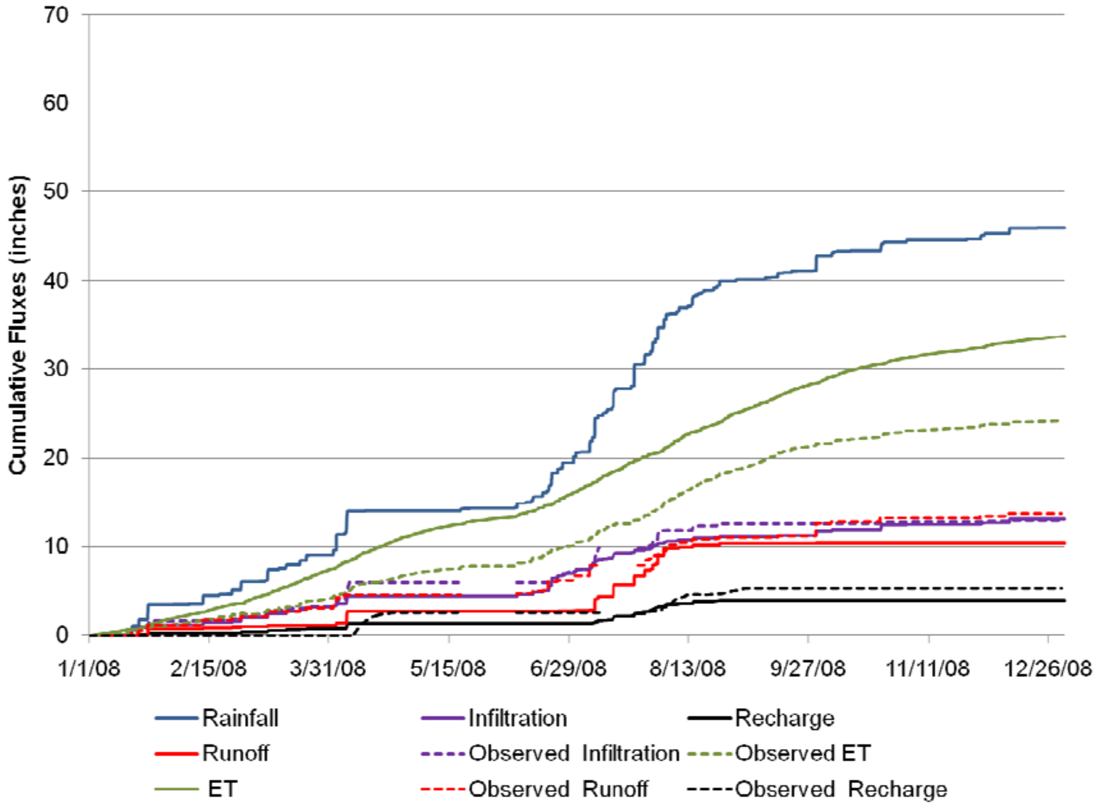

Figure 156 Eco 2 Simulated and Observed Water Balance for 2008

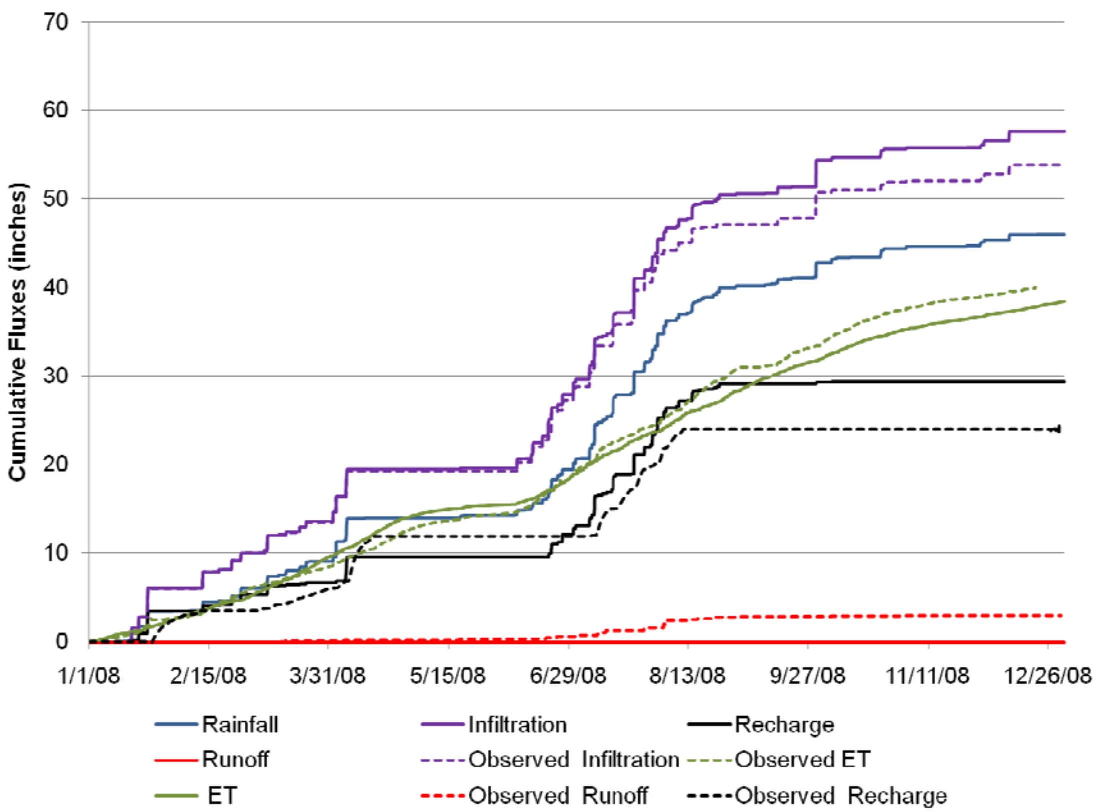

Figure 157 Eco 3 Simulated and Observed Water Balance for 2008

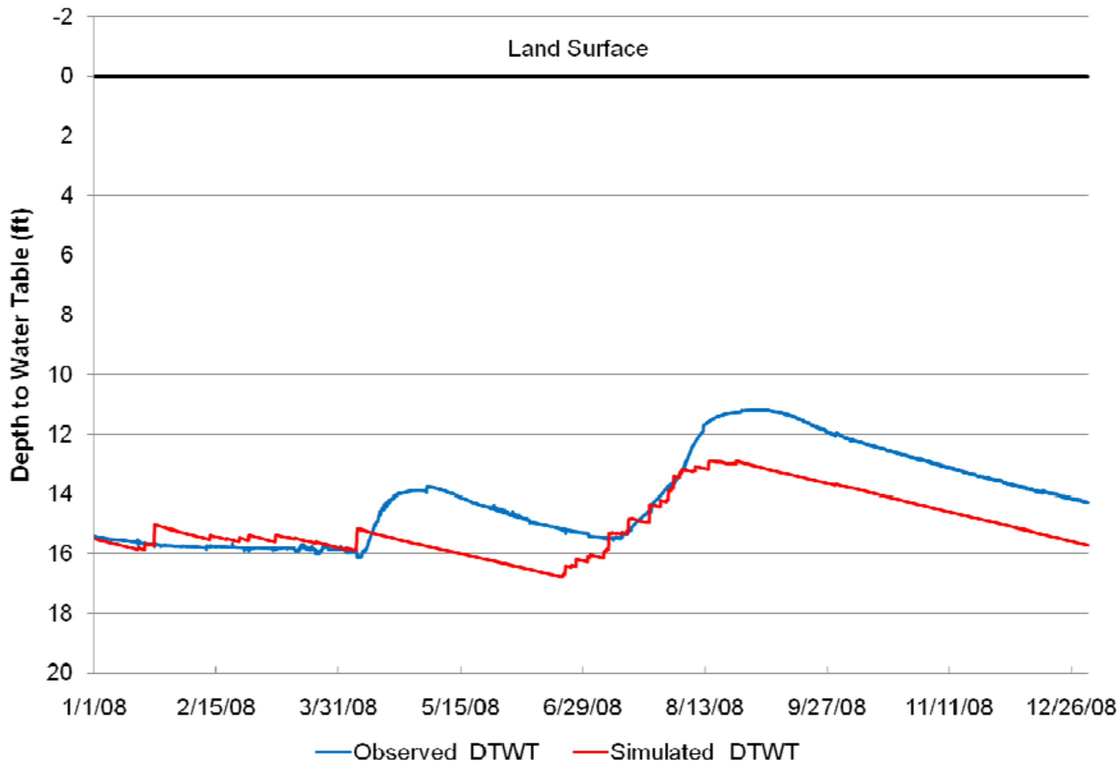

Figure 158 Eco 3 Simulated and Observed Water Table for 2008

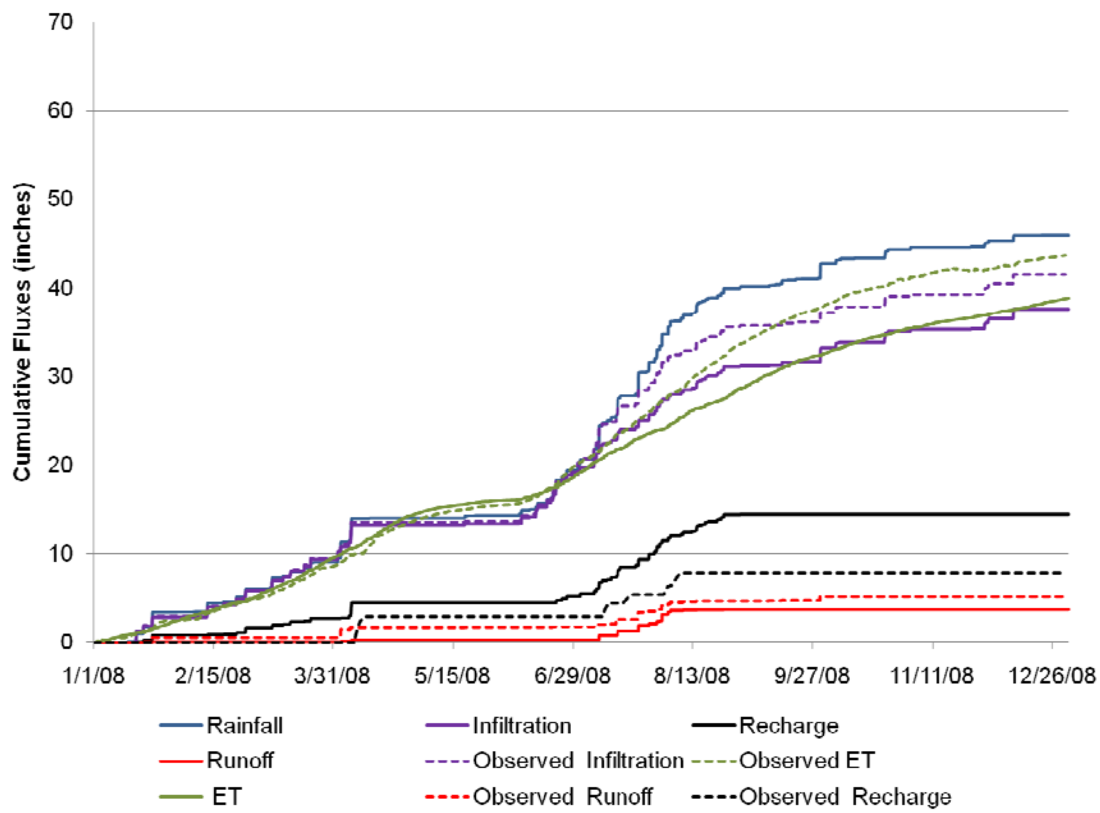

Figure 159 Eco 4 Simulated and Observed Water Balance for 2008

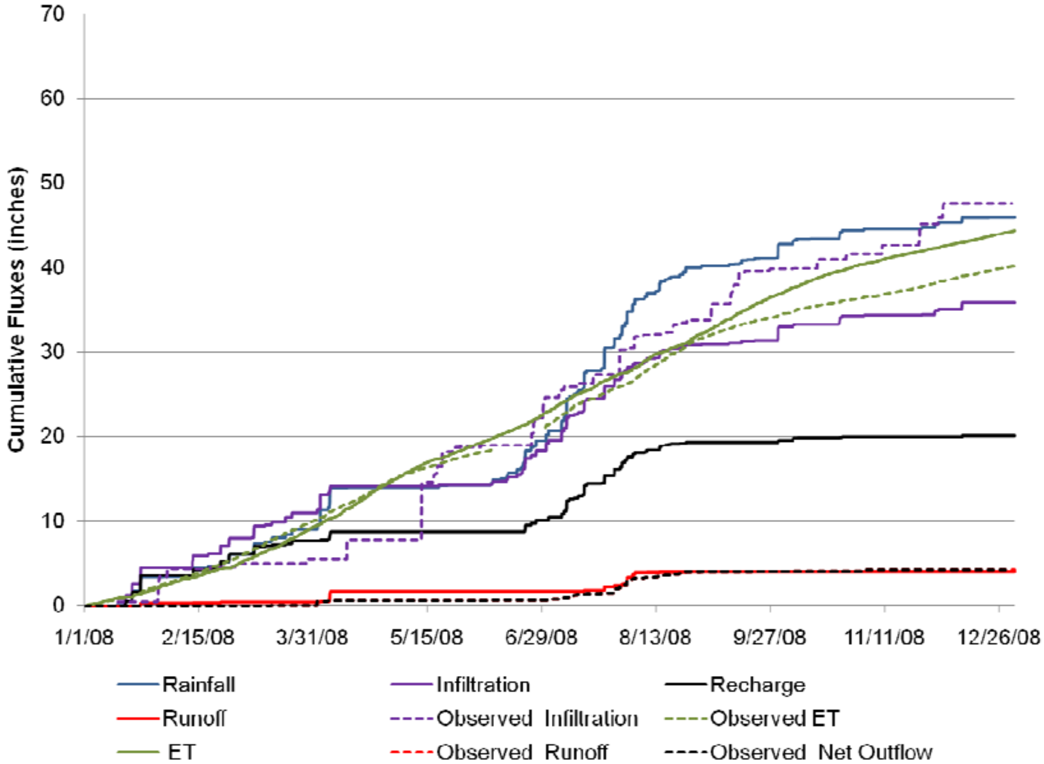

Figure 160 Eco 5 Simulated and Observed Water Balance for 2008

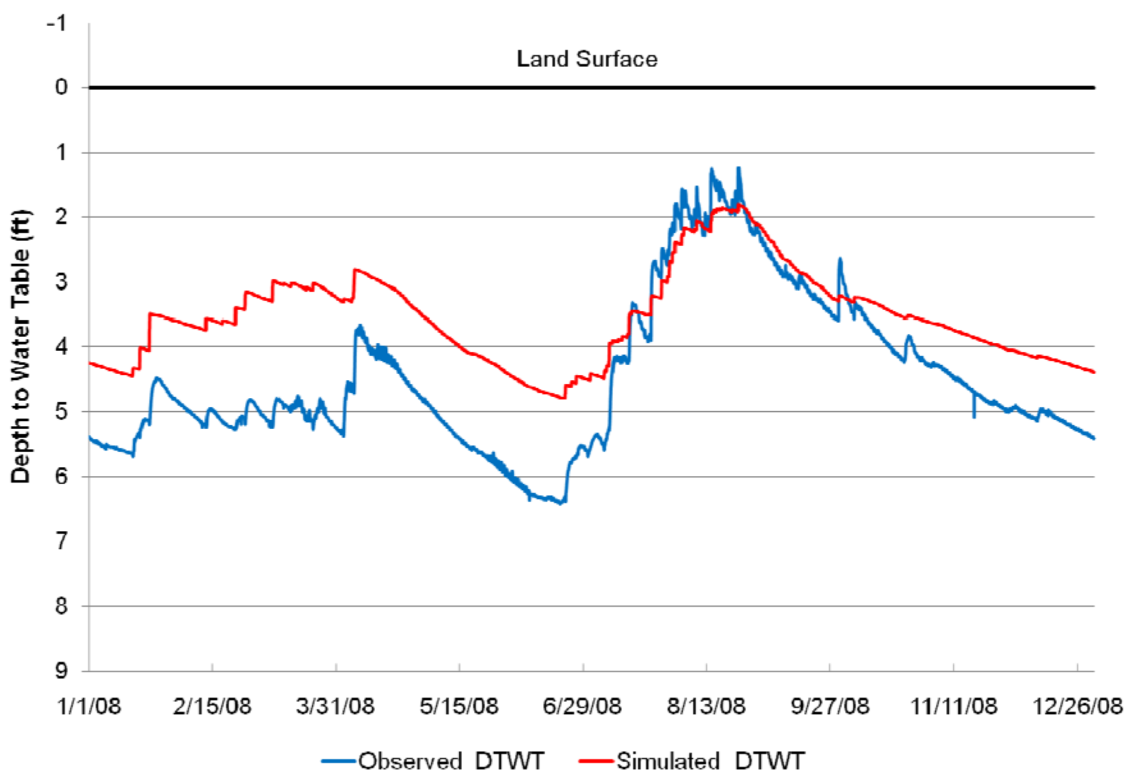

Figure 161 Eco 5 Simulated and Observed Water Table for 2008

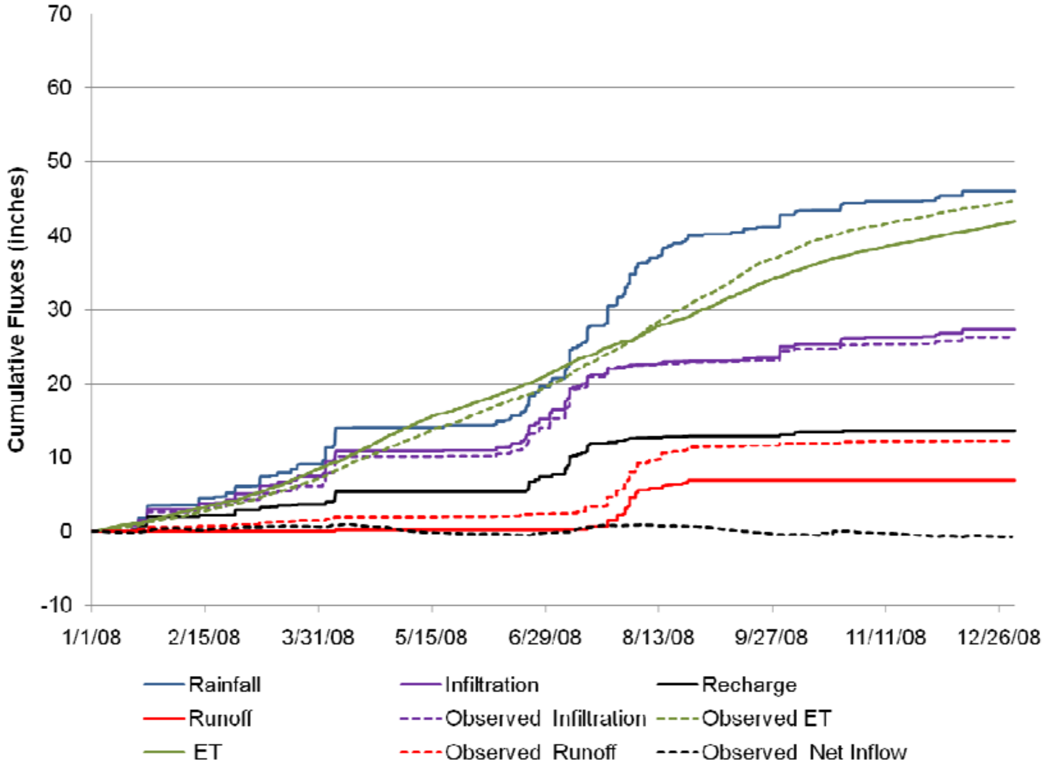

Figure 162 Eco 6 Simulated and Observed Water Balance 2008

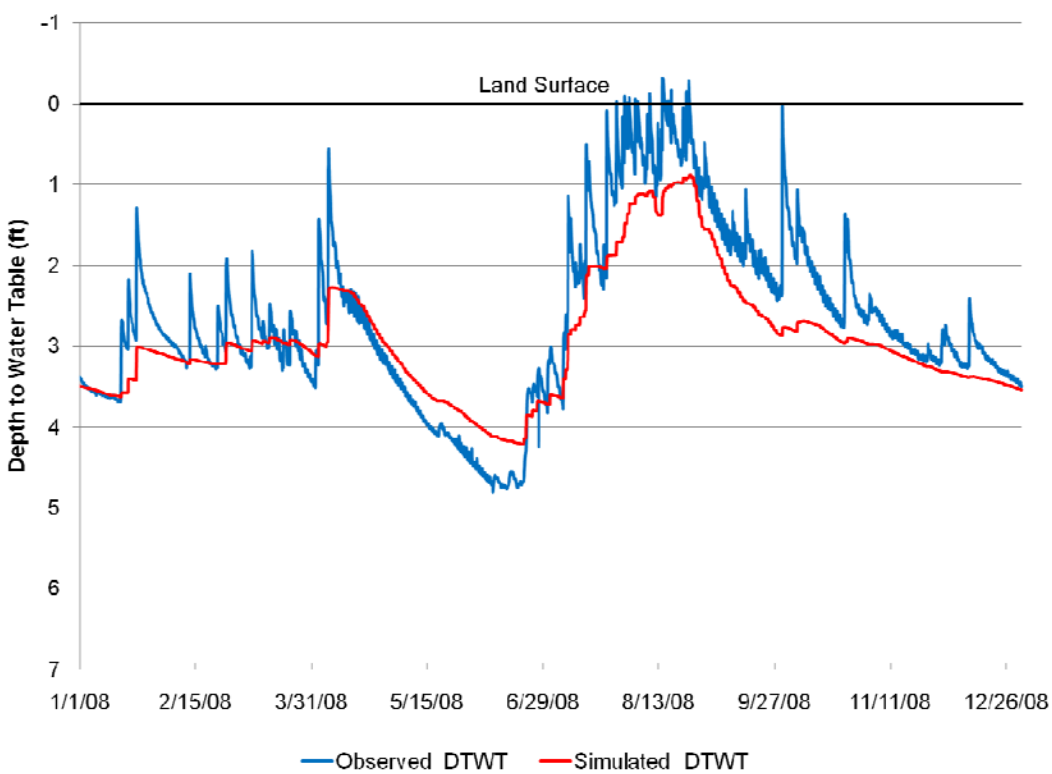

Figure 163 Eco 6 Simulated and Observed water Table for 2008

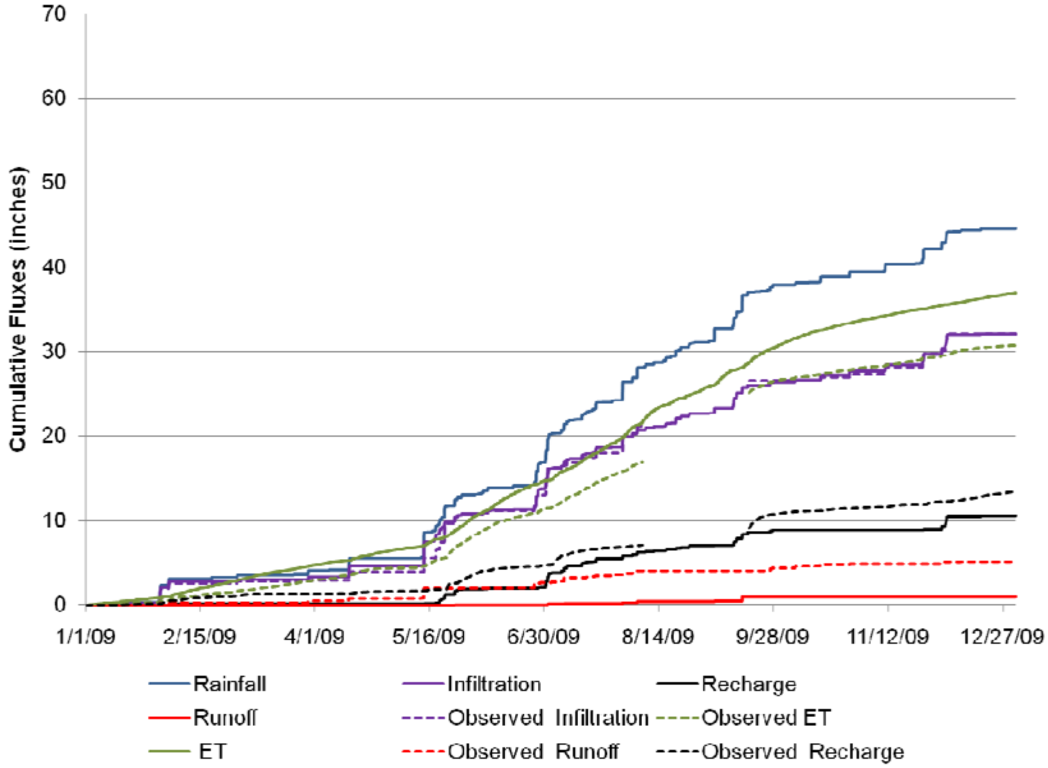

Figure 164 Eco 1 Simulated and Observed Water Balance for 2009

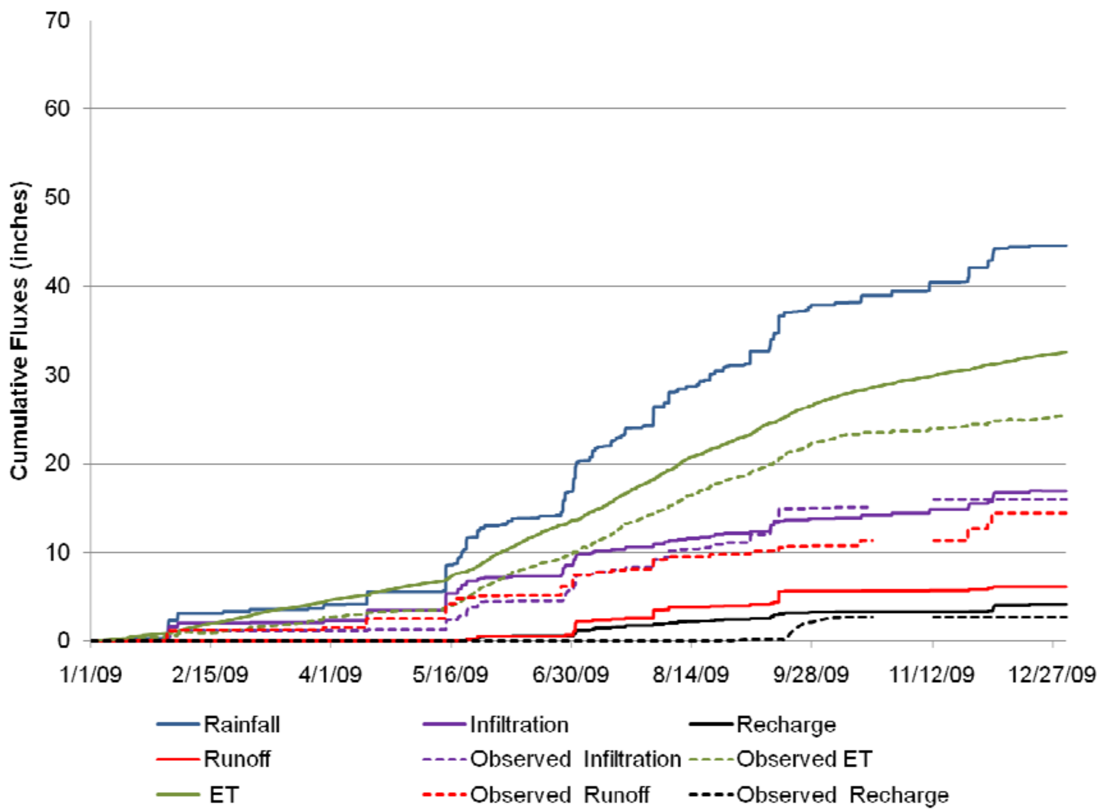

Figure 165 Eco 2 Simulated and Observed Water Balance for 2009

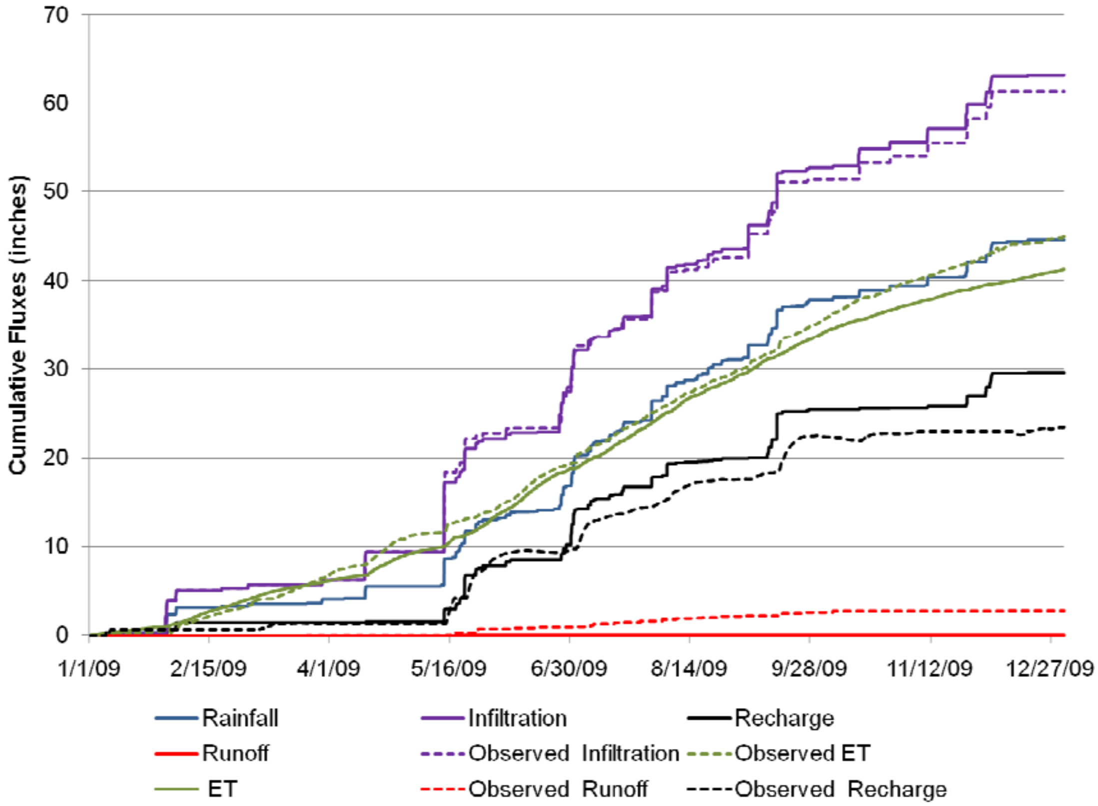

Figure 166 Eco 3 Simulated and Observed Water Balance for 2009

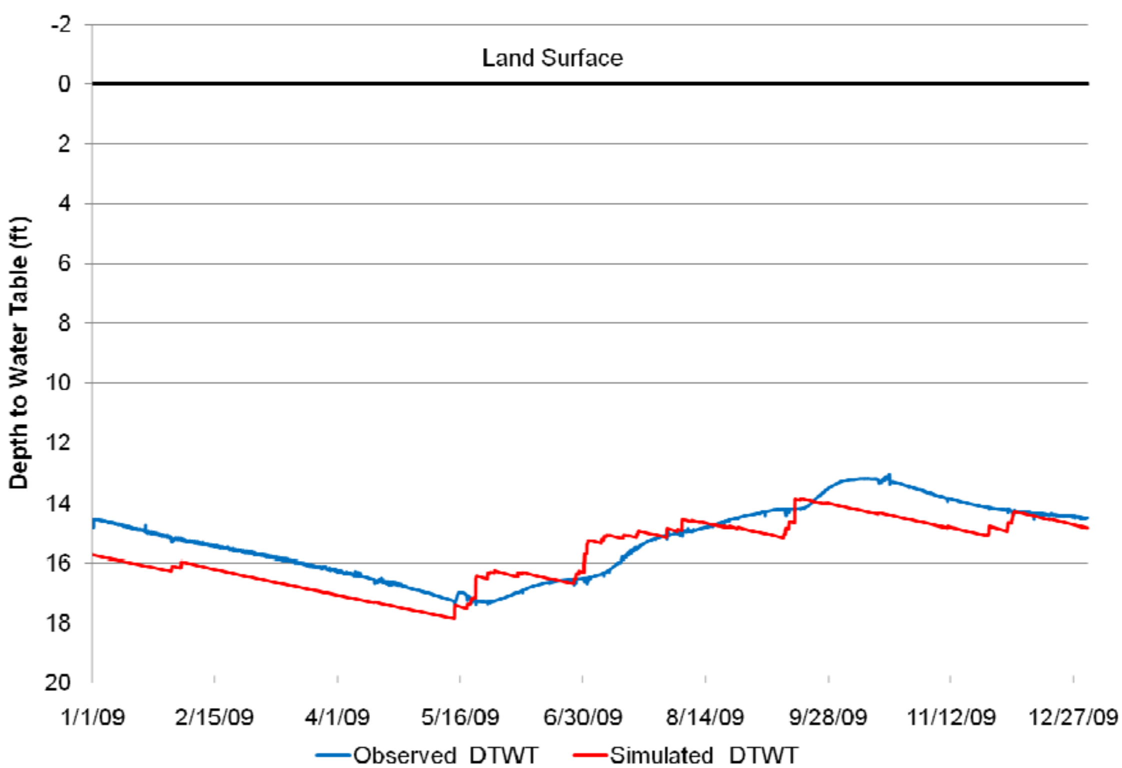

Figure 167 Eco 3 Simulated and Observed Water Table for 2009

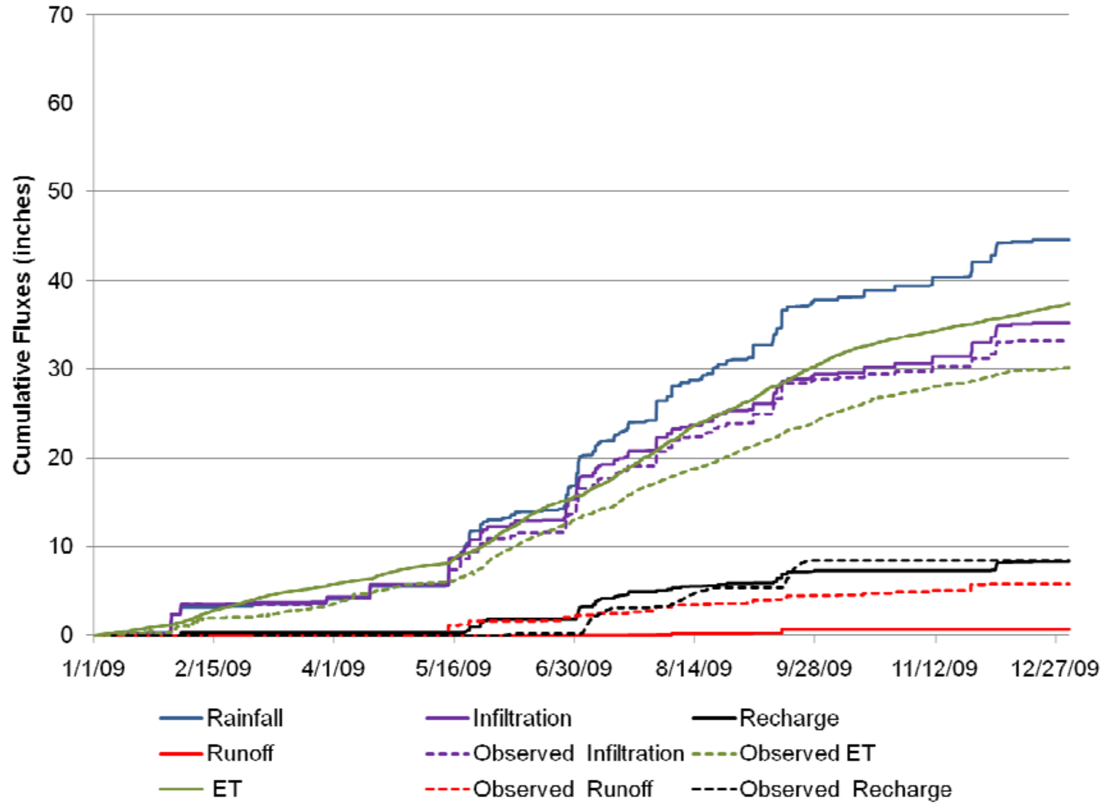

Figure 168 Eco 4 Simulated and Observed Water Balance for 2009

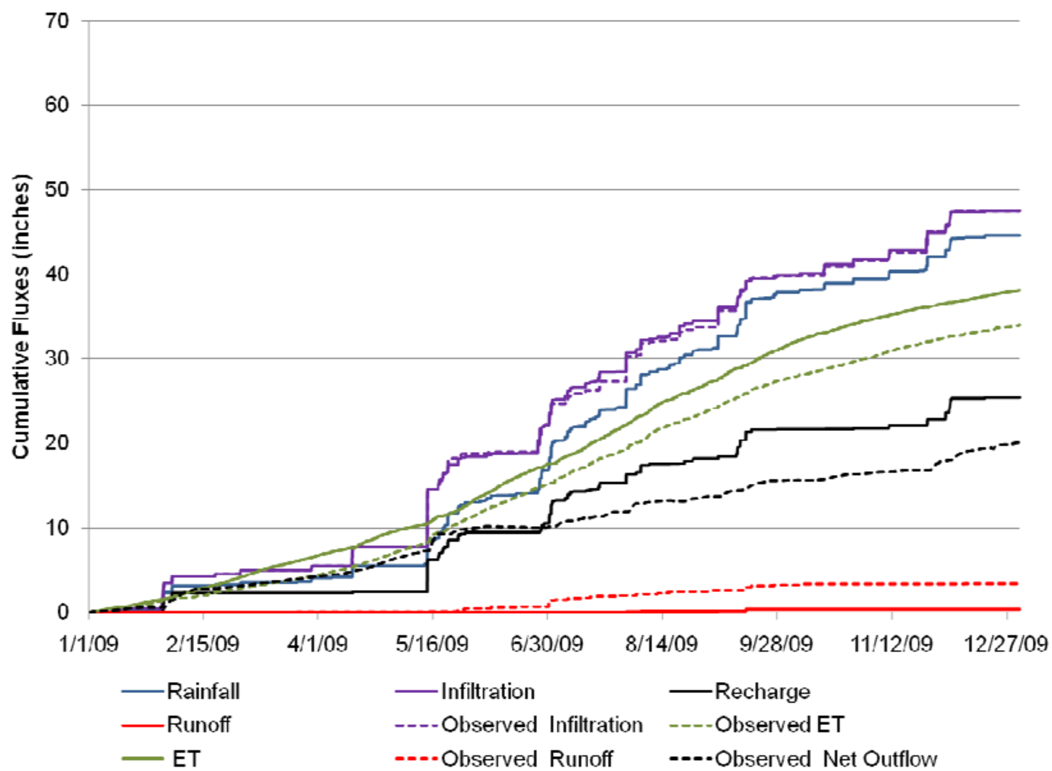

Figure 169 Eco 5 Simulated and Observed Water Balance for 2009

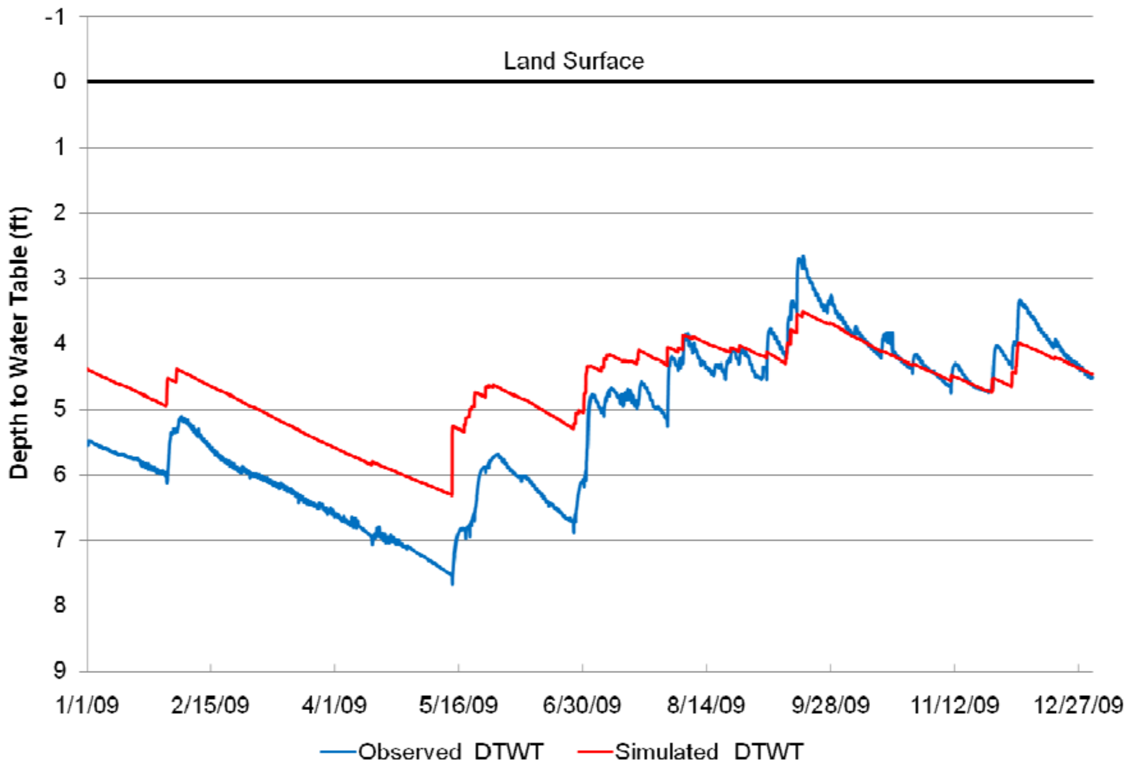

Figure 170 Eco 5 Simulated and Observed Water Table for 2009

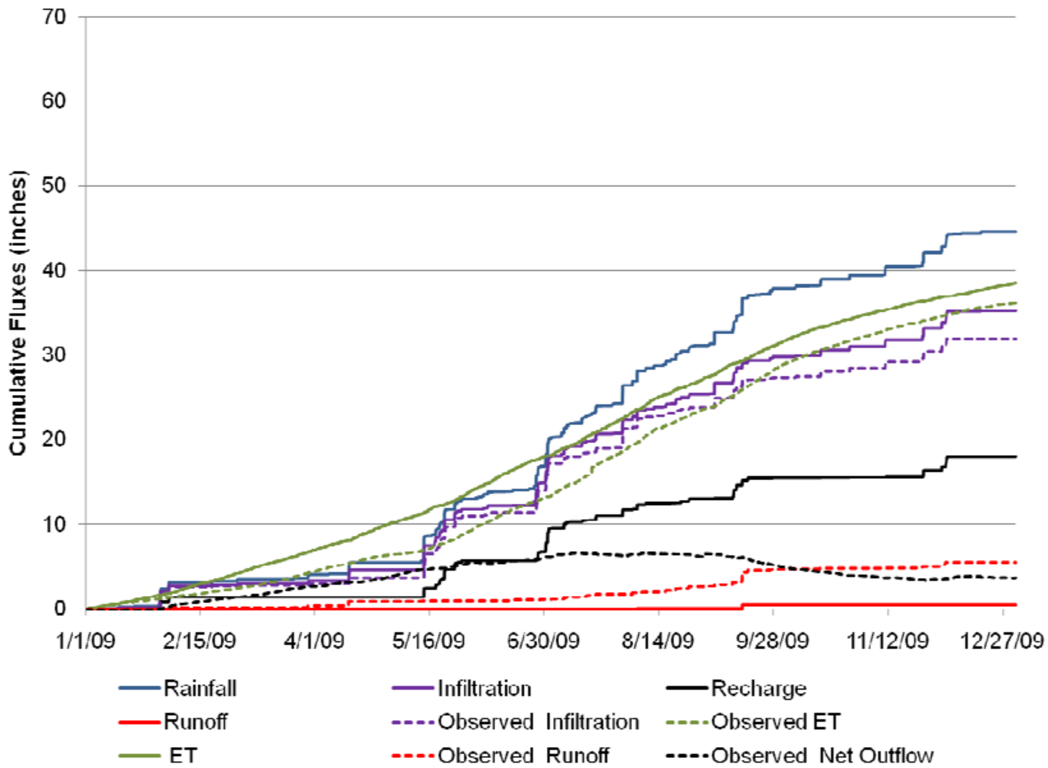

Figure 171 Eco 6 Simulated and Observed water Balance for 2009

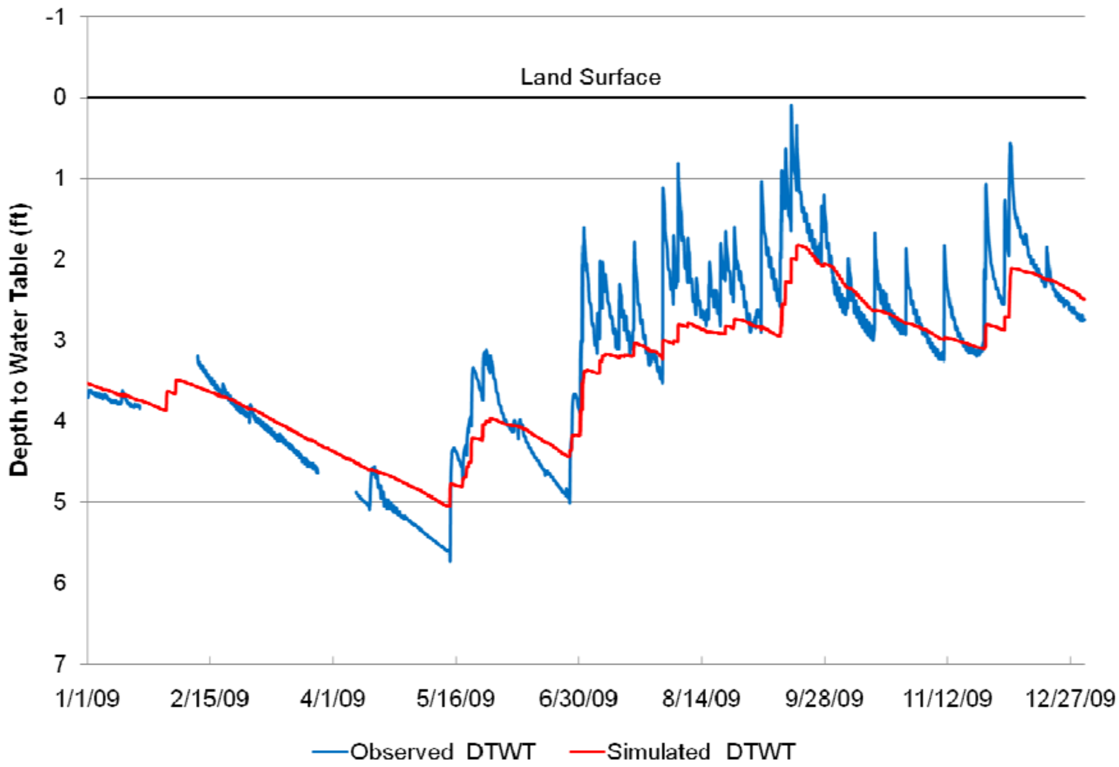

Figure 172 Eco 6 Simulated and Obserevd Water Table for 2009

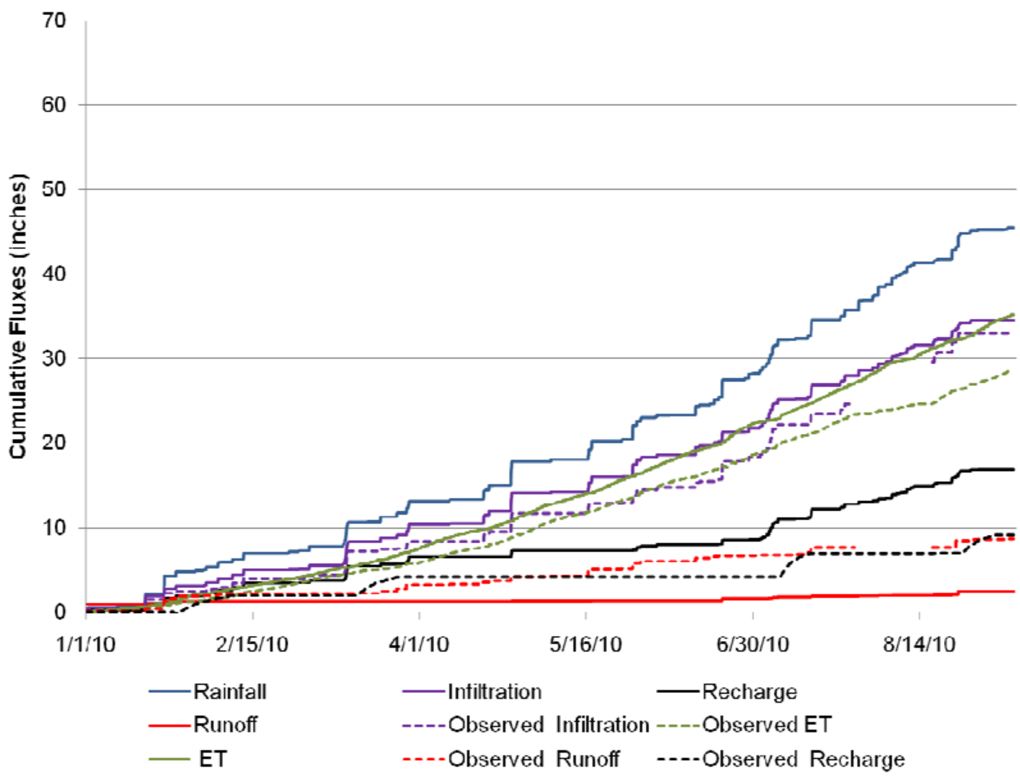

Figure 173 Eco 1 Simulated and Observed Water Balance for 2010

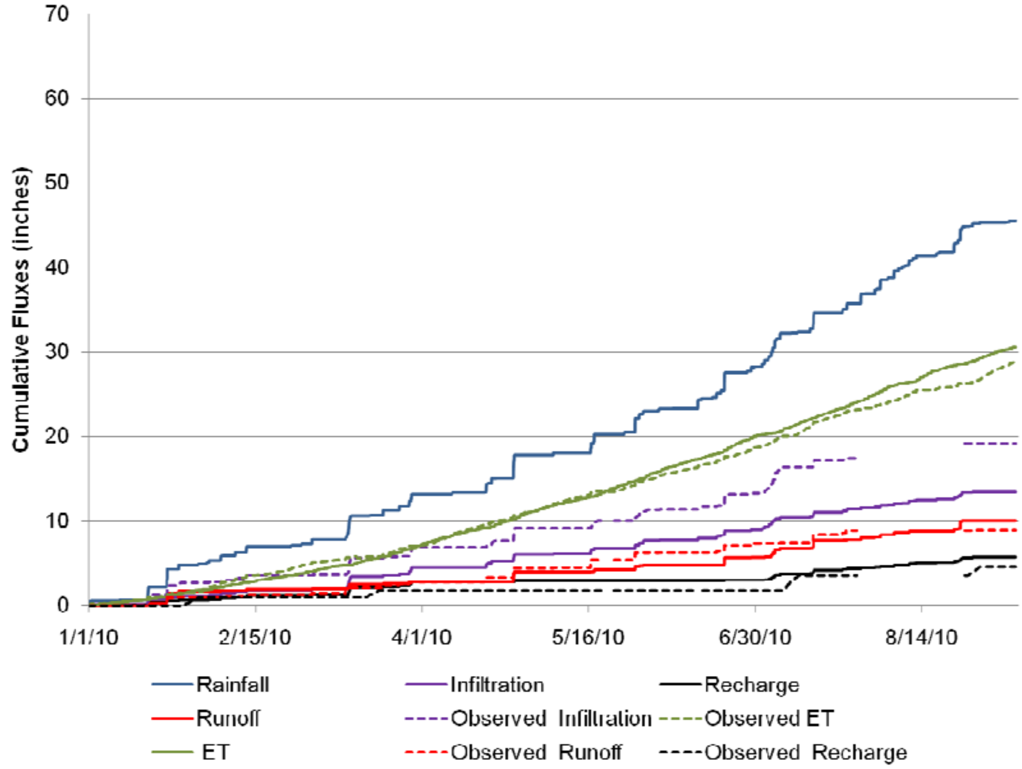

Figure 174 Eco 2 Simulated and Observed Water Balance for 2010

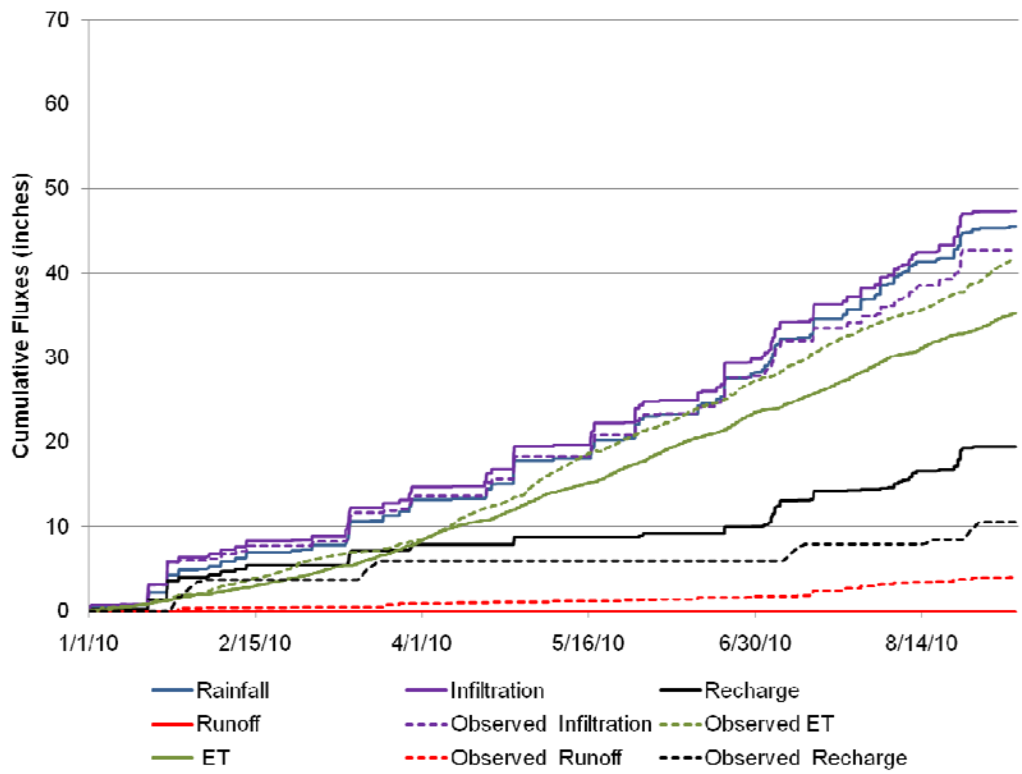

Figure 175 Eco 3 Simulated and Observed Water Balance for 2010

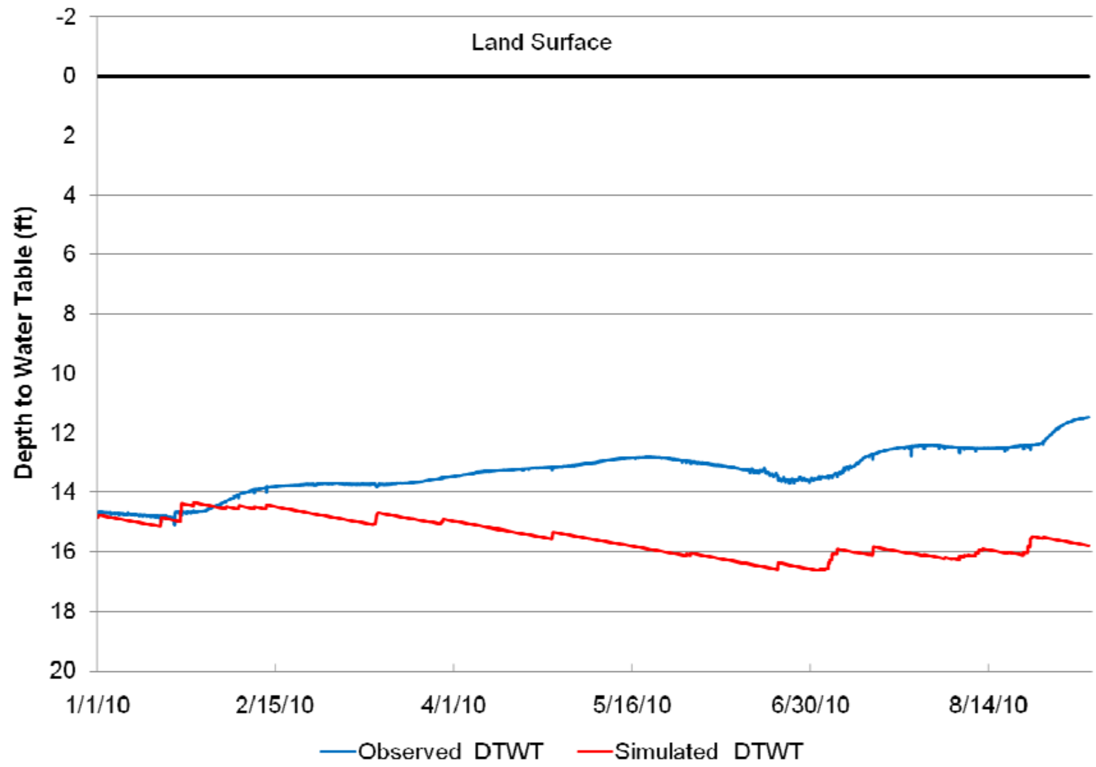

Figure 176 Eco 3 Simulated and Observed Water Table for 2010

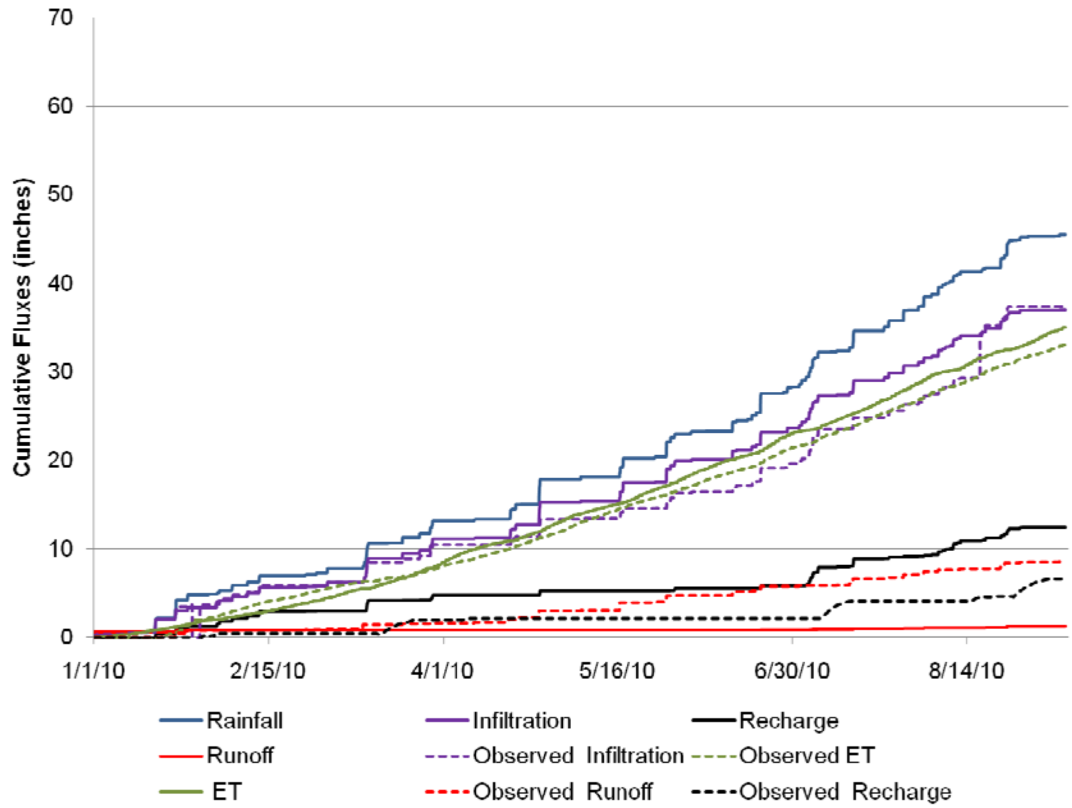

Figure 177 Eco 4 Simulated and Observed Water Balance for 2010

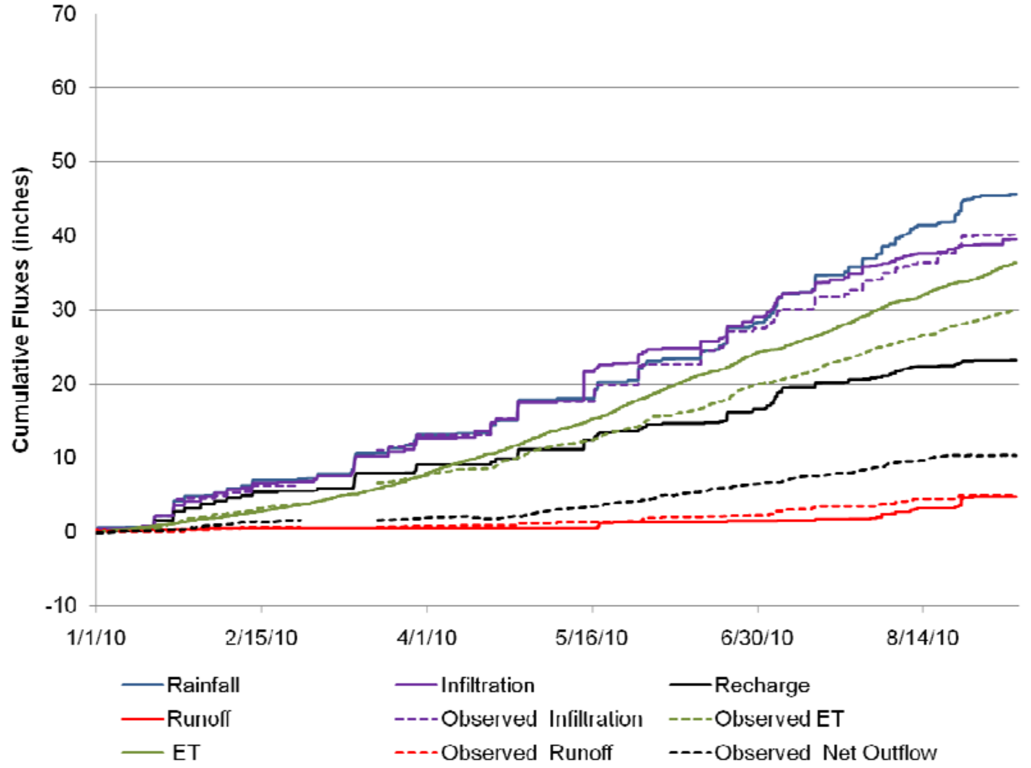

Figure 178 Eco 5 Simulated and Observed Water Balance for 2010

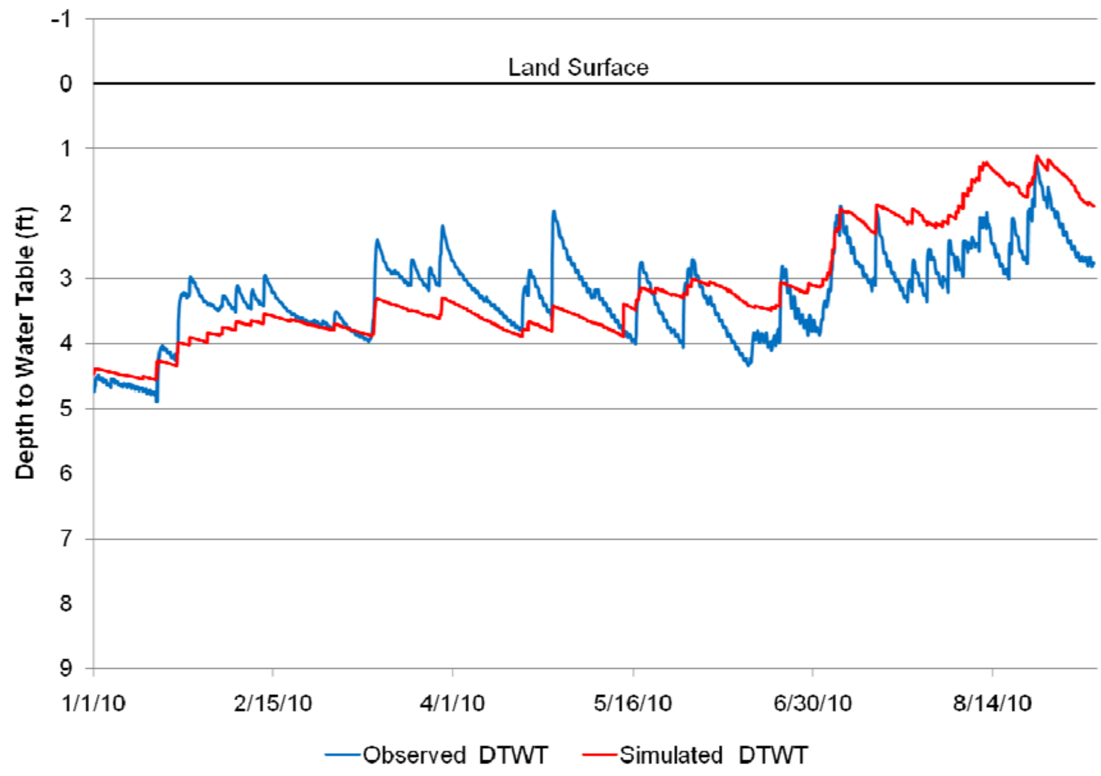

Figure 179 Eco 5 Stimulated and Observed Water Table for 2010

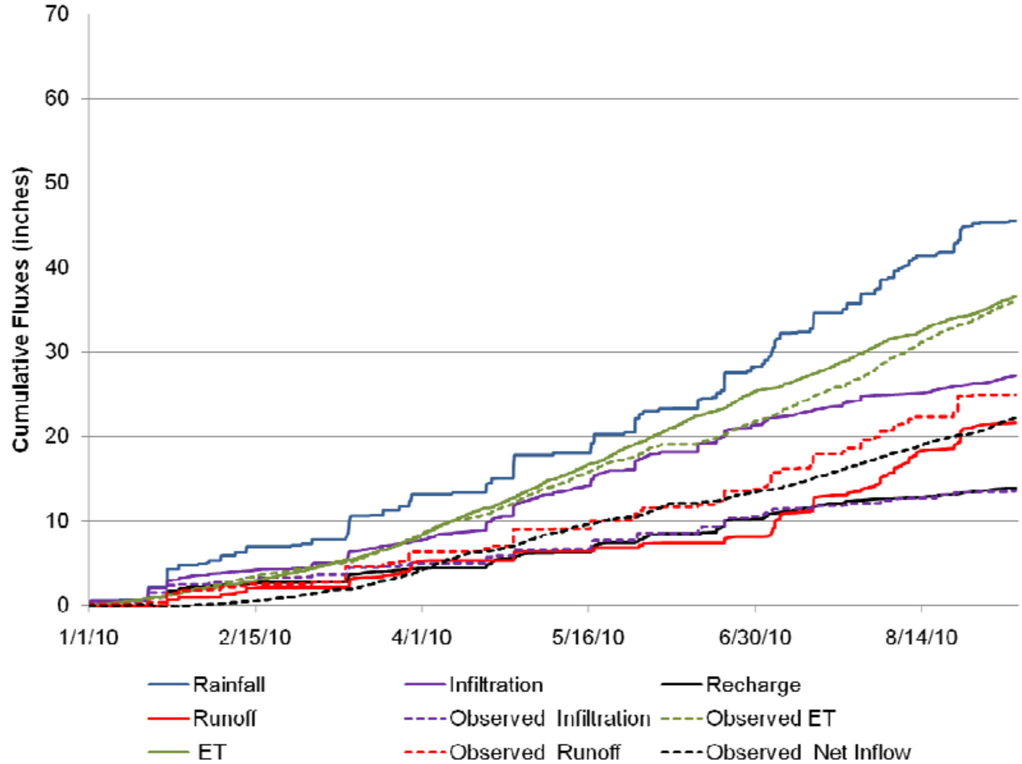

Figure 180 Eco 6 Simulated and Observed Water Balance for 2010

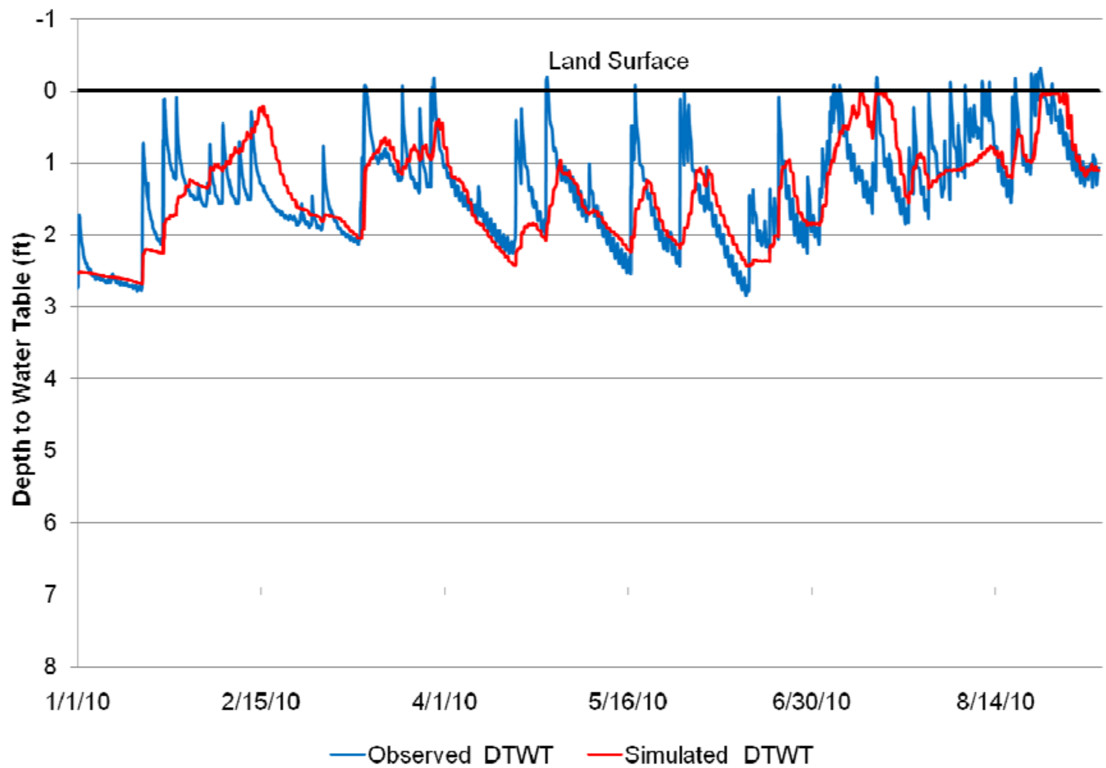

Figure 181 Eco 6 Simulated and Observed Water Table for 2010

Table 14 Summary of Simulated Fluxes at the Eco Sites

Eco 1					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	34.4	37.3	34.0	31.7	34.4
Infiltration	32.8	32.1	32.6	35.0	33.1
Runoff	2.4	6.1	0.8	2.1	2.8
Run In	6.9	8.0	1.6	2.9	4.9
Recharge	13.7	18.2	13.8	20.6	16.6

Eco 2					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	29.8	33.8	32.6	0.6	24.2
Infiltration	14.2	13.1	16.0	13.4	14.2
Runoff	7.3	10.4	6.1	10.0	8.4
Run In	1.4	0.4	0.2	0.7	0.7
Recharge	3.5	3.9	4.1	5.8	4.3

Eco 3					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	37.4	38.4	41.3	35.2	38.1
Infiltration	47.2	57.6	63.2	47.3	53.8
Runoff	0.0	0.0	0.1	0.0	0.0
Run In	13.8	19.9	28.1	8.5	17.6
Recharge	17.7	29.4	29.6	19.5	24.0

Eco 4					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	39.7	38.9	37.5	35.0	37.8
Infiltration	38.2	37.6	35.3	37.0	37.0
Runoff	1.7	3.8	0.7	1.3	1.9
Run In	11.6	9.5	3.1	2.8	6.8
Recharge	11.2	14.5	8.3	12.4	11.6

Eco 5					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	36.4	44.3	38.2	36.4	38.8
Infiltration	44.4	35.9	47.6	39.5	41.8
Runoff	3.8	4.0	0.4	4.8	3.3
Run In	21.3	8.5	14.7	12.0	14.1
Recharge	23.4	20.1	25.4	23.2	23.0

Eco 6					
Cumulative Total (in)	2007	2008	2009	2010	Average
Rain	41.2	46.0	44.4	45.5	44.3
ET (soil + interceptive)	39.2	41.9	38.5	36.6	39.0
Infiltration	37.9	27.3	35.3	26.3	31.7
Runoff	3.8	6.9	1.0	22.3	8.5
Run In	14.5	1.0	1.5	0.3	4.3
Recharge	20.6	13.5	18.0	13.5	16.4

Conclusions and Recommendations

ECO Site Study

Many of the most important conclusions from this study concern the differences in recharge between deep and shallow groundwater settings. The most significant of which is that this study conclusively shows that **there is no correlation between rainfall and recharge in deep water table settings**. Recharge cannot be determined, for water table depths greater than 2 m, from rainfall alone unless ET dynamics (stress rate, depth, antecedent and post-event conditions) are included. Elaboration of this and other observations are provided in the following study conclusions.

Infiltration, recharge, runoff and ET fluxes were shown to be measureable in both deep and shallow water table environments from the results of this study. However, the study finds that the methodologies are different for shallow and deep water table. Ideally, in the shallow water table setting the soil moisture monitoring extends down through the saturated horizon, i.e., below the water table, all the time. In these shallow settings, without a Darcian lateral flow estimate in the manner of Rahgozar (2005), Rahgozar et al. (2005), and Ross et al. (2005), all that can be derived is net groundwater flux. In a shallow water table with topographic gradients lateral flux estimates can be made by calculating the one-dimensional Darcy flow using the water table slope, thickness and conductivity. Then net vertical groundwater flow can be derived from the difference in net groundwater flow and estimated lateral flow. In the case of topographically flat or homogeneous settings, net lateral surficial groundwater flow can be neglected as it is negligible and the net groundwater flux becomes the vertical estimate uniquely.

Measurements, observations and calculations from this study have shown utility for testing the formulation and function of hydrologic models as demonstrated by the system testing the Integrated hydrologic model Ross et al (2004), IHM, as well as improving our understanding of overall hydrologic fluxes in these environments. The data gathered from this study should also prove useful for future hydrologic studies and understanding for 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.

This study demonstrates that there is a pronounced difference in water-table response to rainfall events between deep and shallow water-table environments. In shallow water-table environments, the water table stresses (and thus responses) are very rapid and must be assessed over periods of minutes to an hour. In deep settings, the rainfall/ET dynamics are integrated over the travel period through the uptake environment. These significant timescales are multiple days, and in some cases, weeks to months. In the deep setting, if the vadose zone is sufficiently dry, the infiltrating water (even from very large events) may be completely taken up by the vadose zone before reaching the water table due to post-event low rainfall/high ET stress periods. Again, this behavior is subject to the post-event dynamics over the timescale of weeks to months. How much net flux occurs will depend on the stress period (including season), vegetative cover and extinction depth. For the reasons of higher ET stress and deeper extinction depth, in similar soils, a forested area will provide less recharge than an area containing grassed pasture for the same stress period, except perhaps if it is deciduous and in a winter dormant period. The same is not necessarily the case in shallow water table settings whereby the shallow recharge totals will be more comparable.

This loss of soil moisture and associated maintenance of high vadose zone recharge potential is more pronounced during the late spring when ET is high and the water table is at the annual deepest condition. With the exception of a few heavy rainfall events, almost all of the infiltration and potential percolation water is captured in the vadose zone. During the wetter summer months given that the daily ET burden is continually being mostly satisfied by interception and shallow soil storage, much more recharge to the water table occurs. However, accumulates and percolates gradually over the whole period in the case of deeper water table settings (>2m). At a deep water-table location, a significant rainfall event may produce no recharge during the dry season or significant recharge when the soil moisture is sufficient to allow infiltration later on during the wetter period. In general, small rainfall events at the deep water-table locations, where shown to produced no recharge during the dry season. There was no correlation between rainfall and recharge when soil moisture was ignored. For these environments, attempting to estimate recharge by multiplying rainfall by a factor will likely overestimate recharge during dry periods and underestimate recharge during wet periods.

In contrast, at the shallow water table location most rainfall events produced some recharge. Much of that recharge, however, was quickly lost to ET. Plants in this environment are able to extract water directly from the water table in contrast to plants in the deep water-table environment whereby they are only able to derive moisture from a limited storage vadose zone. In shallow water table settings, during the wet season, the water table was near land surface. When the capillary fringe approaches the land surface, near-saturation soil moisture conditions exist and there is little fillable pore space available for infiltration. Small rainfall events can produce a large rise in the water table which is quickly offset by a large decline in the water table from ET. Much of the wet season is characterized by frequent large and rapid changes in the position of the water table. Deeper water table conditions show a delayed and subdued response to rainfall.

At the deep water-table sites, there were significant delays (up to nearly a month) between rainfall and recharge to the water table. The delay was a function of the depth to the water table, antecedent condition (the initial moisture content in the vadose zone), and the post-event rainfall/ET stress period. The deeper the water table the greater the delay, and the greater the moisture content the less the delay. Because the percolation process through the deep uptake horizon is many days, if post–event conditions become dry and the ET stress is high, the percolation flux becomes taken up by the plants, further hindering recharge.

Another factor affecting recharge is slope. One of the wells and moisture profiles was installed in a high slope (>9%) setting along an old dune ridge (ECO-2). Infiltration at the mid-slope location calculated using the water-balance method was observed to be approximately ½ the infiltration at other locations that were on milder (but still relatively steep) topographic gradients. Runoff was observed to be very high at the mid-slope location as well as directly proportional to slope for the other settings. Similarly, the low slope environments down-gradient from the high slope stations were observed to receive disproportionately higher run-in infiltration. Slopes have shown to be an important consideration with hydrologic modeling; high slopes produce more runoff and less infiltration consistent with the literature, and should play a role in discretization.

Water balance and flux terms were developed for each site using soil moisture, weather data and water-table elevations. The methodology created to derive these terms will be useful for providing data to test the response of hydrologic models in various settings and to provide calibration targets. The demonstration that water budgets can be measured with this technology is an important contribution to the understanding of recharge and evapotranspiration which have been particularly difficult to quantify.

Recommendations for Future Research

It would be useful to further investigate the timing of recharge to rainfall in a range of deeper surficial wells. ECO-3 was the only well that had a reasonably deep water table (~13 feet). Because recharge is a function of the depth to the water table and the antecedent soil moisture condition, data from wells with a variety of water table depths collected over a period of several years should provide valuable information for the timing of recharge through wet and dry periods.

The soil moisture sensors in this study were limited to six feet in depth. There are now single soil moisture sensors that can be installed to greater depths. A more thorough investigation would require that moisture sensors be placed closer to the water table in deeper environments so that the wetting front could be tracked to the water table.

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. The Water Management District encompasses many areas of significant relief, notably along ridge features and in the vicinity of drainage features. Because higher slope environments appear to generate reduced recharge and increased runoff, more data from a variety of hillslope sites would be desirable.

The surficial-aquifer soil at the Eco Site is a fine-grained quartz sand with little to no clay content. Although this is a common surficial-aquifer material within the District, there are other types of surficial-aquifer materials, such as mucks and clayey soils, that may have different recharge and ET properties. Similar types of data collected in surficial aquifers that are representative of the various soil types in the District would be useful in District-wide scale models.

The USGS has a MODFLOW package available, UZF1, that models groundwater flow in the unsaturated zone. This package has the capability to calculate ET fluxes and recharge fluxes with the appropriate time lag based on soil moisture conditions and depth to the water table. These capabilities could be particularly important for more complete groundwater models and may have an application to integrated surface water-groundwater models. The UZF1 package uses a kinematic-wave approximation of the Richards equation. The approximation ignores capillary forces which may adversely affect recharge volume and timing. The data collected for the Eco Site project could prove valuable for testing the UZF1 package in true field setting. The UZF1 package is an integral component in the USGS public-domain integrated model GSFLOW and the reliability of the UZF1 calculations could be an important consideration in future District studies.

IHM apportions infiltration to vadose-zone storage based on soil moisture conditions, but was not designed to apply recharge to the underlying aquifers with a delay as a function of soil moisture or depth to the water table. Data collected for this project can be used to refine the recharge algorithms in IHM for deep-water-table environments leading to improved prediction capabilities for IHM.

References

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. Operational estimates of reference evapotranspiration. Agron. J. 81:650–662.

Buss, P. 1993. "The use of capacitance based measurements of real time soil water profile dynamics for irrigation scheduling." Proc. of the National Conf. of the Irrig. Assoc., Irrig. Assoc. of Australia, Homebush, NSW, Australia.

Fares, A., and. Alva, A. K. 2000. "Evaluation of capacitance probes for optimal irrigation of citrus through soil moisture monitoring in an entisol profile." Irrig. Sci., 19: 57-64.

Monteith, J. L., 1965. Evaporation and environment, in: The state and movement of water in living organisms, Symposium of the Society of Experimental Biology: San Diego, California G.E. Fogg, ed., Academic Press, New York, p.205-234.

Morgan, K. T., Parsons, L. R., Wheaton, T. A., Pitts, D. J. and Obreza, T. A. 1999. "Field calibration of a capacitance water content probe in fine sand soils." Soil Sci. Soc. Am. J., 63: 987-989.

Penman, H., L. 1948. Natural evaporation from open water, bare soil, and grass: Proceedings of Loyal Society of London, Series A, v. 193, p. 120-146.

Rahgozar, M. M., 2005. Ph.D. Dissertation, University of South Florida.

Rahgozar, M., M. Ross, and A. Said, 2005. Estimation of Evapotranspiration and Water Budget Components Using Continuously Soil Moisture and Water Table Monitoring, Hydrological Science & Technology, 21(1-4): 21(1-4): 119-142.

Ross, Mark, Ken Trout, Swarna Pujari, Ahmed Said,., and Manda Rahgozar. (2005). Measurement of Surficial Aquifer Recharge, ET, Rainfall, Runoff and Stream-Aquifer Interaction Characteristics of the Central and Southern Region of the Southwest Florida Water Management District. Prepared for Tampa Bay Water (TBW) and Southwest Florida Water Management District, Publication no: USF-CMHAS 0353.0509.59, Center for Modeling Hydrologic and Aquatic Systems, University of South Florida, September 2005

Ross, M., A. Said, J. Geurink, P. Tara, and A. Aly, 2005. Evapotranspiration Hierarchy and Allocation for Integrated Surface and Groundwater Models in West-Central Florida, Hydrological Science & Technology, 21(1-4): 157-168.

Ross, M., Geurink, J., Tara, P., Trout, K., and Jobes, T., 2004. Integrated Hydrologic Model (IHM) Volume 1: Theory Manual, Prepared for Tampa Bay Water, Publication Number USF-CMHAS 0383.0304.58, Center for Modeling Hydrologic and Aquatic Systems. University of South Florida, Tampa Florida, March, 2004

Trout, Ken and Mark Ross, 2005. Intensive Hydrologic Data Collection in a Small Watershed in West-Central Florida, Hydrological Science & Technology, 21(1-4): 187-195.

Trout, Ken and Mark Ross, 2006. Estimating Evapotranspiration in Urban Environments, *Urban Groundwater Management and Sustainability*, J.H. Tellam, et al., editors, pgs 157-168, Springer.

Appendix A – Stratigraphic Logs

Table A - 1. Stratigraphic well log for ECO-1.

Eco-1

Well Log 6/1/2006

Depth (ft)	Soil Description
0-1	Brown Fine Sand
1-4	Light Brown Fine Sand
4-6	Light Brown-Red Fine Sand
6-10	Very Light Brown Fine Sand
10-12	Very Light Brown Fine Sand
12-12.5	Light Brown Fine Sand
12.5-13.5	Tan Clayey Sand
13.5-16	Gray Clay

Notes:
Total Depth: 16 ft
Screen Length: 5 ft
Screened Interval: 11-16 ft

Figure A - 1. ECO-01 Core 0-16 feet.

Table A - 2. Stratigraphic well log for ECO-2.

Eco-2	
Well Log	6/1/2006
Depth (ft)	Soil Description
0-1.5	Light Brown Fine Sand
1.5-6.5	Very Light Brown Very Fine Sand
6.5-10	Very Light Brown Very Fine Sand-almost white
10-10.7	Light Brown Fine Sand
10.7-11.3	Brown Fine Sand (maybe fall)
11.3-13.5	Very Light Brown Very Fine Sand
13.5-14.5	Red-Tan Very Fine Sand
14.5-18	Red Clayey Sand
18-22	Light Brown Sandy Clay

Notes:
Total Depth: 21 ft
Screen Length: 10 ft
Screened Interval: 11-21 ft
Top of screen in Very Light Brown Very Fine Sand

Figure A - 2. ECO-2 Core, 0-14 ft.

Figure A - 3. ECO-2 Core, 14-22 ft.

Table A - 3. Stratigraphic well log for ECO-3.

Eco-3	
Well Log	6/1/2006
Depth (ft)	Soil Description
0-4	Brown Fine Sand
4-10	Light Brown Fine Sand
10-19	Light Brown Fine Sand
19-24	Light-Red Clayey Sand, with Red Lenses

Notes:
Total Depth: 22 ft
Screen Length: 10 ft
Screened Interval: 12-22 ft
wet at 14 ft; water table possible at 17 ft

Figure A - 4. ECO-3 Core, 0-24 ft.

Table A - 4. Stratigraphic well log for ECO-4.

ECO-4	
Well Log	6/2/2006
Depth (ft)	Soil Description
No Core taken	

Notes:
Total Depth: 27 ft
Screen Length: 10 ft
Screened Interval: 17-27 ft
No obvious confining layer observed when well installed
Rock (may be Limestone or Chert) at 27 ft

Table A - 5. Stratigraphic well log for ECO-5.

ECO-5	
Well Log	6/2/2006
Depth (ft)	Soil Description
0-1	Gray Fine-Medium Sand
1-2	Brown Fine-Medium Sand with Organics
2-4	Light Brown Fine Sand
4-5.5	Brown Fine Sand with darker brown Organics
5.5-13	Light Gray Fine Sand
13-13.5	Light Gray to Orange Grading Fine Sand
13.5-14	Orange Clayey Sand
14-19	Light Gray Clayey Sand - Grading to More Clay Content

Notes:
Total Depth: 19 ft
Screen Length: 10 ft
Screened Interval: 9-19 ft

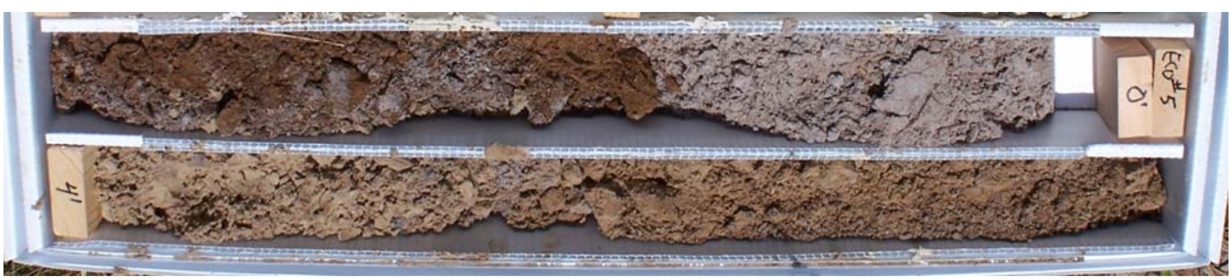

Figure A - 5. ECO-5 Core, 0-4 ft.

Figure A - 6. ECO-5 Core, 4-19 ft.

Table A - 6. Stratigraphic well log for ECO-6.

ECO-6	
Well Log	6/5/2006
Depth (ft)	Soil Description
0-2	Dark Brown Medium-Fine Sand
2-9	Light Brown Fine Sand
9-10	Very Light Fine Sand-Clean Quartz, Well Rounded and Sorted
Notes: Wet at 5 ft Standing Water inhole at 6 ft below land surface	

Figure A - 7. ECO-6 Core, 0-10 ft.

Table A - 7. Stratigraphic well log for FL-1.

Well Log	9/11/2006
Depth (ft)	Soil Description
0-6	Light Red-Brown Fine Sand - Hollow Stem
6-14	Very Light Brown Fine Sand
14-19	Brown Clayey Sand
19-28	Gray Clay - Tight
28-31	Clayey Sand
31-32	Very Light Brown Dry with Small Limestone Nodules
32-33	Red-Brown Clayey Sand - Wet
33-36	Very Light Brown Clayey Sand with Limestone Pieces
36-37	Gray-Brown Sandy Clay
37-38	Blue-Gray Clay with Limestone Pieces
38	Stopped core sampling, began mud drilling; Lost circulation at 40 ft

Notes:
Total Depth: 60 ft
Screen Length: 15 ft
Screened Interval: 45-60 feet

Figure A - 8. FL-1 Core, 0-40+ ft.

Table A - 8. Stratigraphic well log for FL-2.

Well Log	6/2/2006
Depth (ft)	Soil Description
0-8	Light Brown Fine Sand-loose
8-12	Very Light Brown Fine Sand-damp
12-13	Very Light Brown Fine Sand-damp
13-21	Light Gray Fine Sand-water table near 16 ft
21-21.5	Reddish Fine Sand
21.5-22	Orange Silty Fine Sand, some clay
22-29.5	Gray Clay with Orange Staining
29.5-30	Orange Clay with weathered Limestone
30-30.5	Gray Clay with Orange Staining
30.5-32	Red-Gray Clay with Limestone nodules
32-33	Orange Wet Sandy Clay with Limestone
33-34	Gray Silty Medium Sand
34-35	Orange-Gray Sandy Clay with Small Chert Fragments
35-36	Gray Sandy Clay
37-37	Wet (sat) Sandy Clay with Limestone Pieces
37-37.8	Orange-Gray Clay with Limestone fragments
37.8-38	Light Gray Limestone Chips
38-40	Tan-Gray Sandy Clay with Limestone
40-42.5	Light Brown Silty Clay with Limestone Pieces
42.5-43.7	Light Tan Silty Clay with Limestone pieces (up to 2.5 inch diameter)
43.7+	Rock at 44 feet; Stopped core sampling, began mud drilling

Notes:
Total Depth: 58 ft
Screen Length: 15 ft
Screened Interval: 43-58 feet
Well drilled into limestone to 64 feet with button bit.
When augers removed, 6 feet of casing pulled out of well.
When pumped, yield from well was good as was water clarity.

Figure A - 9. FL-2 Core, 0-28 ft.

Figure A - 10. FL-2 Core, 28-43.7 ft.

Appendix B – Procedure to Determine Net Soil Moisture Flux

For this analysis, each of the column's eight vertically placed sensors was used to determine the soil moisture content present in the 2 m vadose zone. The sensor observed values, recorded every ten minutes, were then averaged hourly. The resultant hourly moisture content is integrated over the depth in the manner of Rhagozar (2005) and converted into depth/area (inches of water present). From this total soil moisture (TSM) value, the differences between successive hourly values were used to determine either a net increase or decrease in the soil column. From these hourly fluctuations, positive changes in TSM are indicative of either infiltration (if in the presence of a rain event), or groundwater seepage support (if in the absence of a rain event). Conversely, negative changes in TSM are indicative of soil evapotranspiration (ET), net negative groundwater processes, or a combination thereof.

Due to the time it takes a rainfall event to percolate down through the soil column, it was determined that changes in TSM are spuriously noisy on average up to four hours following small rain events (< 0.4-inches) and up to 12 hours following larger events (> 0.4-inches). For this reason, 4- and 12-hour periods, respectively, following rain events were used to calculate net event infiltration. Following these omitted periods the net ET and percolation fluxes can be derived through numerical integration of the hourly derived TSM differences. The first step in arriving at the water budget was to establish an estimate of the vertical processes which are present due to availability of radiation stress (based on the time of the day). It was assumed that changes between midnight and 6 am are indicative of groundwater fluxes and changes during daylight hours include ET stress in the manner of Trout and Ross, 2005. Steps for determining this smooth vertical flow (SVF) are outlined below;

Procedure for Determining the net Groundwater (Vertical Flow) and ET Estimates:

- Filtering of data during rainfall events (omission of changes) was required based on the event magnitude:
  - Events generally under 0.1-0.15" (the interception storage was found for each site described later in this section) were assumed to be completely captured by interception and therefore did not need to be filtered since effects on TSM were minimal
    - The 0.1-1.15" rainfall threshold values varied based on the interception capture observed for each individual site were fixed for each site for the duration of the study
  - A threshold filtering (omission) time for small events (.1"<x<.4") was set at 4 hours based on observations of the data. This period following the event was used to evaluate net infiltration.
- The threshold for larger events (>0.4") was set to 12 hours (again, after scrutinizing the data) Net Groundwater Fluxes found from night-time changes:
    - Changes in TSM outside of the filtered window and between midnight and 6 am were used as an indication of the net groundwater flow at that time.
- The midnight to 6 am changes are smoothed (averaged) and allowed to vary smoothly (hourly) through the day using a 3-day central smoothing technique using the previous and next day estimates
- This final hourly groundwater net flow estimate is subtracted from the actual hourly changes and the difference (which principally during the daylight hours) is

accumulated as the net ET. Thus ET estimates where derived hourly and where accumulated through time.

- Infiltration, runoff and run-in estimates where derived by event considering the overall change in soil moisture (TSM) from the start of the event through the variable filtering ("blanking") time

Thus, in the absence of a rainfall event, ET and net groundwater fluxes are calculated by taking the difference of the hourly change in TSM and the nighttime groundwater (vertical flow) estimates. In a case in which the TSM increases, there is said to be groundwater support either by lateral flow (given high water table and deep gradients) or delayed surface seepage (e.g., from depression storage infiltration). More often occurring during the day however, is a larger net decrease in TSM rate seen, understandably, directly correlated to solar radiation and moisture availability. This difference was used to arrive at the hourly ET values.

- On rare occasions (order dozen per year) large periodic one-time changes in TSM, in the absence of a rain event, are observed in the data record. Investigation reveals that these large instantaneous changes are usually resulting from sensor disturbance during maintenance but, on rarer occasions seemingly occurring for no apparent reason (believed to be electrical surges). They are for the most part pared meaning a large positive departure is followed by a similarly large negative departure some time (maybe the next hour) later. To filter these changes from the plausible values, thresholds for maximum positive and negative changes are imposed on the record. The threshold for minimum (maximum negative) change of -0.06 inches and maximum positive change of 0.03 inches were used in this analysis. However, Changes which exceed these limits are summed and later incorporated into the overall annual water budget to insure this is not a significant error possibility in the resultant water budget estimates.

For event analysis of both small and large rainfall events, as mentioned earlier, a period of four and 12 hours, respectively, are used to determine the net increase in TSM. During a rainfall event, the TSM at both the beginning and end of the 4- or 12-hour period is derived. The differences in TSM over these event periods were used to arrive at the total infiltration for the rain event.

These event changes were used to first calculate the interception evapotranspiration at each site. Since most events have no runoff, a derived interception capture rate (selectively excluding obvious events with runoff or run-in) was determined from an average for the differences between the event total rainfall amount and the observed infiltration. An example of this behavior is shown in Figure B1 and discussed below.

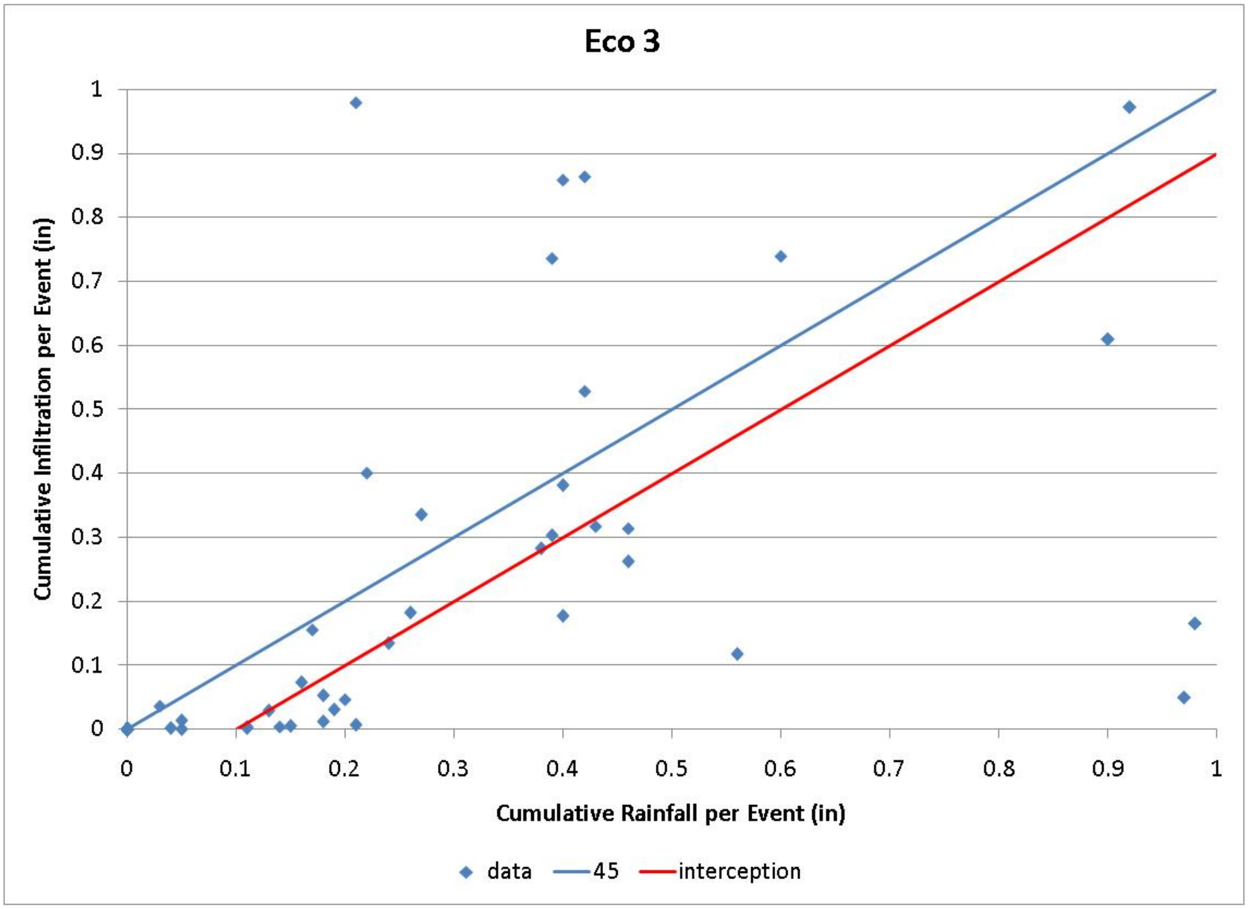

Figure B1. Derivation of 0.15 inch interception capture capacity at ECO-3.

This derived interception capture rate is then applied to all rain events to determine "net rainfall" for all event periods separated by at least 12 hours to derive net event fluxes. For those rain events which are less than the interception capture, rainfall is observed to be completely intercepted and therefore contributes to the overall ET budget and is summed as a separate water budget item. Conversely, for those rain events larger than this rate, the calculated interception is used to derive the net rainfall, runoff (or in some instances net run-in) from the net rainfall depth minus the infiltration. In rare events and more prevalent in sections downstream of high slope settings, TSM increases more than rainfall observed in the field to be from upstream run-in. These differences are accumulated as net run-in.

Net rainfall in excess of event infiltration is reported as net runoff however some of this volume is undoubtedly contributing to delayed depression storage and subsequent percolation and ET. However the exact contributions to depression storage of net runoff cannot be precisely separated by this methodology. Some moisture increases following the event "blanking" period where observed in some stations and for generally larger events indicating the presence and uncertain magnitude of depression storage effects.

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 is summed annually, whether positive or negative, and is then incorporated into the annual water budget as a separate item. Given the unpredictable variables associated with a period of missing data, no further analysis is made during such periods.

In arriving at a water budget for all six sites, two slightly different approaches were used. This is due to the classification of the environments. In ECO-1 through ECO-4, deeper water table conditions apply when compared to that of ECO-5 and ECO-6. Looking at the topography of the area and analyzing acquired water table data, Eco sites one through four never experienced a water table shallower than the 2m soil moisture measurement depth. It is for this reason that negative column fluxes exceeding and not associated with ET are characterized as net recharge. In contrast, given the shallow water table associated with both ECO-5 and ECO-6, water table recharge is some uncertain fraction of the soil moisture change when the water table is within the 2m measurement depth. Therefore, negative fluxes exceeding ET can only be characterized as net groundwater discharges out of the section. Therefore, net groundwater positive and negative fluxes which exist outside of rainfall events and not ET are accumulated as net groundwater.

Figure B1 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.

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:	3/1/2010
End Date:	2/28/2011
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

1. Norton, S. Quantifying the Near-Borehole Geochemical Response During ASR. Masters Thesis. University of Florida. May, 2007.
2. Stuart Norton, Hydrogeologist, Jones Edmunds & Associates, Inc., Gainesville, FL, Don Ellison, ASR Projects Coordinator, Southwest Florida Water Management District, Brooksville, FL and Seth Kohn,Engineer, City of Bradenton, Bradenton, FL: Preliminary Results of Full-Scale Membrane Deoxygenation at the Bradenton ASR Facility. A Status Update. September 22, 2008.
3. Wallis, I., Prommer, H., Pichler, T., Post, V., Norton, S., Annable, M.D., Simmons, C.T., (In Review), A process-based reactive transport model to quantify arsenic mobility during aquifer storage and recovery of potable water, submitted to ES&T April 15, 2011.
4. Stuart Norton and Mike Annable. Evaluation of Trace Metal Mobilization during Managed Aquifer Recharge (MAR). UF Water Institute Symposium. February 24, 2010. - Awarded 1st Place Prize.

WRRC 104B

Fiscal Year 2010

Project Status Report

Investigating Arsenic Mobilization During Aquifer Storage Recovery (ASR)

May 1, 2011

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 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.
- The City of Bradenton has authorized the use of the data set in this study and has granted site access.

Project Status

The following research was completed during Fiscal Year 2010 or are currently underway:

Demonstration Testing at Project Site

The first full-scale low-DO (degasification) ASR cycle test was completed at the Bradenton ASR site. Results indicate that degasification and dechlorination prior to recharge can control arsenic mobility during ASR. In addition to incorporation into Mr. Norton's dissertation, test results are being summarized in a manuscript for submittal to a peer-reviewed journal article.

Reactive Transport Modeling

A reactive transport model has been developed for the Bradenton ASR site to simulate high-DO test conditions. A summary of the model results has been submitted for publication (see below). The model is currently being extended to simulate the low-DO test event and continuous cycle testing under high-DO (standard ASR) conditions.

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 has been used in batch studies and preliminary column studies, discussed below.

ASR Batch Studies

Batch studies have been completed at the FGS laboratory in Tallahassee to investigate the effects of using preserved versus un-preserved core materials in ASR batch studies. These tests simulated both native groundwater and ASR conditions.

Core-column Design

The design of intact core-column experiments is nearly complete. 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. Preliminary intact core-column experiments have been completed to determine the magnitude and timing of the peak arsenic concentration observed during column experiments. This information will be used to improve the design of the column experiments.

Ph. D. Examinations

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

Mr. Norton is preparing to defend his dissertation in late June or early July, 2011.

Presentations and Publications

Wallis, I., Prommer, H., Pichler, T., Post, V., Norton, S., Annable, M.D., Simmons, C.T., (In Review), A process-based reactive transport model to quantify arsenic mobility during aquifer storage and recovery of potable water, submitted to ES&T April 15, 2011.

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

References

Arthur, Jonathan D., Dabous, Adel A., and Cowart, James B., 2002, Mobilization of arsenic and other trace elements during aquifer storage and recovery, southwest Florida: USGS Open-File Report 02-89

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

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:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	19
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Methods, Models
Descriptors:	
Principal Investigators:	Ramesh Teegavarapu

Publications

1. Teegavarapu, R. Characterizing Rain Gage-Radar (NEXRAD) Relationships using Inductive Modeling. AGU Fall Meeting, Abstract Published, San Francisco, December 11, 2007.
2. Teegavarapu, R. Evaluation of Functional Forms of Rain Gage - Radar (NEXRAD) Data Relationships. ASCE, World Environmental and Water Resources Congress, 2008, Hawaii, published in CD ROM proceedings, 8 pages.
3. Teegavarapu, R. Infilling of Rain Gage Records using Radar (NEXRAD) Data: Influence of spatial and temporal variability of rainfall processes. ASCE, World Environmental and Water Resources Congress, 2008, Hawaii, published in CD ROM proceedings, 8 pages.
4. Characterizing Rain gage- Radar (NEXRAD) Relationships using Inductive Models, FAU, MSc thesis, 2008.
5. Teegavarapu, R. Innovative spatial interpolation methods for estimation of missing precipitation records: concepts and applications, Hydro-Predict, International Conference, 2008. paper Published.
6. Geo-Spatial Grid-based Transformations of Multi-Sensor Precipitation Estimates, AGU Fall Meeting, 2008. (poster presentation)
7. Utility of Optimal Reflectivity-Rain Rate (Z-R)Relationships for Improved Precipitation Estimates, EWRI-ASCE World Environmental and Water Congress, 2010
8. Infilling Missing Precipitation Data using NEXRAD Data: Use of Optimal Spatial Interpolation and Data-Driven Methods, EWRI-ASCE World Environmental and Water Congress, 2010
9. Extreme Precipitation and Climate Change, IFI, Book Series Meeting, UNESCO, Paris, April 29, 2010.
10. Spatial Precipitation Analysis for Continuous Estimation: Issues, Approaches and Applications, Seoul National University, Seoul, BK21 Seminar Series, April 22, 2010.
11. Uncertainties in Z-R Relationships for Radar based Precipitation Estimates, SWFWMD, Tampa, March11, 2010.
12. Improvement of NEXRAD Data using new methods of Bias Corrections, SWFWMD, Tampa, March 11, 2010.
13. Spatial Precipitation Analysis for Continuous Estimation (SPACE): Patterns, Organization and Processes (POP), ASEC-EWRI 2010, India Conference, Chennai, India, January 5, 2010.
14. Evaluation of Improvised Spatial Interpolation Methods for Infilling Missing Precipitation Records, ASCE/EWRI International Conference, Kansas City, May 2009.

15. Evaluation of Spatial Weighting Methods for Transformation of Multi-Sensor Precipitation Estimates, ASCE/EWRI International Conference, Kansas City, May 2009
16. Optimal Spatial Interpolation and Data-Driven Methods for Infilling Missing Rain Gage Records using Radar (NEXRAD) based Precipitation Data, Ramesh S. V. Teegavarapu, Singaiah Chinatalapudi, Chandra Pathak, Ricardo Brown, 2011. Submitted to Journal of Hydrologic Engineering, ASCE.
17. Optimized Reflectivity (Z)-Rainfall Rate (R) Relationships for Improved Radar-based Precipitation Estimates, Ramesh S. V. Teegavarapu, Kandarp Pattani, Chandra Pathak, Submited to Journal of Hydrologic Engineering, 2011, ASCE.
18. Ramesh S. V. Teegavarapu, and Chandra Pathak, Development of Optimal Forms of Z-R relationships, Weather Radar and Hydrology Symposium, Exeter, England, April 2011, 6 pages.
19. Ramesh S. V. Teegavarapu, Anurag Nayak, Chandra Pathak, Assessment of Long-term Trends in Extreme Precipitation: Implications of In-filled Historical Data and Temporal Window-Based Analysis, AGU, Fall Meeting 2010.
20. Ramesh S. V. Teegavarapu, Anurag Nayak, Chandra Pathak, Assessment of Long-term Trends in Extreme Precipitation: Implications of In-filled Historical Data and Temporal Window-Based Analysis, 10 pages, ASCE, 2011
21. Chandramouli Viswanathan, Madhusudhan Gowda, Ramesh S. V. Teegavarapu, Developing Fecal TMDLs using Fuzzy-based Approach. Proceedings of Watershed Management Conference, Wisconsin, Madison, August 2010.
22. Noemi Gonzalez, Ramesh S. V. Teegavarapu, Lin Huang, Spatial and Temporal Distribution of Extreme Precipitation Events and their Relation to Peak Flooding, AGU Fall Meeting, December, 2010.
23. Ramesh S. V. Teegavarapu, Chandra Pathak, Utility of Optimal Reflectivity-Rain Rate (Z-R) Relationships for Improved Precipitation Estimates, EWRI-ASCE World Environmental and Water Congress, December, 2010.
24. Pradeep Behera, Yiping Gao, Ramesh Teegavarapu, Evaluation of Antecedent Storm Event Characteristics for different Climatic Regions based on Inter-event Time Definition (IETD), EWRI-ASCE World Environmental and Water Congress, May, 2010.
25. Ramesh Teegavarapu, Sharika Senerath, Chandra Pathak, Sampling Schemes for Uncertainty Assessment of a Hydrologic Simulation Model, EWRI-ASCE World Environmental and Water Congress, May, 2010.
26. Ramesh Teegavarapu and Chandra Pathak, Infilling Missing Precipitation Data using NEXRAD Data: Use of Optimal Spatial Interpolation and Data-Driven Methods, EWRI-ASCE World Environmental and Water Congress, May, 2010.
27. Extreme Precipitation and Climate Change, IFI, Book Series Meeting, UNESCO, Paris, April 29, 2010.

WRRC 104B Project Annual Report

(Activities during the period March 1, 2010 through February 28, 2011)

Project Title:

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

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
Department of Civil, Environmental and Geomatics Engineering,
Florida Atlantic University
Boca Raton, Florida, 33431

May 5, 2011

EXECUTIVE SUMMARY

This report summarizes the work completed for the second 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 proximity-based imputation, K-nearest neighbor classification and K-means clustering methods for estimation of missing precipitation. Initially the models are tested on rain gage data (in this phase of the study) and in the next phase, infilling of rain gage data using NEXRAD based precipitation estimates will be carried out using these methods. Variants of K-NN classification and K-means clustering schemes embedded in optimization formulations are also assessed for estimation of missing precipitation records. Mathematical programming models are developed to optimize the weighing schemes involving proximity measures. Ten binary and ten real valued distance metrics are used as proximity measures. Results from these models were evaluated using four different performance measures and appropriate weight functions. The best model based on performance evaluations will be selected for infilling the missing rain gage data at several rain gages in the South Florida Water Management District (SFWMD).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 II of the project is now completed. The second phase of the project was 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. Currently Mr. Aneesh Goly and Mr. Husain El Sharif are working on the new proximity-based methods, K-NN classification methods and K-means clustering methods.

Publications

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

Conference Publications/Presentations

1. Ramesh S. V. Teegavarapu, and Chandra Pathak, Development of Optimal Forms of Z-R relationships, Weather Radar and Hydrology Symposium, Exeter, England, April 2011, 6 pages.

2. Ramesh S. V. Teegavarapu, Anurag Nayak, Chandra Pathak, Assessment of Long-term Trends in Extreme Precipitation: Implications of In-filled Historical Data and Temporal Window-Based Analysis, AGU, Fall Meeting 2010.

3. Ramesh S. V. Teegavarapu, Anurag Nayak, Chandra Pathak, Assessment of Long-term Trends in Extreme Precipitation: Implications of In-filled Historical Data and Temporal Window-Based Analysis, 10 pages, ASCE, 2011

4. Chandramouli Viswanathan, Madhusudhan Gowda, Ramesh S. V. Teegavarapu, Developing Fecal TMDLs using Fuzzy-based Approach. Proceedings of Watershed Management Conference, Wisconsin, Madison, August 2010.

5. Noemi Gonzalez, Ramesh S. V. Teegavarapu, Lin Huang, Spatial and Temporal Distribution of Extreme Precipitation Events and their Relation to Peak Flooding, AGU Fall Meeting, December, 2010.

6. Ramesh S. V. Teegavarapu, Chandra Pathak, Utility of Optimal Reflectivity-Rain Rate (Z-R) Relationships for Improved Precipitation Estimates, EWRI-ASCE World Environmental and Water Congress, December, 2010

7. Pradeep Behera, Yiping Gao, Ramesh Teegavarapu, Evaluation of Antecedent Storm Event Characteristics for different Climatic Regions based on Inter-event Time Definition (IETD), EWRI-ASCE World Environmental and Water Congress, May, 2010

8. Ramesh Teegavarapu, Sharika Senerath, Chandra Pathak, Sampling Schemes for Uncertainty Assessment of a Hydrologic Simulation Model, EWRI-ASCE World Environmental and Water Congress, May, 2010

9. Ramesh Teegavarapu and Chandra Pathak, Infilling Missing Precipitation Data using NEXRAD Data: Use of Optimal Spatial Interpolation and Data-Driven Methods, EWRI-ASCE World Environmental and Water Congress, May, 2010

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

Journal Papers

1. Optimal Spatial Interpolation and Data-Driven Methods for Infilling Missing Rain Gage Records using Radar (NEXRAD) based Precipitation Data, Ramesh S. V. Teegavarapu, Singaiah Chinatalapudi, Chandra Pathak, Ricardo Brown' 2011. Submitted to Journal of Hydrologic Engineering, ASCE.
2. Optimized Reflectivity (Z)-Rainfall Rate (R) Relationships for Improved Radar-based Precipitation Estimates, Ramesh S. V. Teegavarapu, Kandarp Pattani, Chandra Pathak, Submited to Journal of Hydrologic Engineering, 2011, ASCE.

List of students supported by 104B funding last year (March 2010 – February 2011)

1. Mr. Andre Ferreira, Graduate Student, graduated December, 2009
2. Mr. Ricardo Brown, Graduate student, expected graduation, Summer, 2011
3. Mr. Kandarp Pattani, Graduate student, graduated, Fall 2010
4. Mr. Aneesh Goly, Graduate Student (Ph.D), expected graduation, December 2012.
5. Mr. Husain El Sharif, Undergraduate student, Sept-Dec, 2010.
6. Lin Huang, Graduate Student, Sept-Dec, 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. Spatial interpolation of precipitation data for imputation of missing records is an essential and crucial step in the development of continuous precipitation data without any gaps needed for hydrologic frequency analysis, modeling and design. Often precipitation data gaps of different length are unavoidable due to random and systematic errors. Incorrect recording and transcription of precipitation data creates gaps in the data to be filled and casts doubt on the reliability of data for statistical analysis (Hosking and Wallis, 1998; Wallis et al., 1991). Precipitation as a vital input for many hydrological modeling studies has a direct bearing on the hydrological modeling and water resources management at different spatial and temporal scales. The importance of rainfall as being the most sensitive input in hydrologic simulation models is stressed by many researchers in their studies (e.g., Larson and Peck, 1974; Vieux, 2001; Xu and Singh, 1998). Xu and Singh (1998) indicate that the accuracy of a streamflow simulation model primarily depends on how well the variability of the rainfall can be defined. Spatial interpolation methods ranging from conceptually simple weighting techniques to methods using stochastic variance dependent techniques are now available for estimation or imputation of missing precipitation data (Teegavarapu, 2008). In many precipitation studies, gaps are attributed to be as data missing completely at random (MCAR) as defined by Little and Rubin (1987). In the current study missing rainfall data and techniques for its estimation or imputation methods are of interest. The main limitations of some of the available deterministic interpolation methods is the lack of objectivity in the selection of weighting parameters, number of neighbors and functional forms that account for spatio-temporal correlations among observations. In the current study optimal proximity-based imputation, nearest neighbor classification and cluster-based methods are proposed and developed for estimation of missing precipitation data at a single site.

Weighting methods (Smith, 1993), reciprocal distance based methods (Simanton and Osborn, 1980; Wei and McGuiness, 1973), nonlinear deterministic and stochastic variance dependent interpolation methods (e.g. kriging) (Teegavarapu, 2007; Zimmerman et al., 1999), and regression and time series analysis methods (Salas, 1993) are among the most commonly used methods for estimating missing precipitation records. Comparative studies of rainfall estimation using these methods can be found in Singh and Chowdhury (1986), Tabios and Salas (1985) and Tung (1983). Variants of local regression models incorporating meteorological and variables that change in spatial domain (i.e., elevation) were proposed by Daly et al. (1994) and Daly et al. (2002). PRISM (precipitation-elevation regression on independent slopes model) (Daly et al., 1994) is one of such variants. Models incorporating locally weighted polynomials (Loader, 1999; Regonda et al. 2006) are conceptual improvements over traditional weighting methods in which the number of neighbors and polynomial functions are objectively chosen. The coefficient of correlation weighting method (CCWM) proposed by Teegavarapu and Chandramouli (2005) was adopted in several recent studies (e.g., Kim et al., 2008; Westerberg, et al., 2009).

Inverse distance weighting method (IDWM) or reciprocal distance weighting method recommended by the Handbook of Hydrology (ASCE, 2001) is the most commonly used method for estimating missing data in the fields of Hydrology and Geosciences. Teegavarapu and Chandramouli (2005) and Tomczak (1998) provided several improved variants of IDWM for estimating missing precipitation data. Lu and Wong (2008) modified IDWM weights by distance based decay parameters to adjust the diminishing strength in relationships with increasing distances. Teegavarapu (2009) used an association rule mining (ARM) approach to improve estimates of missing precipitation data. Global interpolation methods that use trend surface analysis with polynomial equations of spatial coordinates (Wang, 2006) are equally applicable for spatial interpolation of precipitation data. However, selection of the appropriate functional form to model the trend poses a major problem due to large number of possible candidate functions (Sullivan and Unwin, 2010). Xia et al. (1999) used inverse distance, normal ratio, single best estimator, multiple regression methods for estimation of missing climatological data. Regression was proved to be the best among all the methods investigated in their study. Xia et al. (2001) also reported the use of thin-splines, closest station, multiple linear regression techniques and Shepards' method (Shepard, 1968) for estimation of daily climatalogical data. They indicated that thin-splines method was the best among all the methods investigated. While thin-plate spline methods have several advantages over others, however they tend to generate steep gradients in data-poor areas leading to compounded errors in the estimation process (Chang, 2004). Improvements in interpolations are possible using thin-spline with tension method. Ramos-Calzado et al. (2008) proposed a new approach for estimating missing precipitation data considering the rainfall measurement uncertainty. Improvements were achieved in the estimation of precipitation data when the stations with lowest measurement uncertainty were selected in the interpolation process.

Stochastic surface interpolation methods, belonging to the general family of Kriging have been applied to hydrological spatial interpolation problems (Vieux, 2001; Grayson and Bloschl, 2001). Conceptual variants of Kriging have been used in the past to estimate missing precipitation data as well as to interpolate precipitation from point measurements (Dingman, 2002; Vieux, 2001, Ashraf et al., 1997). Co-kriging of radar and rain gage data has been employed by Krajewski (1987) to estimate mean areal precipitation. Seo et al. (1990a, 1990b) and Seo (1996) described the use of co-kriging and indicator kriging for interpolating rainfall data. Seo and Smith (1993) employed a Bayesian approach for short-term rainfall prediction using radar data in conjunction with rain gage data. Real-time estimation of rainfall fields using radar and rain gage data was discussed by Seo (1998). The use of ordinary kriging along with universal function approximation for estimating missing daily precipitation data was recently reported by Teegavarapu (2007). Kriging in its various forms by far dominates any study involving precipitation interpolation and estimation.

Regression and time series models belong to class of inductive modeling approaches with functional forms of the relationships defined a priori are useful for estimation of missing data (Dingman, 2009). Empirical models derived using evolutionary and biological principles, namely, Genetic algorithms (Goldberg, 1989), artificial neural networks ((Zurada, 1992), and genetic programming (Koza, 1992) have found numerous applications in the development and application of inductive models in the field of hydrologic forecasting. Applications of artificial neural networks (ANNs) in the fields of hydrology and water resources (ASCE, 2001a; 2001b; French et al., 1992; Govindaraju and Rao, 2000; Teegavarapu and Chandramouli, 2005; Kuligowski and Barros, 1998) are not new. The universal functional approximation abilities of ANNs were already confirmed independently by Cybenko (1989) and Hornik et al. (1989). Teegavarapu (2007) demonstrated the use of universal functional approximation within a stochastic variance dependent interpolation technique for estimation of missing precipitation data. Genetic programming (GP) can be used to create models with the help of mathematical operations and variables for function approximation (Giustolisi and Savic, 2004). Recent work of Teegavarapu et al. (2009) focused on the development of optimal functional forms using genetic algorithms and mathematical operators for estimating missing precipitation data. The functional forms provided better estimates compared to those by traditional geographical distance-based methods. In spite of several improvements in traditional methods, limitations of spatial interpolation methods continue to exist. Veiux (2001), Grayson and Bloschl (2001), Sullivan, and Unwin, (2010), Teegavarapu (2007, 2008, 2009), Teegavarapu et al. (2009) and Brimicombe (2003) discussed numerous limitations of the inverse distance weighting method (IDWM) and other spatial interpolation methods. Eischeid et al. (2000) report similar limitations of interpolation methods used for estimation of missing daily temperature and precipitation records. The success of inverse distance weighting method and many other interpolation methods depend primarily on the existence of positive spatial autocorrelation (Griffith, 1987; Vasiliev, 1996, Sullivan and Unwin, 2010). Reciprocal distances as weights in IDWM may not serve as surrogate measures to quantify spatial autocorrelations. In some instances the existence of negative autocorrelation may be become a major limitation in the application of IDWM. Another important issue relevant to many spatial interpolation approaches is the selection of neighborhood points of observations for estimation of missing data at a point of interest. The arbitrariness in the choice of weighting parameter and the definition of the neighborhood are two major limitations of weight based interpolation methods. The limitations are common to deterministic and stochastic interpolation methods except locally weighted polynomial based methods. The methods proposed and investigated in the current study are aimed at developing data-dependent objective weighting schemes using proximity measures common in numerical taxonomy and new variants of k-nearest neighbor classification and clustering techniques. Variants of few traditional spatial interpolation methods are also investigated in the current study.

The functional relationships that link point rain gage and grid-based radar observations are generally nonlinear (Teegavarapu et al., 2008; Skinner et al., 2009). Skinner et al. (2009) indicated that a power functional form can characterize the rain and radar data relationship and was appropriate for a region in South Florida. The main motivation of the study reported in this paper is to assess different grid-based linear optimal weighting methods in estimation of missing data at rain gage. Radar data available as gridded data can be used for estimation of missing precipitation data at a rain gage using local filters (Lloyd, 2006) with focal functions to derive the value of a cell using values from a group of cells. Moving window approach is adopted in this study in which pixels (grids) with radar-based precipitation estimates surrounding a rain gage are used to estimate missing data at that gage. Spatial domain filters (Mather, 2004) are common in the remotely sensed image processing studies which use moving average windows to reduce the variability of image. These spatial filters are forms of focal operators (Lloyd, 2005; 2007) where values of any given cell (grid, or pixel) are a function of values from the surrounding pixels. However, no optimization methods are generally involved. The optimization methods used in the current study can be referred to as geographically weighted optimization (GWO) methods. The current study evaluates the use of local along with moving window optimization and data-driven methods for estimation of missing precipitation data at gage using grid-based radar data. 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.

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.

In the second phase of this study, development of optimal K-NN classification approach and K-means clustering methods developed from original concepts of nearest neighbor techniques are carried out. Traditional deterministic and stochastic interpolation methods along with their proposed variants are described. Applications of these methods for estimating missing precipitation to few stations in SWFWMD are attempted as initial evaluation of these newly proposed methods. The proximity-based imputation, K-NN classification and K-means clustering are discussed in the next few sections. The measures are

DISTANCE METRICS

Distance measures based on observations at two rain gage stations, β and α, (θ_β and θ_α) can be defined as real-valued functions. The functions are referred to as distance metrics if they satisfy several conditions given by the following inequalities.

$$d_{\beta,\alpha} \gg 0 \qquad (1)$$

$$d_{\beta,\alpha} = 0 \;\; if\ and\ only\ if \quad \theta_{\beta,n} = \theta_{\alpha,n} \qquad \forall n \qquad (2)$$

$$d_{\beta,\alpha} = d_{\alpha,\beta} \qquad (3)$$

$$d_{\beta,\omega} \ll d_{\beta,\alpha} + d_{\alpha,\omega} \qquad (4)$$

Inequality 1, indicates that distance measure is always non-negative. Equation 2 indicates hat distance measure is equal to zero if an only if all the observations at station β are exactly equal to observations at station α. The variable n is the observation number. Distance measures between any two stations are equal showing the property of commutativity. Inequality 4 indicates the property referred to as triangular inequality defined based on distances between stations β and ω, β and α and α and ω.

Distance Metrics for Precipitation Data

Distance metrics refer to those measures which satisfy conditions defined by inequalities and equalities (1 - 4). Brief description of the distance metrics developed for precipitation data used in the current study are defined in this section.

Euclidean

The Euclidean distance (Tan et al., 2006, Myatt and Johnson, 2009) or L_2 norm is the simplest measure of distance between a pair of rain gage observations. This measure represented by equation 5 is used in many data mining applications for proximity calculations and in classification and clustering schemes.

$$d_{\beta,\alpha} = \sum_{n=1}^{no} \sqrt[2]{(\theta_{\beta,n} - \theta_{\alpha,n})^2} \qquad (5)$$

Squared Euclidean

The squared Euclidean is a minor variant of the Euclidean distance. The square Euclidean (Myatt and Johnson, 2009) is the sum of the squares of the difference between the two rain gage observations, and it is given by the equation 6. This metric magnifies distances between observations that are further apart.

$$d_{\beta,\alpha} = \sum_{n=1}^{no} (\theta_{\beta,n} - \theta_{\alpha,n})^2 \qquad (6)$$

Manhattan

Manhattan (Krause, 1987) distance is also referred to as city block distance, taxicab and L_1 norm (Tan et. al., 2006; Myatt and Johnson, 2009). This distance is less affected by outliers compared to Euclidean and squared Euclidean (Fielding, 2007).

$$d_{\beta,\alpha} = \sum_{n=1}^{no} \left|\theta_{\beta,n} - \theta_{\alpha,n}\right| \qquad (7)$$

Maximum

Maximum distance (Tan, et al., 2006; Myatt and Johnson, 2009) is the maximum distance between two observations, the absolute difference between each variable is determined and the highest difference given by equation 8.

$$d_{\beta,\alpha} = max\left|\theta_{\beta,n} - \theta_{\alpha,n}\right| \qquad \forall n \qquad (8)$$

Minkowski

The Minkowski (Basilevski, 1983) distance is generalized distance measure given by equation 9. The value of λ defines a specific distance. When λ is equal to 1, the measure is Manhattan and when λ is equal to 2, the measure becomes Euclidean distance.

$$d_{\beta,\alpha} = \sqrt[\lambda]{\sum_{n=1}^{no}\left|\theta_{\beta,n} - \theta_{\alpha,n}\right|^{\lambda}} \qquad (9)$$

Gower

The Gower (Gower and Legendre, 1986) distance is used for mixed variables (continuous and discrete) and is given by equation 10. The variable ω_n is the weight which is equal to one when both observations in a given time interval, *n*, are available and zero when one of them is not available. The variable τ_n is the maximum range value based on the observations.

$$d_{\beta,\alpha} = \sqrt{\frac{\sum_{n=1}^{no}\omega_n {d_n}^2}{\sum_{n=1}^{no}\omega_n}} \qquad (10)$$

$$d_n = \frac{\left|\theta_{\beta,n} - \theta_{\alpha,n}\right|}{\tau_n} \qquad \forall n \qquad (11)$$

Cosine

The Cosine (Basilevski, 1983; Tan et al., 2006) distance is based on cosine similarity measure that measures similarity between sets of observations. The distance is calculated as provided by equation 12.

$$d_{\beta,\alpha} = 1 - \frac{\sum_{n=1}^{no}\theta_{\beta,n}\theta_{\alpha,n}}{\sqrt{\sum_{n=1}^{no}\theta_{\beta,n}^2 \sum_{n=1}^{no}\theta_{\alpha,n}^2}} \qquad (12)$$

Canberra

The Canberra (Lance and William, 1966) distance given by equation 13 defines the sum of the fractional differences for each variable (Myatt and Johnson, 2009).

$$d_{\beta,\alpha} = \sum_{n=1}^{no} \frac{|\theta_{\beta,n} - \theta_{\alpha,n}|}{(|\theta_{\beta,n}|+|\theta_{\alpha,n}|)} \quad (13)$$

Correlation Distance

The correlation distance is conceptually based on similarity between observations as defined by correlation coefficient or a measure of linear relationship between two data sets. The correlation distance is given by equation 14.

$$d_{\beta,\alpha} = 1 - \rho_{\beta,\alpha} \quad (14)$$

Mahalanobis

The Mahalanobis distance (Myatt and Johnson, 1996) takes into account correlations within a data set between the variables. The distance is scale independent and is calculated using equation 15. The calculated distance requires covariance (*S*) and transformed matrices using the data sets (Tan et al., 2006).

$$d_{\beta,\alpha} = \sqrt{(\theta_{\beta,n} - \theta_{\alpha,n})S^{-1}(\theta_{\beta,n} - \theta_{\alpha,n})^T} \quad (15)$$

Boolean Distance Measures for Precipitation Data

Boolean distance measures are applied to observations that are binary variables (i.e., 0 and 1) and to also to categorical variables when these variables are expressed as binary variables. Similarity measures indicate how alike two observations are to each other, with high similarity values representing situations when the two observations are alike (Myatt and Johnson, 2008). Similarity measure differs from distance measure, where low magnitudes of the latter measure indicate that observations from the two series are alike. The precipitation data sets from any two stations contain real values with zero and positive values above zero.

The real-valued precipitation time series at any station can be converted into binary form using the following expression.

$$if\,(\theta_l^n > \theta_{th}), then\ \theta_l^n = 1, else\ \ \theta_l^n = 0 \qquad \forall l, n \quad (16)$$

The variable θ_l^n is the observed precipitation value at station *l*, in time interval, *n*, and θ_{th} is the threshold value (lower limit) that defines the limits for the assignment of binary values. The similarity and distance calculations for binary variables are based on the number of common and different values in the four situations as described in Figure 1.

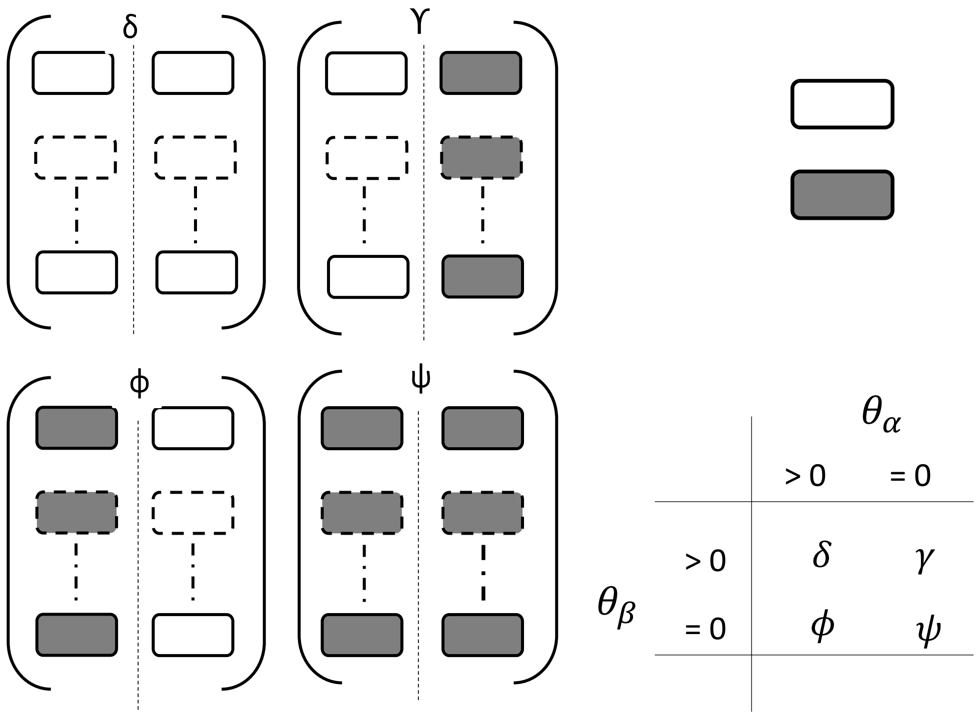

Figure 1. Binary transformation of precipitation data at two stations and the corresponding similarity measures and counts

The count (number) for these specific conditions is obtained from the historical data using all the rain gage stations and well as the station (i.e., base station) with the missing precipitation data. For each time interval, the common and different values are evaluated and counts (δ_n, γ_n, $\emptyset_n$ and ψ_n) required for distance metrics are calculated for each time interval, *n*, using conditions expressed by 17-20. The $\theta_{\beta,n}$ is the observed precipitation at station β and $\theta_{\alpha,n}$ is the precipitation value at base station (i.e., station with missing precipitation data) with in time interval *n.*

$$if\left(\theta_{\beta,n} = 1, \theta_{\alpha,n} = 1\right), then\ \ \delta_n = 1, \qquad \beta \in l, \alpha = m \qquad \forall \beta, n \tag{17}$$

$$if\left(\theta_{\beta,n}=1,\theta_{\alpha,n}=0\right), then\ \gamma_n=1, \qquad \beta\in l, \alpha=m \qquad \forall\beta,n \tag{18}$$

$$if\left(\theta_{\beta,n}=0,\theta_{\alpha,n}=1\right), then\ \emptyset_n=1, \qquad \beta\in l, \alpha=m \qquad \forall\beta,n \tag{19}$$

$$if\left(\theta_{\beta,n}=0,\theta_{\alpha,n}=0\right), then\ \psi_n=1, \qquad \beta\in l, \alpha=m \qquad \forall\beta,n \tag{20}$$

The aggregated values of these counts (δ, γ, ϕ and ψ) are calculated using equations 21-24 with all the available observations, *no*.

$$\delta=\sum_{n=1}^{no}\delta_n \tag{21}$$

$$\gamma=\sum_{n=1}^{no}\gamma_n \tag{22}$$

$$\phi=\sum_{n=1}^{no}\phi_n \tag{23}$$

$$\psi=\sum_{n=1}^{no}\psi_n \tag{24}$$

Simple Matching

The simple matching distance calculates the similarity measure linked to the total number of times any two stations have conditions 16 and 19 satisfied. The distance is given by subtracting this similarity coefficient from one.

$$d_{\beta,\alpha}=1-\frac{\delta+\gamma}{\delta+\gamma+\phi+\psi} \tag{25}$$

Jaccard

The Jacard (Jacard, 1908) distance calculates the total number of times any two stations have conditions 17 and 18 satisfied. The lower the number of dissimilar values (i.e., binary values), the closer are the time series observations as indicated by equation 26. In this metric, joint absences are excluded from consideration and equal weight is given to matches and mismatches.

$$d_{\beta,\alpha}=\frac{\gamma+\phi}{\delta+\gamma+\phi} \tag{26}$$

Rusell and Rao

The Russell and Rao distance (Russel and Rao, 1940) calculates similarity coefficient that relates to the total number of times any two stations have condition 16 satisfied compared all conditions. The similarity coefficient is then transformed to distance measure as given by equation 27.

$$d_{\beta,\alpha} = 1 - \frac{\delta}{\delta+\gamma+\phi+\psi} \qquad (27)$$

Dice

The Dice distance (Dice, 1945, Sorensen, 1948) uses similarity index which accounts for commonly values (δ, γ) between two observation time series. The distance is calculated by equation 28, gives more importance to common ones. The Dice distance is similar to Jaccard distance and was developed to measure ecological association between species. This is measure in which joint absences are excluded from consideration and matches are doubled (Fielding, 2007). The measure is also known as Czekanowski measure.

$$d_{\beta,\alpha} = \frac{\gamma+\phi}{2\delta+\gamma+\phi} \qquad (28)$$

Rogers and Tanimoto

The Rogers and Tanimoto distance (Roger and Tanimoto, 1960) gives importance to common ones and zeros. The distance metric was mainly developed for classifying plant species. The distance measure is given by equation 29.

$$d_{\beta,\alpha} = \frac{2(\gamma+\phi)}{\delta+2(\gamma+\phi)+\psi} \qquad (29)$$

Pearson

The Pearson distance (Ellis et al., 1993) as defined by equation 30 was initially used to measure the degree of similarity between objects in text retrieval systems.

$$d_{\beta,\alpha} = \frac{1}{2} - \frac{\delta\varphi+\phi\gamma}{2\sqrt{(\delta+\gamma)(\delta+\phi)(\gamma+\psi)(\phi+\psi)}} \qquad (30)$$

Yule

The Yule distance (Yule, 1912) was initially developed as a method for identifying association between two attributes. The distance is given by equation 31.

$$d_{\beta,\alpha} = \frac{\gamma\phi}{\delta\psi+\gamma\phi} \quad (31)$$

Sokal-Michener

The Sokal-Michener distance (Sokal and Michener, 1958) is one of the distance metrics used in numerical taxonomy used for classifying organisms and building evolutionary trees. The distance is defined by equation 32.

$$d_{\beta,\alpha} = \frac{\delta+\psi}{\delta+\gamma+\phi+\psi} \quad (32)$$

Kulzinksy

Kulzinsky distance (Holliday et al., 2002) as defined by equation 33 is used in ecology for finding similarity is sites with similar species and also in calculation of intermolecular similarity and dissimilarity.

$$d_{\beta,\alpha} = \frac{2\gamma+2\phi+\psi}{\delta+2\gamma+2\phi+\psi} \quad (33)$$

Hamming

The Hamming distance (Hamming, 1950) as given by equation 34 was originally developed to identify and correct errors in digital communication systems.

$$d_{\beta,\alpha} = \gamma + \phi \quad (34)$$

Optimal Exponent weighting of Proximity Measures

The proximity measures are used in an optimal weighting method in which the objective function and the constraints are specified by equations 35, 36 and 37. This formulation helps in obtaining optimal exponent for each of the distance measure.

Minimize $$\sum_{n=1}^{no} \left| \hat{\theta}_m^n - \theta_m^n \right| \quad (35)$$

Subject to:

$$\hat{\theta}_m^n = \frac{\sum_{j=1}^{ns-1} w_{mj}^k \theta_j}{\sum_{j=1}^{ns-1} w_{mj}^k} \qquad \forall n \qquad (36)$$

$$w_{mj} = 1/d_{mj} \qquad \forall j \qquad (37)$$

The formulation is solved using historical data to minimize the objective function and obtain optimal exponent value (*k*) using a nonlinear optimization solver.

OPTIMAL K-NEAREST NEIGHBOR CLASSIFICATION METHOD

An optimal K-nearest neighbor (K-NN) interpolation method is developed in the current study. Initially the *k*-nearest-neighbor method is used as a classifier based on spatial and temporal precipitation data. This training data is referred to as training tuples (Han and Kamber, 2006; Tan et al., 2006) and the classification is achieved based on learning by analogy, that is, by comparing a given test tuple with training tuples that are similar to it. Each tuple indicates a point in an *n*-dimensional space. In this way, all of the training tuples are stored in an *n*-dimensional pattern space. When given an unknown tuple, a ***k***-nearest-neighbor classifier searches the pattern space for the *k* training tuples that are closest to the unknown tuple. These *k* training tuples are the *k* "nearest neighbors" of the unknown tuple. "Closeness" is defined in terms of a distance metric, such as Euclidean distance. The Euclidean distance between two points or tuples, say, $\boldsymbol{X} = (\theta_{1,1}, \theta_{1,2}, \ldots \theta_{1,ns-1})$ and $\boldsymbol{X}_{c=1} = (\theta^{\circ}_{1,1}, \theta^{\circ}_{1,2} \ldots \ldots, \theta^{\circ}_{1,ns-1})$.

$$X = \begin{pmatrix} \theta_{1,1} & \cdots & \theta_{1,ns-1} \\ \vdots & \ddots & \vdots \\ \theta_{n,1} & \cdots & \theta_{n,ns-1} \end{pmatrix} \qquad (38)$$

$$X_c = \begin{pmatrix} \theta^{\circ}_{1,1} & \cdots & \theta^{\circ}_{1,ns-1} \\ \vdots & \ddots & \vdots \\ \theta^{\circ}_{c,1} & \cdots & \theta^{\circ}_{C,ns-1} \end{pmatrix} \qquad (39)$$

X represents the *n* x *ns-1* matrix of observed precipitation values at *ns-1* stations and for n time intervals and X_c represents a *C* x *ns-l* classes of observations. The historical observations at *ns-1* stations are evaluated for their proximity to each of the classes defined in X_c and each observation is designated to a specific class, c belonging to *C* using a distance metric.

$$D_i = f(X, X_c) \qquad (40)$$

The distance metric can be Euclidean, correlation, cosine and others. Once the observations are designated to specific classes, then correlations of observations in specific class, c, are obtained using observations at station at which missing data exist.

$$\rho_{ns,m,c} = \frac{\sum_{i=1}^{nc} \theta_{i,ns,c}\, \theta_{m,i,c} - \sum_{i=1}^{nc} \theta_{i,ns,c} \sum_{i=1}^{nc} \theta_{m,i,c}}{\sqrt{\sum_{i=1}^{nc} \theta_{i,ns,c}^2 - \left(\sum_{i=1}^{nc} \theta_{i,ns,c}\right)^2} \sqrt{\sum_{i=1}^{nc} \theta_{m,i,c}^2 - \left(\sum_{i=1}^{nc} \theta_{m,i,c}\right)^2}} \qquad \forall ns,c \qquad (41)$$

These correlations are then used in coefficient of correlation weighting method (CCWM) (Teegavarapu and Chandramouli, 2005) for estimation of missing precipitation data at station, *m*.

The estimated value of missing precipitation value at station, m is given by

$$\hat{\theta}^n_{m,i,c} = \frac{\sum_{j=1}^{ns-1} \rho_{m,j,c}\theta_{j,c}}{\sum_{j=1}^{ns-1} \rho_{m,j,c}} \qquad \forall i,c,n \qquad (42)$$

Optimal weights for each class can be obtained by solving an optimization formulation given by the following objective function and constraint.

Minimize $$\left\| \theta_i^c \alpha_c - \theta_m^n \right\|_2^2 \quad \forall i \qquad (43)$$

Subject to:

$$\alpha_c \geq 0 \qquad \forall c \qquad (44)$$

The formulation minimizes the norm given by the equation 43 with constraint on the weights (inequality 44). This formulation provides nonnegative optimal coefficients when solved.

OPTIMAL K-MEANS CLUSTERING METHOD

K-means clustering method (Larose, 2005; Han and Kamber, 2006; Tan et al., 2006) is used to identify spatial clusters of rain gage stations from the network of stations in the region. Initially the method is used to obtain a specific number of (say *k*) clusters of precipitation stations. The steps involved are: 1) an initial spatial partition of precipitation stations into k random clusters; 2) re-partition of the stations by assigning each station to the nearest center of cluster by using a proximity measure (e.g., distance metric); 3) re-calculation of the cluster centers as centroids. The steps two and three are repeated until an optimum of the criterion function is found.

Optimal weights for Selected Neighbors

Nonnegative constraints requirements to obtain positive weights can be enforced using the nonlinear least square constraint formulation defined by equation 44.

Minimize $$\left\| \theta_n^{cl} \alpha_{cl} - \theta_m^n \right\|_2^2 \quad \forall n \qquad (45)$$

Subject to:

$$\alpha_{cl} \geq 0 \qquad \forall cl \qquad (46)$$

The formulation minimizes the norm given by the equation 45 with constraint on the weights (inequality 46). This formulation provides nonnegative optimal coefficients when solved.

$$\theta_n^{cl} = \sum_{j=1}^{N_{cl}} \theta_n^j \quad \forall n,cl \qquad (47)$$

The variable θ_n^{cl} is sum of all the observations in a cluster *cl* and N_{cl} is the number of stations in the cluster.

$$\theta_n^{cl} = \theta_{n,cl\,\max}^{jc} \quad \forall n,cl \qquad (48)$$

The variable $\theta_{n,cl\,\max}^{j}$ is the observation value at a station *jc* that has the maximum correlation with the base station. The estimation of missing precipitation data is given by equation 49 using the weights obtained by solution of the optimization formulation given by equations 45-46. The value of θ_n^{cl} can be obtained by either equation 47 or 48.

$$\hat{\theta}_m^n = \sum_{cl=1}^{ncl} \alpha_{cl} (\theta_n^{cl}) \qquad \forall n \tag{49}$$

RESULTS AND ANALYSIS

The application of methods developed in this study was carried out for rain gages in located in Southwest Florida, daily historical data from year 1994 to 1999 available at forty three rainfall gauging stations are used for analysis. Results related to one station are provided in this report. Data is assumed to be missing at station # 3 (shown in Figure 2) for testing the imputation methods. The training and testing data sets used for this region are 1419 (67% of data) and 710 days (33% of the data) respectively. The models are formulated and solved using a nonlinear mathematical programming solver.

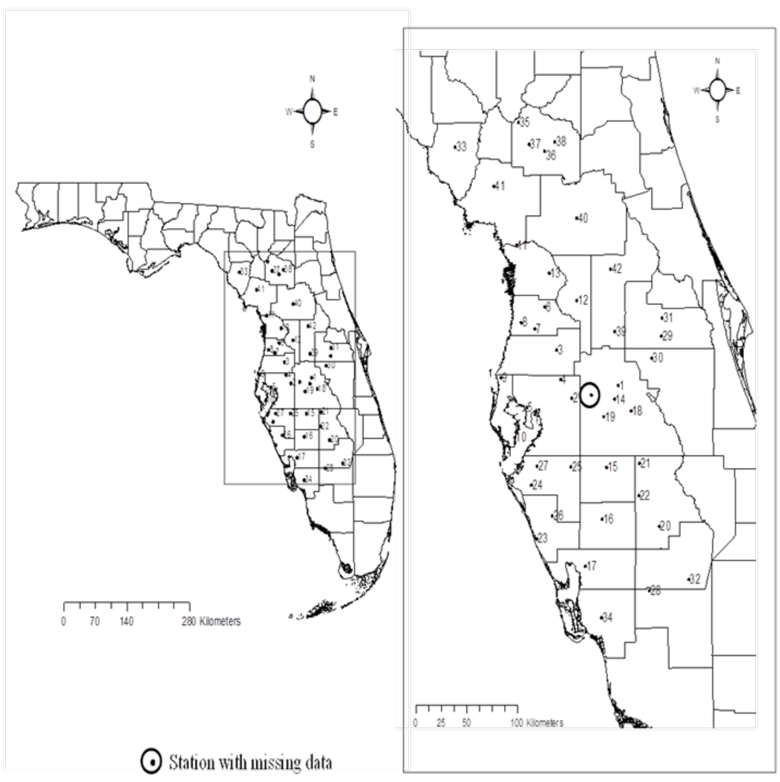

Figure 2. Location of rain gage stations and the station with missing data in SWFWMD

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 50 - 53.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{\phi}_i - \phi_i)^2} \quad (50)$$

$$AE = \sum_{i=1}^{n}\left|\hat{\phi}_i - \phi_i\right| \quad (51)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{\phi}_i - \phi_i\right| \quad (52)$$

$$\rho = \frac{\sum(\hat{\phi}_i - \mu_g)(\phi_i - \mu_n)}{(n-1)\sigma_g \sigma_n} \quad (53)$$

Table 9 and Table 10 provide the performance measures for real valued distance metrics. Table 9 provides the performance measures based on the optimal exponent weighting method. The average values of performance measures before and after optimization are 2545, 3.602, 7.1661, 0.666 and 2350, 3.311, 7.0525 and 0.6781 for AE, MAE, RMSE and ρ respectively. In general there is higher variability in the performance measures for optimized distance metrics compared to non-optimized distance metric. The two best methods are based on Manhattan and Euclidean distance metrics and Cosine and squared Euclidean using the optimal weighting functions.

The performance measures for binary distance metrics are provided in Table 11 and Table 12. The average values of performance measures before and after optimization are 2579, 3.631, 7.153, 0.667 and 2408, 3.391, 7.037, 0.680 for AE, MAE, RMSE and ρ respectively. The average values for Boolean measures are better than the real valued distance metrics. The variability in performance values is similar for both the performance measures. The two best methods are Sokal-Mischener and Russell and Rao and Pearson and Yule using optimal wweighting functions.

The four methods based on Manhattan, Euclidean, Canberra and Cosine distance metrics are ranked high among all the real valued and binary metrics.

Table 9. Performance measures based on different real-valued distance metrics used proximity-based imputation

Proximity Measure	AE (mm)	MAE (mm)	RMSE (mm)	ρ
Euclidean	2518	3.635	7.153	0.668
Squared Euclidean	2549	3.591	7.089	0.676
Manhattan	2518	3.635	7.153	0.668
Maximum	2581	3.635	7.153	0.667
Minkowski	2427	3.418	7.413	0.639
Gower	2578	3.631	7.149	0.668
Cosine	2546	3.585	7.090	0.675
Canberra	2573	3.624	7.131	0.669
Correlation	2545	3.585	7.093	0.674
Mahalanobis	2619	3.689	7.237	0.656

Table 10. Performance measures based on different real-valued distance metrics used in optimal proximity-based imputation for region II

Proximity Measure	AE (mm)	MAE (mm)	RMSE (mm)	ρ
Euclidean	2223	3.131	6.841	0.704
Squared Euclidean	2261	3.183	6.994	0.685
Manhattan	2272	3.200	6.722	0.714
Maximum	2420	3.408	7.203	0.660
Minkowski	2427	3.418	7.413	0.639
Gower	2446	3.445	6.947	0.692
Cosine	2252	3.176	6.945	0.690
Canberra	2258	3.181	6.831	0.702
Correlation	2256	3.177	7.022	0.684
Mahalanobis	2693	3.793	7.607	0.611

Table 11. Performance measures based on different Boolean distance metrics used in proximity-based imputation for region II

Proximity Measure	AE (mm)	MAE (mm)	RMSE (mm)	ρ
Simple Matching	2592	3.651	7.173	0.665
Jaccard	2596	3.656	7.165	0.666
Russell Rao	2614	3.682	7.201	0.661
Dice	2629	3.704	7.239	0.656
Rogers and Tanimoto	2597	3.659	7.181	0.664
Pearson	2423	3.412	6.925	0.692
Yule	2535	3.570	7.077	0.676
Sokal-Mischener	2594	3.653	7.175	0.665
Kulzinksky	2613	3.682	7.230	0.661
Hamming	2592	3.651	7.171	0.665

Table 12. Performance measures based on different Boolean distance metrics used in optimal proximity-based imputation for region II

Proximity Measure	AE (mm)	MAE (mm)	RMSE (mm)	ρ
Simple Matching	2334	3.286	7.171	0.667
Jaccard	2595	3.655	7.163	0.666
Russell and Rao	2356	3.318	6.888	0.696
Dice	2327	3.277	7.143	0.669
Rogers and Tanimoto	2448	3.442	6.967	0.688
Pearson	2423	3.419	6.925	0.693
Yule	2450	3.451	6.961	0.689
Sokal-Mischener	2245	3.162	6.804	0.705
Kulzinksky	2311	3.256	7.183	0.666
Hamming	2592	3.651	7.171	0.665

The K-NN classification method is used to classify the precipitation data into several pre-specified classes. Once precipitation data is classified into classes, correlation weighting scheme (Teegavarapu and Chandramouli, 2005) or linear weighted optimization with positive weights method can be used to obtain weights for each class. The classification is based on historical precipitation data (i.e. train data set) at stations and pre-defined classes. The weights are then used for estimation of missing precipitation data at the base station. The observed data from the test data set at all other stations other than base station is again used for classification to pre-fixed classes. In general, the performance improved when the number of classes is increased. The optimal weighting scheme provided better results compared to correlation weighting in both the regions. The best performance was achieved when fourteen and three classes are used for correlation and optimization-based methods respectively. In both the regions, the optimal K-NN classification with classes provided the best performance measures. Results for correlation and optimized K-NN classification methods are provided in Table 13 and Table 14.

Table 13. Performance measures based on different classes used in correlation weighted K-NN classification imputation for region II

Number of classes	AE (mm)	MAE (mm)	RMSE (mm)	ρ
14	2449	3.449	6.895	0.697
10	2539	3.577	7.204	0.660
7	2534	3.569	7.147	0.667
3	2550	3.593	7.142	0.671

Table 14. Performance measures based on different classes used in optimal K-NN classification imputation for region II

Number of classes	AE (mm)	MAE (mm)	RMSE (mm)	ρ
14	2474	3.484	7.041	0.696
10	2557	3.604	7.608	0.628
7	2448	3.449	7.450	0.658
3	2306	3.248	6.812	0.708

The application of K-means clustering approach required spatial partitioning of rain gage stations into several clusters. Several clusters are experimented in the current study. Two approaches are described earlier in sections, indicate the use of one station (the station with maximum correlation with station with missing data) in each cluster or weighted sum of observations from all the stations in each cluster. Results related to this method are provided in Table 15. Based on limited experiments conducted, a total of six clusters resulted in the best performance measures.

Table 15. Performance measures based on different distance metrics used in Optimal K-means cluster imputation for region II

Number of clusters	Selected stations in cluster	AE (mm)	MAE (mm)	RMSE (mm)	ρ
2	1,2,4,5,10,14-30,32,34	2484	3.498	7.664	0.637
	3,6,7,8,9,11-13,31,33,35-42				
4	15-17,20-28,32,34	2356	3.312	7.043	0.686
	1,14,18,19,29-31,39,42				
	2-10,12,13				
	11,33,35-38,40,41				
6	6,11,12,13,40,42	2348	3.307	7.034	0.694
	10,15,23-27				
	1,14,18,19,29-31,39				
	33,35-38,41				
	16,17,20-22,28,32,34				
	2-9				

The models developed in the current study are evaluated and ranked based on the weighting functions (Teegavarapu and Elshorbagy, 2005). The rankings of the models are shown in Table 16. A conceptually simple missing data estimation method, the normal ratio method, receives the highest ranking. Again three proximity metric-based optimal weighting methods are among the top ten methods. The ordinary kriging approach, artificial neural networks, thin-plate splines with tension and robust-fit regression are also ranked high. The performances of the models are assessed after the negative precipitation values are corrected for kriging, ANN, thin-plate splines and robust-fit regression methods.

Table 16. Ranking of different imputation methods and their variants for region II

Method	Rank	Method	Rank
Normal Ratio (correlation)	1	Dice	31
Ordinary Kriging (Circular Semi-Variogram)	2	Kulzinksky	32
Thin plate splines with tension	3	K-NN Classification (correlation, 14 classes)	33
Robust-fit Regression	4	Step-Wise Regression	34
Euclidean	5	Reciprocal Variance Weighting (Spherical Semi-variogram)	35
Manhattan	6	Simple Matching	36
Sokal-Mischener	7	Gower	37
Inverse Distance (optimal exponent)	8	Rogers and Tanimoto	38
Correlation Coefficient Weighting (optimal exponent)	9	Yule	39
Artificial neural networks	10	K-NN Classification (optimization, 14 classes)	40
Gauge Mean Estimator (correlation)	11	Maximum	41
Optimal Weighting (postive weights, nearest neighbors-correlation based)	12	Multiple Linear Regression	42
K-NN Classification (optimization, 3 classes)	13	Trend surface model (global, cubic)	43
Optimal Weighting (postive weights - all neighbors)	14	Trend surface model (global, quadratic)	44
Cosine	15	Single Best Estimator (distance)	45
Quadrant (one neighbor)	16	K-NN Classification (correlation, 7 classes)	46
Inverse Distance	17	K-NN Classification (optimization, 7 classes)	47
Squared Euclidean	18	K-NN Classification (correlation, 3 classes)	48
Ordinary Kriging (Spherical Semi-variogram)	19	Minkowski	49
Inverse exponential (radius limited)	20	K-NN Classification (correlation, 10 classes)	50
Natural Neighbor	21	Jaccard	51
Correlation	22	Hamming	52
Russell and Rao	23	Trend surface model (global, linear)	53
Correlation Coefficient Weighting	24	K-Means Cluster (optimization, 2 clusters)	54
Gauge Mean Estimator (distance)	25	K-NN Classification (optimization, 10 classes)	55
K-Means Cluster (optimization, 6 clusters)	26	Ordinary Kriging (Exponential Semi-variogram)	56
Thin plate spline	27	Mahalanobis	57
Normal Ratio(distance)	28	Artificial neural networks	58
K-Means Cluster (optimization, 4 clusters)	29	Single Best Estimator (correlation)	59
Pearson	30	Ordinary Kriging (Guassian Semi-variogram)	60

CONCLUSIONS

The study reports development, implementation and evaluation of several optimal proximity-based formulations, interpolation and data-driven models for estimating missing precipitation records at several rain gage stations in SFWMD region. These methods are developed as a part of the second phase of the infilling precipitation data study. The infilling of missing data was initially based on data from rain gages. Upon successful evaluation of the methods, they will be extended to NEXRAD data for grid-based estimation of missing precipitation data. Of all the methods developed, the best method based on the evaluation of several performance measures will be selected to obtain NEXRAD grid based data for infilling missing rain gage records. In this report, work completed under the second phase of the project is discussed. Data available at pre-selected rain gages located in the SWFWMD was used for the preliminary assessment of the methods. The selected method will be recommended to infill missing precipitation estimates based on NEXRAD data in the SFWMD region.

REFERENCES

Abramowitz, M., and I.A. Stegun. 1965. *Handbook of Mathematical Functions*, National Bureau of Standards, Applied Math. Series #55, Dover Publications.

Ahrens, B., 2006. Distance in spatial interpolation of daily rain gauge data. *Hydrology and Earth System Sciences*, 10, 197-208.

ASCE 2001b. Task Committee on Artificial Neural Networks in Hydrology, Artificial Neural Networks in Hydrology. II Hydrologic Applications, *Journal of Hydrologic Engineering*, ASCE, 52, 124-137.

ASCE., 2001a. Task Committee on Artificial Neural Networks in Hydrology, Artificial Neural Networks in Hydrology. I. Preliminary concepts, *Journal of Hydrologic Engineering*, ASCE, 52, 115-123.

ASCE., 1996. *Hydrology Handbook*, second edition, American Society of Civil Engineers ASCE, New York.

Ashraf, M., Loftis J. C. and Hubbard K.G., 1997. Application of geostatisticals to evaluate partial weather station network. *Agricultural Forest Meteorology*, 84: 255-271.

Batagelj, V. 1995. Comparing resemblance measures. *Journal of Classification*. 12: pp. 73–90. 1995.

Brimicombe, A., 2003. *GIS, Environmental Modeling and Engineering*. Taylor and Francis, London, UK.

Brooke, A., Kendrik, D., and Meeraus, A., 1996. GAMS: A User's Guide, 286.

Daly, C., Gibson, W.P., Taylor, G.H., Johnson, G.H., Pasteris, P., 2002. A knowledge-based approach to the statistical mapping of climate. Climate Research 22, 99– 113.

Daly, C., R. P. Neilson and D. L. Phillips., 1994. A statistical topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33: 140-158.

Davis, J. C., 2002. Statistics and Data Analysis in Geology, John Wiley.

Deutsch, C. V. and A. G. Journel., 1992. *Geostatistical Software Library and User's Guide*, Oxford University Press, New York.

Dingman, S. L., 2002. *Physical Hydrology*, Prentice Hall, NJ.

Dungan, J. L., Perry, J. N., Dale, M. R. T., Legendre, P., Citron-Pousty, S., Fortin, M.-J., Jakomulska, A., Miriti, M., Rosenberg, M. S. 2002. A balanaced view of scale in spatial statistical analysis. Ecography, 25, 626-40.

Edelbrock, C. Mixture model tests of hierarchical clustering algorithms: the problem of classifying everybody. Multivariate Behavioral Research. 14: pp. 367–384. 1979.

Eischeid J. K., Pasteris, P. A., Diaz H.F., Plantico, M.S., Lott, N. J., 2000. Creating a serially complete, national daily time series of temperature and precipitation for the Western United States. Journal of Applied Meteorology, 39, 1580-1591.

Ellis, D, Furner-Hines, J, Willett, P. 1993. Measuring the degree of similarity between objects in text retrieval systems. Perspectives in Information Management 3(2): 128-149.

Fisher, RA The use of multiple measurements in taxonomic problems. Annals of Eugenics, 7(2): 179-188. 1936

Fortin, M-J., Dale, M. 2005. *Spatial Analysis: A Guide for Ecologists*, Cambridge University Press.

Franke, R. 1982. Smooth Interpolation of Scattered Data by Local Thin Plate Splines. *Computers and Mathematics with Applications.* Vol. 8. No. 4. pp. 237–281.

Freeman, J. A. and Skapura, D. M., 1991. *Neural Networks: Algorithms, Applications and Programming Techniques*, Addison-Wesley Inc., USA, 1991.

French, M. N., Krajewski, W.F., and Cuykendal, R.R., 1992. Rainfall forecasting in space and time using a neural network, *Journal of Hydrology*, 137, 1-37.

Goldberg, D.E., 1989. Genetic Algorithms in Search Optimization and Machine Learning. Addison-Wesley, New York

Goovaerts, P. 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology, 228, 113-129.

Govindaraju, R. S., and A. R. Rao., 2000. *Neural Networks in Hydrology*, Kluwer Academic Publishers, Netherlands.

Gower, JC and Ross, GJS. "Minimum Spanning Trees and Single Linkage Cluster Analysis." Applied Statistics. 18(1): pp. 54–64. 1969.

Grayson, R. and Bloschl, G, 2001. *Spatial Patterns in Catchment Hydrology: Observations and Modeling*, Cambridge University Press.

Griffith, D. A., 1987. *Spatial Autocorrelation: A Primer*, Association of American Geographers, Washington, D. C.

Hastie, T., Tibshirani, R., Sherlock, G., Eisen, M., Brown, P., and Botstein, D. (1999). Imputing missing data for gene expression arrays, Technical Report, Division of Biostatistics, Stanford University.

Haykin, S. 1994. *Neural Networks: A Comprehensive Foundation*, Macmillan Publishing, NY.

Hodgson, M. E., 1989. Searching methods for rapid grid interpolation, *Professional Geographer*, 411: 51-61.

Hosking, J. R. M., and J. R. Wallis. 1998.Regional Frequency Analysis: An Approach Based on L-Moments, Cambridge University Press.

Isaaks, H . E., and R. M. Srivastava., 1989. *An Introduction to Applied Geostatisitics*, Oxford University Press, New York

Jain, A., and Dubes, R., "Algorithms for Clustering Data." Prentice-Hall. Englewood Cliffs, NJ. 1988.

Johnson, SC. Hierarchical clustering schemes. Psychometrika. 32(2): pp. 241–254. 1966.

Journel, A. G. and C. J. Huijbregts, 1978. *Mining Geostatistics*, Academic Press, New York.

Krajewski, W. F., 1987. Co-kriging of radar and rain gage data, *Journal of Geophysics Research*, 92D8, 9571-9580.

Kuligowski, R. J. and Barros, A. P. (1998) Using artificial neural networks to estimate missing rainfall data. Journal of American Water Resources Association, **34**(6), 1437–1447.

Lance, G. N., Williams, W. T., 1966. Computer programs for hierarchical polythetic classification. Computer Journal 9: 60-64.

Lagarias, J. C., J. A. Reeds, M. H. Wright, and P. E. Wright. 1998. Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions, *SIAM Journal of Optimization*, Vol. 9 Number 1, pp. 112-147.

Larose, T., 2005. Discovering Knowledge in Data: An Introduction to Data Mining, Wiley, USA.

Larson, L. W., and E. L. Peck., 1974. Accuracy of precipitation measurements for hydrologic forecasting*, Water Resources Research*, 156, 1687 - 1696.

Lawson, C.L. and R.J. Hanson, 1974. *Solving Least Squares Problems*, Prentice-Hall, Chapter 23, p. 161.

Little, D. G. and D. B. Rubin, 1987. Statistical Analysis with Missing Data,Wiley, New York.

Lloyd, C. D., 2007. Local Models for Spatial Analysis, CRC Press, USA.

Llyod, C. D., 2005. Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain, Journal of Hydrology, 308,128-150.

Loader, C., 1999. Local Regression and Likelihood. Springer Verlag.

Lu, G. Y., D. W. Wong. 2008. An adaptive inverse-distance weighting spatial interpolation technique Computers & Geosciences, 34(9) 1044-1055

McCuen, R. H., 2005. *Hydrologic Analysis and Design*, Prentice-Hall, NJ

Mitas, L., and H. Mitasova. 1988. General Variational Approach to the Interpolation Problem. *Computers and Mathematics and Applications*. Vol. 16. No. 12. pp. 983–992.

Osborn, H. B., K.G. Renard, and J. R. Simanton., 1979. Dense networks to measure convective rainfall in the southwestern United States, *Water Resources Research*, 156 : 1701-1709.

Pang-Ning, T., M. Steinbach, V. Kumar., 2006. Introduction to Data Mining, Pearson, USA.

Ramos-Calzado, P., J. Gomez-Camacho, F. Perez-Bernal and M. F. Pita-Lopez., 2008. A novel approach to precipitation series completion in climatological datasets: Application to Andalusia, International Journal of Climatalogy, 28, 1524-1535.

Regonda, S.K., Rajagopalan, B., Clark, M., Zagona, E., 2006. A multi-model ensembleforecast framework: application to spring seasonal flows in the Gunnison River Basin. Water Resources Research 42 (9), W09404.

Rogers, D. J. and Tanimoto, T. T., 1960. A computer program for classifying plants. Science, 132: 1115-1118.

Salas, J. D.-J., 1993. Analysis and Modeling of Hydrological Time Series, *Handbook of Hydrology*, D. R. Maidment, ed, Mc-Graw-Hill, NY

Seber, G. A. F., and C. J. Wild. 2003. *Nonlinear Regression*. Hoboken, NJ: Wiley-Interscience.

Seo, D. J., 1998. Real-time Estimation of Rainfall Fields Using Radar Rainfall and Rain Gage Data, *Journal of Hydrology*, 208: 37-52.

Seo, D.-J. 1996. Nonlinear Estimation of Spatial Distribution of Rainfall - An Indicator Cokriging Approach. *Stochastic Hydrology and Hydraulics,* 10,127-150.

Seo, D.-J. and J. A. Smith, 1993. Rainfall Estimation Using Rain gages and Radar: A Bayesian Approach, *Journal of Stochastic Hydrology and Hydraulics*, 5(1), 1-14.

Seo, D.-J., Krajewski, W.F., Bowles, D.S. 1990a. Stochastic Interpolation of Rainfall Data from Rain Gages and Radar Using Cokriging - 1. Design of Experiments. *Water Resources Research*, 26(3), 469-477.

Seo, D.-J., Krajewski, W.F., Bowles, D.S. 1990b. Stochastic Interpolation of Rainfall Data from Rain Gages and Radar Using Cokriging - 2. Results. *Water Resources Research*, 26(5), 915-924.

Shepard, D., 1968. A Two-dimensional Interpolation Function for Irregularly Spaced Data, *Proceedings of the Twenty-Third National Conference of the Association for Computing Machinery*, 517-524.

Simanton, J. R., and H. B. Osborn, 1980. Reciprocal-Distance Estimate of Point Rainfall, *Journal of Hydraulic Engineering Division*, 106HY7

Singh, V. P., and K. Chowdhury., 1986. Comparing Some Methods of Estimating Mean Areal Rainfall, *Water Resources Bulletin*, 222, 275-282.

Smith, J. A., 1993. Precipitation, chapter 3, *Handbook of Hydrology*, D. R. Maidment, ed.. McGraw Hill, New York.

Sneath, PH and Sokal, RR. “Numerical taxonomy.” Nature. 193: pp. 855–860. 1962.

Sokal, RR and Michener, CD. A statistical method for evaluating systematic relationships. Scientific Bulletins. 38(22): pp. 1409–1438. 1958.

Speed, T. (2003). Statistical Analysis of Gene Expression Microarray Data (Chapman & Hall/CRC).

Sullivan, D. O. and David J. Unwin., 2010. *Geographical Information Analysis*, John Wiley & Sons, Inc, NJ

Tabios, G. Q., III and J. D. Salas., 1985. A Comparative Analysis of Techniques for Spatial Interpolation of Precipitation, *Water Resources Bulletin*, 21: 365-380.

Teegavarapu, R. S. V., 2011. Spatial Interpolation using Nonlinear Mathematical Programming Models for Estimation of Missing Precipitation Records, Hydrological Sciences Journal.

Teegavarapu, R. S. V., M. Tufail, L. Ormsbee, 2009. Optimal functional forms for estimation of missing precipitation records, Journal of Hydrology, 374, 106-115.

Teegavarapu, R. S. V., 2007. Use of universal function approximation in variance-dependent interpolation technique: An application in Hydrology, Journal of Hydrology, 332, 16-29.

Teegavarapu, R. S. V., 2008. Innovative spatial interpolation methods for estimation of missing precipitation records: concepts and applications, Proceedings of HydroPredict 2008, Prague, J. Bruthans, K. Kovar, Z. Hrkal, editors, 79- 82.

Teegavarapu, R. S. V., 2009. Estimation of Missing Precipitation Records Integrating Surface Interpolation Techniques and Spatio-Temporal Association Rules, Journal of Hydroinformatics, 11 (2), 133–146.

Teegavarapu, R. S. V., Chandramouli, V. 2005. Improved weighting methods, deterministic and stochastic data-driven models for estimation of missing precipitation records, Journal of Hydrology, 312, 191 -206.

Teegavarapu, R. S. V., Elshorbagy A., 2005. Fuzzy Set-Based Error Measure for Hydrologic Model Evaluation, Journal of Hydroinformatics, 7, 199-208.

Teegavarapu, R. S. V., T. Meskele, C. Pathak, 2011. Geo-spatial grid-based transformation of precipitation estimates using spatial interpolation methods, Computers and Geosciences.

Teegavarapu, R. S. V., C. Pathak, 2008. Infilling of Rain Gage Records Using Radar (NEXRAD) Data: Influence of Spatial and Temporal Variability of Rainfall Processes, Proceedings of World Environmental and Water Resources Conference, R. W. Babcock, R. Walton (editors), EWRI-ASCE, Hawaii, pp. 1-9, (doi 10.1061/40976(316)406)

Tobler, W. R., 1970. A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography*, 46: 234-240.

Tomczak, M., 1998. Spatial Interpolation and its uncertainty using automated anisotropic inverse distance weighting (IDW) – cross-validation/jackknife approach. Journal of Geographic Information and Decision Analysis 2, 18–30

Troyanskaya, O., Cantor, M., Sherlock, G., Brown, P., Hastie, T., Tibshirani, R., Botstein, D., and Altman, R. (2001). Missing value estimation methods for DNA microarrays. Bioinformatics *17(6)*, 520–525.

Tsanis, I. Orographic Precipitation Modeling with Multiple Linear Regression, Journal of Hydrologic Engineering, 9(2), 79-102 (March/April 2004)

Tung, Y. K., 1983. Point Rainfall Estimation for a Mountainous Region, *Journal of Hydraulic Engineering, American Society of Civil Engineering ASCE*, 10910:1386 -1,393.

Vasiliev, I. R., 1996. Visualization of Spatial Dependence: An Elementary View of Spatial Autocorrelation, in *Practical Handbook of Spatial Statistics*, CRC Press, Boca Raton.

Vieux, B. E., 2001. *Distributed Hydrologic Modeling using GIS*, Water Science and Technology Library, Kluwer Academic Publishers.

Wallis, J. R., D. P. Lettenmaier, E. F. Wood, 1991. A daily hydroclimatological data set for the continential United States, Water Resources Research, 27, 1657-1663.

Wang, F. , 2006. Quantitative Methods and Applications in GIS, CRS press, USA.

Ward Jr, J. H. Hierarchical grouping to optimize an objective function. Journal of the American Statistical Association. 58(301): pp. 236–244. 1963.

Webster, R. A., and M. A. Oliver., 2001. *Geostatistics for Environmental Scientists*, John Wiley and Sons, Chichester, UK.

Wei, T. C., and J. L. McGuinness., 1973. Reciprocal Distance Squared Method, a Computer Technique for Estimating Area Precipitation, *Technical Report ARS-Nc-8., U.S. Agricultural Research Service*, North Central Region, Ohio.

Wheatly, D., and Gillings, M. (2002). Spatial Technology and Archaeology: The Archaeological Applications of GIS, Taylor and Francis, UK.

Xia, Y., Fabian, P., Stohl, A., Winterhalter, M., 1999. Forest Climatology: estimation of missing values for Bavaria, Germany. Agricultural and Forest Meteorology, 96, 131-144.

Xia, Y., Fabian, P., Stohl, A., Winterhalter, M., Zhao, M., 2001. Forest Climatology: estimation and use of daily climatological data for Bavaria, Germany. Agricultural and Forest Meteorology, 106, 87-103.

Yang, X., and T. Holder., 2000. Visual and Statistical Comparisons of Surface Modeling Techniques for Point-Based Environmental Data, *Cartography and Geographic Information Science*, 27: 165-75.

Zimmerman, D. C., C. Pavlik, A. Ruggles, M. P. Armstrong. 1999. An experimental comparison of ordinary and universal kriging and inverse distance weighting. Mathematical Geology, 31, 375-390.

Zurada, J.M., 1992. Introduction to Artificial Neural Systems. Boston, MA, USA.

SOUTH FLORIDA WATER MANAGEMENT DISTRICT - REFERENCES

Ali, A., and W. Abtew. 1999. Regional Rainfall Frequency Analysis for Central and South Florida. Technical Publication WRE#380. South Florida Water Management District. West Palm Beach, Florida.

Ali, A., W. Abtew, S.V. Horn and N. Khanal. 1999. Frequency and Spatial Analysis for Monthly Rainfall in Central and South Florida. Technical Publication WRE#371. South Florida Water Management District. West Palm Beach, Florida.

Huebner, R.S., C.S. Pathak and B.C. Hoblit. 2003. Development and Use of a NEXRAD Database for Water Management in South Florida. ASCE World Water & Environmental Resources Congress, June 2003, Philadelphia, Pennsylvania.

Kollias, P., J. Tenerelli, B.A. Albrecht, and P. Trimble. 2003. A multi-year high resolution precipitation product for south Florida using NEXRAD and gages. 31st International Conference on Radar Meteorology, American Meteorology Society, August 2003, Seattle, Washington. http://orca.rsmas.miami.edu/proj/brace/mrl/Kollias2.pdf

Moss, M. 1996. Testing the Adequacy of a Kriging Model of the SFWMD Rain Gage Network. Bayeswater, Inc., Tucson, AZ.

Pathak, C.S. 2001. Frequency Analysis of Daily Rainfall Maxima for Central and South Florida, Technical Publication, EMA Report # 390, South Florida Water Management District, West Palm Beach, Florida.

Pathak, C.S., R.S. Huebner and E.P. Swartz. 2005. Rainfall Monitoring Using NEXRAD Data for Water Management in South Florida. First Florida Radar Rainfall User Workshop, November 15, 2005. University of Central Florida, Orlando, Florida.

Pathak, C.S. and S. Palermo. 2006. Rainfall Based Management Plan for Water Conservation Area 3A in Florida Everglades. ASCE/EWRI World Water & Environmental Congress, Annual Conference, May 21-25. Omaha, Nebraska. Proceeding.

Pathak, C. S. (Ed.). 2006. Hydrologic Monitoring Network of South Florida Water Management District – Draft Report. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2006. Rain Gauge Network Optimization Study – Report. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2008. An Assessment of Interpolation Methods for Estimating Missing Daily Precipitation Records for Rain Gauges in Central and South Florida. – Final Report by Intera, Inc.. August 2008 South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2008a. In-filling Missing Historical Daily Rainfall Data Study. – Final Report by Tristan Landot, Serena Sgellari, Carlos Lima, and Upmanu Lall. February 2008. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2007. An Assessment of In-filling Methods for Estimating Missing Daily Precipitation Records – Final Report by Dr. Jon Ahlquist, Dr. Henry Fuelberg, and Dr. Ramesh Teegavarapu. December 2007. South Florida Water Management District, West Palm Beach, Florida.

Skinner, C. 2006. Developing A Relationship Between NEXRAD Generated Rainfall Values and Rain Gauge in South Florida. Master's Thesis. Department of Civil Engineering, Florida Atlantic University, Boca Raton, Florida.

Van Lent, T.J. and J.C.Tracy. 1994. Assessment of the Rain Gage Network in the South Florida Water Management District. College of Engineering, South Dakota State University, Brookings, South Dakota.

Development and Sensitivity and Uncertainty Analysis of Spatially Distributed Hydrological and Water Quality Models in South Florida

Basic Information

Title:	Development and Sensitivity and Uncertainty Analysis of Spatially Distributed Hydrological and Water Quality Models in South Florida
Project Number:	2008FL213B
Start Date:	3/1/2010
End Date:	2/28/2011
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. Perez-Ovilla, O. "A generic approach for simulating the removal of runoff pollutants in Vegetative Filter Strips" (poster). University of Florida Water Institute Symposium. Gainesville, FL. February 28 2008.
2. Perez-Ovilla, O. "A generic approach for simulating pollutant runoff dynamics in Vegetative Filter Strips". The 2008 FLORIDA SECTION ASABE ANNUAL CONFERENCE. Duck Key, FL. June 13 2008.
3. Muñoz-Carpena, R. and Pérez-Ovilla, Oscar. A short course on the use of the program vfsmod-w. University of Chiapas, Mexico. November 03 2008.
4. Perez-Ovilla, Oscar. A generic approach for simulating dynamics and removal of runoff pollutants in Vegetative Filter Strips. Juárez University of Tabasco (Universidad Juárez Autónoma de Tabasco), Mexico. November 07, 2008.
5. Perez-Ovilla, O. "A generic approach for simulating pollutant runoff dynamics in Vegetative Filter Strips". The 2008 FLORIDA SECTION ASABE ANNUAL CONFERENCE. Duck Key, FL. June 13 2008.
6. Zajac, Z. Global Sensitivity Analysis using the Method of Morris of the South Florida Regional Hydrologic Model - Regional Simulation Model (RSM). American Geophysical Union (AGU) Joint Assembly, Fort Lauderdale, FL. 28 May 2008.
7. Zajac, Z. Global Sensitivity Analysis using the Method of Morris of the South Florida Regional Hydrologic Model-Regional Simulation Model (RSM). Florida Section Agricultural and Biological Engineers Annual Conference and Trade Show. Duck Key, FL. June 13 2008.
8. Development of a Spatially-Distributed Phosphorus Model for the Everglades: Stuart Muller, University of Florida, Gainesville, FL (R. Muñoz-Carpena, J. Jawitz, A. James). Poster session: 2008 AGU Joint Assembly The Meeting of the Americas, May 27-30, Fort Lauderdale, FL.
9. A Phosphorus Water-Quality Model for the Everglades: Stuart Muller, University of Florida, Gainesville, FL (R. Muñoz-Carpena, J. Jawitz, A. James). Poster session: 2008 Florida Section of the

American Society of Agricultural and Biological Engineers, June 12-13, Duck Key, FL.

10. A Spatially-Distributed Phosphorus Water-Quality Model for the Linked Surface-Water Groundwater Variable-Density Hydrology of the Southern Everglades: Stuart Muller, University of Florida, Gainesville, FL. Presentation: 2008 Greater Everglades Ecosystem Restoration Conference, July 28-Aug 1, Naples, FL.
11. Everglades Water Quality in an Uncertain Future: Stuart Muller, Universty of Florida, Gainesville, FL. Presentation: 2009 American Water Resources Association Spring Specialty Conference Managing Water Resources in a Changing Climate, May 4-6, Anchorage, AK.
12. Jawitz, J., R. Muñoz-Carpena, S. Muller, K. Grace, and A. James (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. Scientific Investigations Report 2008-5029. U.S. Department of the Interior-U.S. Geological Survey: Reston, VA.
13. 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.
14. 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.
15. 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.
16. 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.
17. 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.
18. 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.
19. 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.
20. 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.
21. Muller, S, Muñoz-Carpena, R, and Kiker, G. (2009). Model Relevance: Frameworks for Exploring the Complexity-Sensitivity-Uncertainty Trilemma. In (Eds.) I. Linkov and T.S. Bridges: Climate: Global Change and Local Adaptation p35-65. Springer, Dordrecht, Netherlands.
22. Muller, S. (2010). Adaptive spatially-distributed water-quality modeling: an application to mechanistically simulate phosphorus conditions in the variable-density surface-waters of coastal Everglades wetlands. Ph.D. dissertation: University of Florida, Gainesville, FL. Available online: http://etd.fcla.edu/UF/UFE0042132/muller_s.pdf
23. Muller, S., R. Muñoz-Carpena (in final preparation). Modeling water-quality in the southern Everglades: Hydrodynamic foundations.
24. Muller, S., R. Muñoz-Carpena (in final preparation). Sense and sensitivity: Exploring model complexity.
25. Muller, S., R. Muñoz-Carpena (in preparation). Modeling water-quality in the southern Everglades: Biogeochemical foundations.

26. Mechanistic Water-Quality Modeling in the Southern Everglades: Stuart Muller, University of Florida, Gainesville, FL. Presentation: 2010 Annual Meeting of the Florida Section for the American Society of Agricultural and Biological Engineers, June10-13, Daytona Beach, FL.
27. Adaptive Spatially-Distributed Water-Quality Modeling: An Application to Mechanistically Simulate Phosphorus Conditions in the Variable-Density Surface-Waters of Coastal Everglades Wetlands: Stuart Muller, University of Florida, Gainesville, FL. Presentation: Ph.D. Defense in Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL.
28. Zajac Z., Muñoz-Carpena R., Graham W., Vanderlinden K., Obeysekera J. Effect of spatially distributed numerical inputs on the global sensitivity and uncertainty of hydrological models, a south Florida case study. Submitted to the Journal of Hydrology, February 2011.
29. Zajac. Z. Global Sensitivity and Uncertainty Analysis of Spatially Distributed Watershed Models. PhD. Dissertation. University of Florida. August 2010. Available online: http://etd.fcla.edu/UF/UFE0042111/zajac_z.pdf
30. A flexible numerical component to simulate biogeochemical transport processes through vegetative filter strips. Ph.D. dissertation. [Gainesville, Fla.]: University of Florida. (Advisor: R. Muñoz-Carpena). Available online: http://etd.fcla.edu/UF/UFE0042122/perezovilla_o.pdf
31. Perez-Ovilla, O. and R. Muñoz-Carpena. In preparation for the J. Environ. Qual. A flexible modeling approach for transport and reaction of pollutants in runoff.
32. Flexible Simulation of Surface Runoff Pollutants: Analytical and Lab Scale Testing. The second University of Florida Water Institute Symposium, Gainesville, Fl. February 2010.
33. Design and Evaluation of Vegetative Filter Strips with VFSMOD-W to Control Surface Runoff Pollution of Sediment, Nutrients, Pesticides and other Emerging Contaminants. American Society of Agricultural and Biological Engineers 2010 Annual International Meeting, June 2010.

Status Report
104B Student Assistantship Program
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): Adaptive spatially-distributed water-quality modeling: an application to mechanistically simulate phosphorus conditions in the variable-density surface-waters of coastal Everglades wetlands.

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

Recent publications, proceedings, or presentations.

Publications: Dissertation

Muller, S. (2010). *Adaptive spatially-distributed water-quality modeling: an application to mechanistically simulate phosphorus conditions in the variable-density surface-waters of coastal Everglades wetlands*. Ph.D. dissertation: University of Florida, Gainesville, FL.

Available online: http://etd.fcla.edu/UF/UFE0042132/muller_s.pdf

Publications: Book chapters

Muller, S, Muñoz-Carpena, R, and Kiker, G. (2009). *Model Relevance: Frameworks for Exploring the Complexity-Sensitivity-Uncertainty Trilemma*. In (Eds.) I. Linkov and T.S. Bridges: Climate: Global Change and Local Adaptation p35-65. Springer, Dordrecht, Netherlands.

Publications: Journal articles

Muller, S., R. Muñoz-Carpena (in final preparation). *Modeling water-quality in the southern Everglades: Hydrodynamic foundations.*

Muller, S., R. Muñoz-Carpena (in final preparation). *Sense and sensitivity: Exploring model complexity.*

Muller, S., R. Muñoz-Carpena (in preparation). *Modeling water-quality in the southern Everglades: Biogeochemical foundations.*

Presentations

Mechanistic Water-Quality Modeling in the Southern Everglades: Stuart Muller, University of Florida, Gainesville, FL. Presentation: 2010 Annual Meeting of the Florida Section for the American Society of Agricultural and Biological Engineers, June10-13, Daytona Beach, FL.

Adaptive Spatially-Distributed Water-Quality Modeling: An Application to Mechanistically Simulate Phosphorus Conditions in the Variable-Density Surface-Waters of Coastal Everglades Wetlands: Stuart Muller, University of Florida, Gainesville, FL. Presentation: Ph.D. Defense in Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL.

Academic Status

Stuart Muller has successfully defended his Ph.D. and graduated with a final GPA of 3.92. In addition, all requirements were met for two specializations; the Hydrologic Sciences Academic Cluster, and the Wetlands Certificate.

Final Status Report

Stuart Muller successfully defended in July, 2010, and graduated with his Ph.D. in August, 2010. Following is a list of principle accomplishments from March 1st to final graduation:

- The calibration and validation of hydrodynamic simulations performed using FTLOADDS were finalized.
- A number of significant numerical instabilities were resolved, and one critical bug in the FTLOADDS model discovered and corrected.
- Conceptual models of phosphorus biogeochemistry were developed and tested in FTaRSELOADDS, the new water-quality model developed in this work by coupling FTLOADDS with aRSE.
- Three levels of complexity were tested by comparison of model results with observed surface-water phosphorus concentrations in the southern Everglades.
    - Level 1: Simulated phosphorus as a conservative tracer, assuming that inputs of phosphorus are matched by sinks of phosphorus.
    - Level 2: Simulated phosphorus as a reactive tracer, explicitly accounting for atmospheric deposition and phosphorus uptake from the water column.
    - Level 3: Simulated phosphorus biogeochemical cycling though pools comprising vegetation, periphyton and soils.
- Uncertainties associated with atmospheric deposition inputs to the model were identified as a major obstacle to mechanistic simulations of phosphorus biogeochemistry. Additionally, data paucity hindered more rigorous evaluation of transient concentration results. All levels of complexity proved useful: Level 1 demonstrated reasonable phosphorus concentrations were possible with no explicit treatment of internal phosphorus cycling; Level 2 elucidated the importance of atmospheric deposition estimates in any effort to account for internal phosphorus cycling; Level 3 showed that significant differences exist between water-quality conditions in ridge and slough based on their unique biogeochemical conditions, and their concomitant dependence on reliable simulation of local hydrodynamics.
- All new code associated with this effort was commented and collated for future documentation.
- The dissertation was completed, the Ph.D. defended, and subsequent corrections finalized.

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

Ph.D. Student: 2. Zuzanna Zajac, Agricultural and Biological Engineering

Recent publications, proceedings, or presentations

Publications

Zajac Z., Muñoz-Carpena R., Graham W., Vanderlinden K., Obeysekera J. Effect of spatially distributed numerical inputs on the global sensitivity and uncertainty of hydrological models, a south Florida case study. Submitted to the Journal of Hydrology, February 2011.

Dissertation

Zajac. Z. Global Sensitivity and Uncertainty Analysis of Spatially Distributed Watershed Models. PhD. Dissertation. University of Florida. August 2010.

Available online: http://etd.fcla.edu/UF/UFE0042111/zajac_z.pdf

Academic Status

Successfully defended and graduated with Ph.D. in August, 2010. All UF course requirements were fulfilled by the student with a cumulative UF GPA 3.93.

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.

Final Status Report

With spatially distributed models, the effect of spatial uncertainty of the model inputs is one of the least understood contributors to output uncertainty and can be a substantial source of errors that propagate through the model. The application of the global uncertainty and sensitivity (GUA/SA) methods for formal evaluation of models is still uncommon in spite of its importance. Even for the infrequent cases where the GUA/SA is performed for evaluation of a model application, the spatial uncertainty of model inputs is disregarded due to lack of appropriate tools. The main objective of this work is to evaluate the effect of spatial uncertainty of model inputs on the uncertainty of spatially distributed watershed models in the context of other input uncertainty sources. A new GUA/SA framework is proposed in order to incorporate the effect of spatially distributed numerical and categorical model inputs into the global uncertainty and sensitivity analysis (GUA/SA). The proposed framework combines the global, variance-based method of Sobol and geostatistical techniques of sequential simulation (SS). Sequential Gaussian simulation (SGS) is used for estimation of spatial uncertainty for numerical inputs (such as land elevation), while sequential indicator simulation (SIS) is used for assessment of spatial uncertainty of categorical inputs (such as land cover type). The Regional Simulation Model (RSM) and its application to WCA-2A in the South Florida Everglades is used as a test bed of the framework. The RSM outputs chosen as metrics for GUA/SA for this study are key performance measures generally adopted in the Everglades restoration studies: hydroperiod, water depth amplitude, mean, minimum and maximum. The GUA/SA results for two types of outputs, domain-based (spatially averaged over domain) and benchmark cell-based, are compared. The benchmark cell-based outputs are characterized with larger uncertainty than their domain-based counterparts. The uncertainty of benchmark cell-based outputs is mainly controlled by land elevation uncertainty, while uncertainty of domain-based outputs it also attributed to factors like conveyance parameters. The results indicate that spatial uncertainty of model inputs is indeed an important source of model uncertainty.

The land cover distribution affects model outputs through delineation of Manning's roughness zones and evapotranspiration factors associated to the different vegetation classes. This study shows that in this application the spatial representation of land cover has much smaller influence on model uncertainty when compared to other sources of uncertainty like spatial representation of land elevation. The spatial uncertainty of land cover was found to affect RSM domain-based model outputs through delineation of Manning's roughness zones more than through ET parameters effects.

The relationship between model uncertainty and alternative spatial data resolutions was studied to provide an illustration of how the procedure may be applied for more informed decisions regarding planning of data collection campaigns. The results corroborate a proposed hypothetical nonlinear, negative relationship between model uncertainty and source data density. The inflection point in the curve, representing the optimal data requirements for the application, is identified for the data density between 1/4 and 1/8 of original data density. It is postulated that the inflection point is related to the characteristics of the spatial dataset (variogram) and the aggregation technique (model grid size).

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

Publications: Dissertation

A flexible numerical component to simulate biogeochemical transport processes through vegetative filter strips. Ph.D. dissertation. [Gainesville, Fla.]: University of Florida. (Advisor: R. Muñoz-Carpena).
Available online: http://etd.fcla.edu/UF/UFE0042122/perezovilla_o.pdf

Publications: Journal articles

Perez-Ovilla, O. and R. Muñoz-Carpena. In preparation for the *J. Environ. Qual*. A flexible modeling approach for transport and reaction of pollutants in runoff.

Presentations

- Poster: Flexible Simulation of Surface Runoff Pollutants: Analytical and Lab Scale Testing. The second University of Florida Water Institute Symposium, Gainesville, Fl. February 2010.
- CPD #5: Design and Evaluation of Vegetative Filter Strips with VFSMOD-W to Control Surface Runoff Pollution of Sediment, Nutrients, Pesticides and other Emerging Contaminants. American Society of Agricultural and Biological Engineers 2010 Annual International Meeting, June 2010.

Academic Status

Defended dissertation and graduated with Ph.D. in August 2010.

Final Status Report

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.

Lab scale testing was performed to test the flexible module. Test was based on Yu's experimental work (Yu et al, 2010) for bromide transport in runoff on a sand bed with artificial rainfall. 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.

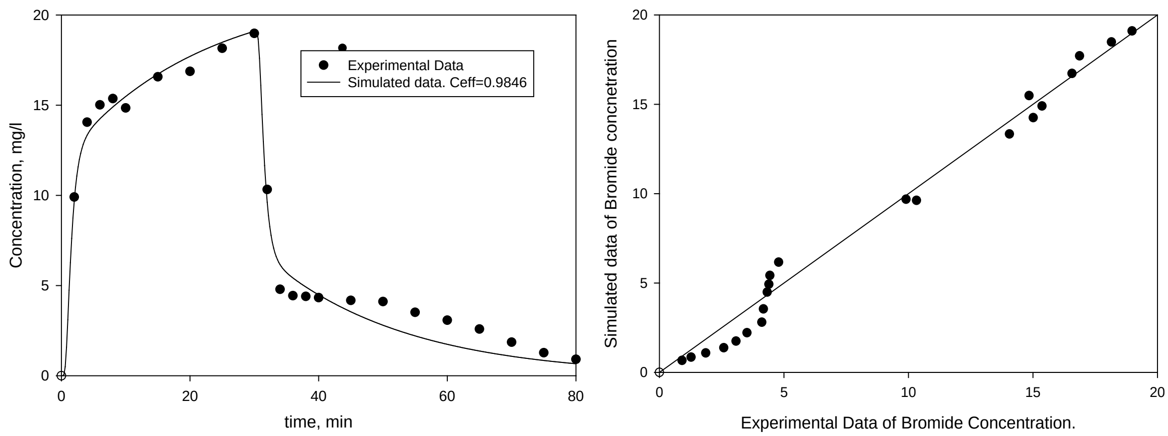

Figure 1. Concentration during the simulation of bromide in runoff at the end of the experimental sand box (x=1.52 m). Bromide was release as a plug during 0<time<30 mins with a constant concentration of 103 mg/l. The Nash-Sutcliffe model efficiency coefficient was 0.9846.

A second test involved the simulation of a field scale experiment for the dissolution of apatite and transport of phosphate under non-steady state conditions in vegetative filter strips using the program VFSMOD. The theory of apatite dissolution (Kuo, 2009) was used in the new water quality module since Kuo and Muñoz-Carpena (2009) conclude that the field scale experimental results in outflow cannot be explained by only considering the transport of phosphorus in runoff, the effect of dilution by rain, and the infiltration.

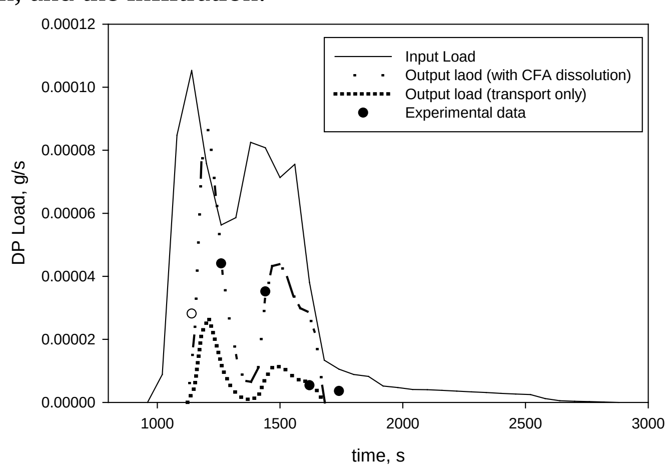

Figure 2. Simulated results for the transport of dissolved phosphorus load considering the effect of apatite dissolution

The flexible water quality model of VFSMOD-W allowed exploring the interactions between the release of phosphorus from apatite dissolution and the loads and concentration of DP in runoff during a rainfall event.

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.

CONGRONG YU, BIN GAO, RAFAEL MUÑOZ-CARPENA, YUAN TIAN, LEI WU AND OSCAR PEREZ-OVILLA. A laboratory study of colloid and solute transport in surface runoff on saturated soil. Journal of Hydrology, 402, 159-164.

KUO, Y. M.R. MUÑOZ-CARPENA, 2009. Simplified modeling of phosphorus removal by vegetative filter strips to control runoff pollution from phosphate mining areas. Journal of Hydrology 378, 343-354.

Addition of Ecological Algorithms into the RSM Model

Basic Information

Title:	Addition of Ecological Algorithms into the RSM Model
Project Number:	2008FL215B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Ecology, Models
Descriptors:	
Principal Investigators:	Gregory Alan Kiker, Wendy D Graham, Rafael Munoz-Carpena

Publications

1. Lagerwall, G. " Linkage of Ecological Algorithms With a Transport and Reaction Simulation Engine (TARSE:ECO) for Implementation with the Regional-Scale Water Simulation Model (RSM)" (presentation). Florida Section of the American Society of Agricultural and Biological Engineers, 12 June - 13 June 2008.
2. Lagerwall, G. "An Integrated Model of Wetland Hydrology, Water Quality, and Ecology" (poster). University of Florida Water Institute Symposium, 27-28 February 2008.
3. 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
4. Lagerwell, G. Methods to Predict Typha domingensis (cattail) Dynamics in the Everglades; Bi-Annual University of Florida Water Institute Symposium; Gainesville, Fl; February 2010.
5. Lagerwall, G.L., Kiker, G.A., Muñoz-Carpena, R., James, A., Hatfield, K., Wang, N., 2011, Modeling Typha domingensis in an Everglades Wetland. University of Florida. Dissertation.
6. Lagerwall, G.L., Kiker, G.A., Muñoz-Carpena, R., 2011, Accounting for the Impact of Management Scenarios on an Everglades Wetland. Ecological Informatics. In Submission.

Status Report
104B Student Assistantship Program
Project: Addition of Ecological Algorithms to the Regional Simulation Model (RSM)

CoPIs: Gregory Kiker, Rafael Muñoz-Carpena, Wendy D. Graham,
SWFMD Coordinator: Naiming Wang
Ph.D. Student: Gareth Lagerwall
Collaborator: Andrew James
External Committee Member: Kirk Hatfield

Recent publications, proceedings, or presentations:

Lagerwall, G.L., Kiker, G.A., Muñoz-Carpena, R., 2011, Accounting for the Impact of Management Scenarios on an Everglades Wetland. Ecological Informatics. In Submission.

Lagerwall, G.L., Kiker, G.A., Muñoz-Carpena, R., James, A., Hatfield, K., Wang, N., 2011, Modeling Typha domingensis in an Everglades Wetland. University of Florida. Dissertation.

Objectives:

This research project aims to systematically review, design and develop selected ecological algorithms for the RSM model (RSM-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 RSM-ECO ecological algorithms.
- Selection of ecological species (habitat, plant and/or animal) to be included in the initial development and testing of RSM-ECO.
- Development of the conceptual model of RSM-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 Report:

All work required for the completion of the PhD has been completed. The abstract of the dissertation can be read below:

The regional simulation model (RSM), developed by the south Florida water management district (SFWMD), was originally coupled with the transport and reaction simulation engine (TARSE) in order to model phosphorus dynamics in an Everglades wetland in Southern Florida, USA. The dynamic nature and user-defined inputs and interactions of this coupled model allowed for adapting it towards modeling ecology. Specifically, it was applied towards modeling Typha domingensis (Southern Cattail, or more generally, cattail) densities across Water Conservation Area 2A (WCA2A). In order to address the issues of complexity, uncertainty, and sensitivity, (i.e. how complex can a model be made in order to reduce uncertainty, while maintaining a relatively low level of sensitivity/instability) five levels of increasing algorithmic complexity were used. The two main factors determining cattail density are water depth and phosphorus concentration, and were thus used to inform the levels of complexity. A simple logistic function was used as the Level 1 complexity to model cattail density. Water depth was used to influence the logistic function in the Level 2 complexity. Water depth along with phosphorus concentration, were used to influence the logistic function in the Level 3 complexity. An inter-species competition factor in the form of a Level 1 Cladium jamaicense (sawgrass) modeled density was used along with water depth and phosphorus concentration to influence the logistic function in the Level 4 complexity. And lastly, an inter-species feed-back mechanism was implemented in the Level 5 complexity, which is essentially a Level 4 complexity but with the cattail density negatively influencing the sawgrass density. Vegetation maps for the years 1991, 1995, and 2003 were used for initialization and comparison of model output during training (1991-1995), testing 1 (1991-2003) and testing 2 (1995-2003) simulations. The growth rate value which influences the logistic function throughout all the levels of complexity was calibrated to 6.7*10-9 g/gs during the training simulation. The difference between model output and historical data was calculated, along with the Moran's I statistic for spatial correlation, and an abundance-area curve for comparing regional density distribution, and it was determined that Level 4 and Level 5 complexities were best suited for matching the historical data. Spatial uncertainty, through the use of sequential indicator simulation, was used to influence a global uncertainty and sensitivity analysis (GUSA). The variance based Sobol method was used to conduct the GUSA, and it was determined here too that a Level 4 complexity was best suited to model cattail densities in the region – providing the best balance between complexity, uncertainty and sensitivity. Finally, based on the previous two findings, a Level 4 and Level 5 complexity was used to determine the impact of alternate management scenarios on the area. Scenarios included high, medium, and low, as well as annually alternating (high and low) water depths and phosphorus concentrations. A GUSA was conducted on these management scenarios to determine their influence relative to the other uncontrollable factors such as the growth and death rates. As with the previous GUSA, the depth was a highly influential parameter, with initial cattail and sawgrass densities coming into play largely through their interaction effects. Time series of select management scenarios were plotted, and it was determined that expansive cattail growth required a high soil phosphorus

concentration. Also, in order to prevent cattail densities increasing significantly, it was determined that a high water depth be used in combination with a low soil phosphorus concentration. In summary, this is a unique, spatially distributed, deterministic, ecological model, providing cattail density values across WCA2A. Provided adequate data, this coupled RSM/TARSE model, along with the groups of analyses conducted, could be applied towards simulating other vegetation species in other habitats.

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 (March 2010 to February 2011), 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 19 peer reviewed journal articles, 4 book chapters, 20 proceedings and presentations and 6 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. As part of the WRRC information and technology transfer mission, the library has being converted to digital form and is provided free to the public through the WRRC Digital Library which is housed on the center website http://www.ce.ufl.edu/~wrrc/reports.html.

Florida Water Resources Information Transfer

Basic Information

Title:	Florida Water Resources Information Transfer
Project Number:	2010FL257B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	6
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Kirk Hatfield, Mark Newman

Publications

1. Klammler, H., K. Hatfield and A. Kacimov. 2010. Capture flows of funnel-andgate reactive barriers without gravel packs. In: Advances in Fluid Mechanics, WITpress, Wessex Institute of Technology, UK, (In Press).
2. Perminova, I.V., A.I. Konstantinov, E.V. Kunenkov, A. Gaspar, P. Schmitt-Kopplin, N. Hertkorn, N. A. kulikova, and K. Hatfield. 2009. Separation Technology as a Powerful Tool for Unfolding Molecular Complexity of Natural Organic Matter and Humic Substances. In: Biophysico-Chemical Processes: Involving Natural Nonliving Organic Matter in Environmental Systems, Sensesi, N., Xing, B., and Huang, P.M. (Eds.) Wiley & Sons Inc., Hoboken, New Jersy, pp. 487-538.
3. Klammler, H., K. Hatfield, I.V. Perminova. 2009. "Groundwater and contaminant travel time distributions near permeable reactive barriers". In: Water Resources Management V. C.A. Brebbia, V. Popov, eds. WIT Transactions on Ecology and the Environment, Vol. 125, ISBN 978-1-84564-199-3, pp. 245-256. doi: 10.2495/WRM090231.
4. Perminova, I.V., L.A. Karpiouk, S.A. Ponomarenko, A.M. Muzafarov, K. Hatfield, and. D. Bochkariov. 2011. Alkoxysilyl-Functionalized Humic Acids: Methods of Modification and Implanting onto Inorganic Surfaces in Aqueous Phase, Langmuir, (In Review).
5. Klammler H., K. Hatfield, J.A.G. Luz, M.D. Annable, M. Newman, J. Cho, A. Peacock, V. Stucker, J. Ranville, S. Cabaniss, and P. S. Rao. 2011. Contaminant Discharge Estimates with Uncertainty Distributions from Passive Flux Meter Measurements, Water Resour. Res. (In Review).
6. Stucker, V., J. Ranville, M. Newman, A. Peacock, and K. Hatfield. 2010. Evaluation and application of anion exchange resins to measure groundwater uranium flux at a former uranium mill site, Water Research, (In Review).
7. Klammler, H., K. Hatfield, B. Nemer, and S.A. Mathias. 2010. A Trigonometric Interpolation Approach to Mixed Type Boundary Problems Associated with Permeameter Shape Factors, Water Resour. Res. (In Press).
8. Mohamed M.M. and K. Hatfield. 2010. Dimensionless monod parameters to summarize the influence of microbial growth kinetics and inhibition on the attenuation of groundwater contaminants, Biodegradation, (In Press).
9. Klammler, H., K. Hatfield, M. McVay, and J. A. G. da Luz. 2010. Approximate Unconditional Up-Scaling of Spatially Correlated Non-Gaussian Variables, Georisk, (In Press).
10. Kacimov, A., H. Klammler, N. Ilyinsky, and K. Hatfield. 2010. Constructal design of permeable reactive barriers: A groundwater hydraulics criteria, J. Engineering Mathematics, (In Press).

11. Mohamed M.M., K. Hatfield, A. Hassan, and H. Klammler. 2010. Stochastic evaluation of subsurface contaminant discharge under physical, chemical, and biological heterogeneities, Advances in Water Resources., 33 (7), 801-812.
12. Klammler, H., K. Hatfield, and A Kacimov. 2010. Analytical solutions for flow fields near drain and gate reactive barriers, Ground Water, 48 (3), 427 437.
13. Bhat, S., J. Jacobs, K. Hatfield, and W. Graham. 2010. A comparison of stormbased and annual-based indices of hydrologic variability: A case study in Fort Benning, Georgia. Environmental Monitoring and Assessment, 167, (1-4), 297-307. DOI: 10.1007/s10661-009-1050-2; 1-11.
14. Padowski, J.C., E.A. Rothfus, J.W. Jawitz, H. Klammler, K. Hatfield, and M.D. Annable. 2009. Effect of Passive Surface Water Flux Meter Design on Water and Solute Mass Flux Estimates, ASCE, Journal of Hydrologic Engineering, 14(12), 1334-1342.
15. 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.
16. Newman, M.A., K. Hatfield, H.R. Klammler, M.D. Annable, J. Cho, B.L. Parker, J.A. Cherry, Ryan Kroeker, and W.H. Pedler. 2010. Demonstration and Validation of a Fractured Rock Passive Flux Meter. Proceedings: SERDP/ESTCP Partners in Environmental Technology Technical Symposium. Washington, D.C., November 30 - December 2, 2010.
17. Hatfield, K. 2010. Demonstration and Validation of a Fractured Rock Passive Flux Meter. Federal Remediation Round Table. Washington, D.C., November 9, 2010.
18. Hatfield, K. Advances in Development of the Fractured Rock Flow and Contaminant Flux Meter. University Consortium for Field-Focused Groundwater Contamination Research, May 20, 2010.
19. Newman, M., V. Stucker, J. Cho, A. Peacock, J. Ranville, S. Cabaniss, I. Perminova, M. Annable, H. Klammler, and K. Hatfield. 2010. A Novel Sensor for the In Situ Measurement of Uranium Fluxes. Proceedings: Department of Energy, Environmental Remediation Sciences Program 4th Annual PI Meeting. Lansdowne, VA. March 29-31, 2010.

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	3	3
Masters	7	0	0	2	9
Ph.D.	7	0	0	6	13
Post-Doc.	0	0	0	3	3
Total	14	0	0	14	28

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 2010.

STEM Education: Recognizing the importance of STEM (Science, Technology, Engineering, and Mathematics) Education initiatives, the Florida Water Resources Research Center is very proud to have supported the research efforts of 13 Ph.D., 9 Masters, and 3 undergraduate students along with 3 post doctoral associates all focusing on water resources issues during Fiscal Year 2010 (March 2009 to February 2010).

UCOWR Dissertation Award (Honorable Mention): Victoria Keener Victoria Keener received Honorable Mention in UCOWR's 2011 Ph.D. National Dissertation Award competition in the category of Natural Science and Engineering, for her dissertation, "Hydro-Climatic Influences of El-Nino/Southern Oscillation on Nutrient Loads in the Southeast United States." Victoria earned her Ph.D. through the Department of Agricultural and Biological Engineering. Victoria's supervisory committee chair was Dr. James Jones. This makes three times in the past 4 years in which a Florida WRRC nominated student dissertation has either won (Heather Byrne, 2009) or received honorable mention (Victoria Keener, 2010 and Leslie Gowdish 2007) for the national dissertation award demonstrating the quality of student research performed at the University of Florida.

104B Student Lead Seed Project Extended: 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. The project was named the best student lead research project at the 2010 UF Water Institute Symposium.