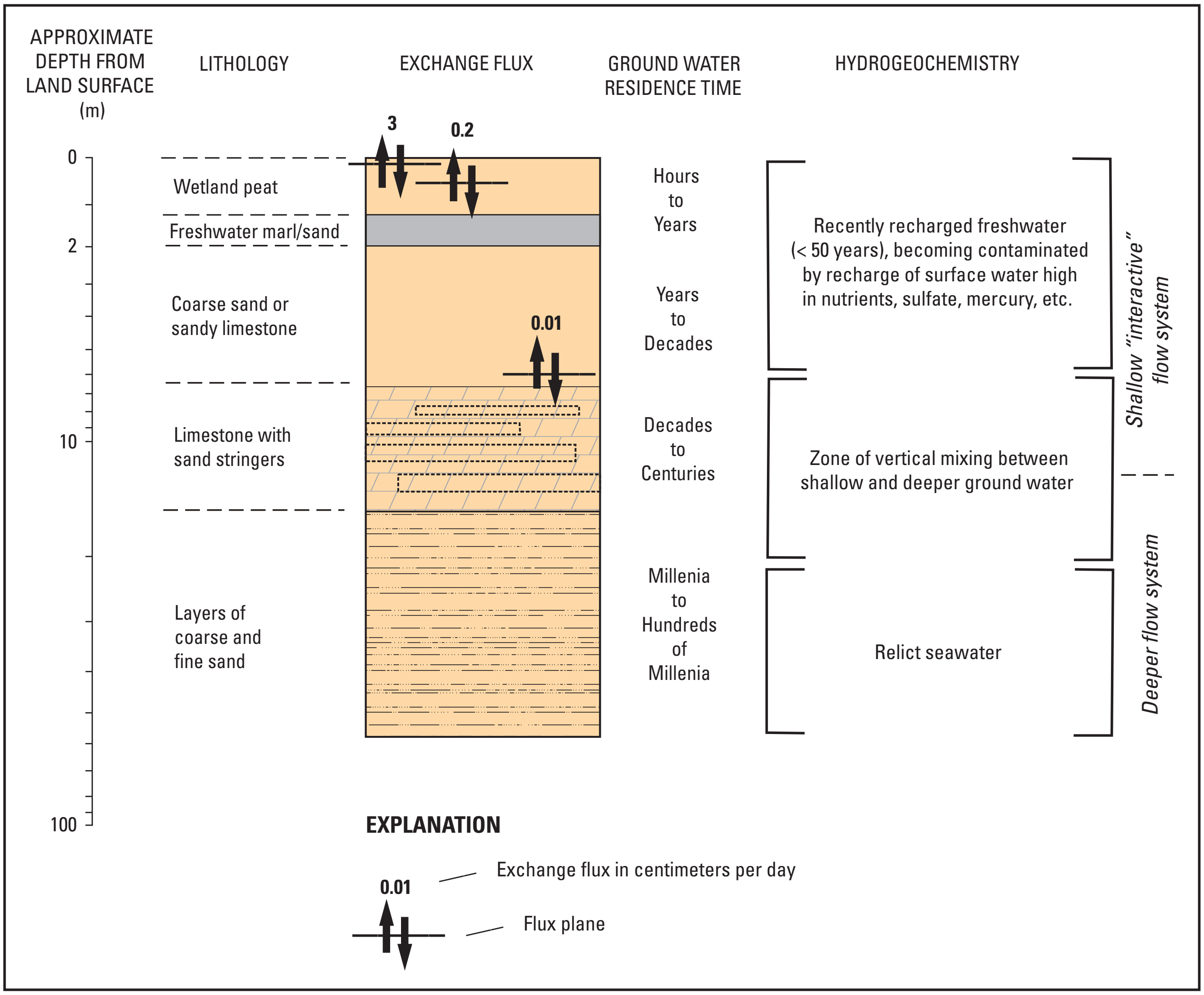
Prepared in cooperation with South Florida Water Management District

Surface-Water and Ground-Water Interactions in the Central Everglades, Florida



Scientific Investigations Report 2004–5069

U.S. Department of the Interior
U.S. Geological Survey

Cover figure showing summary of lithology, water exchange fluxes, residence time of ground water, and hydrogeochemistry in the interior wetlands of Water Conservation Area 2A, central Everglades, south Florida.

Surface-Water and Ground-Water Interactions in the Central Everglades, Florida

By Judson W. Harvey[1], Jessica T. Newlin[1], James M. Krest[1], Jungyill Choi[1], Eric A. Nemeth[1], and Steven L. Krupa[2]

[1] U.S. Geological Survey
[2] South Florida Water Management District, West Palm Beach, Florida

Prepared in cooperation with South Florida Water Management District

Scientific Investigations Report 2004–5069

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2005

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For additional information, contact:
Jud Harvey
U.S. Geological Survey
430 National Center
Reston, VA 20192
jwharvey@usgs.gov

Contents

Figures

Tables

Appendix

Conversion Factors, Vertical Datum, and Abbreviated Units

Multiply	By	To obtain
	Length	
foot (ft)	30.48	centimeter (cm)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.405	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Mass	
pounds (lbs)	0.454	kilograms (kg)
	Flow rate	
foot per day (ft/d)	30.48	centimeter per day (cm/d)
	Hydraulic conductivity	
foot per day (ft/d)	30.48	centimeter per day (cm/d)

Vertical coordinate information is referenced to the North Geodetic Vertical Datum of 1929 (NGVD 29).

Hydraulic Conductivity: The standard unit for hydraulic conductivity is volume per time per unit cross-sectional area of sediment, such as $cm^3/(cm^3 \cdot d)$. In this report, the mathematically reduced form, foot per day (cm/d), is used for convenience.

Abbreviated water-quality units used in this report: Constituent concentrations, water temperature, and other water-quality measures are given in metric units. Constituent concentrations are given in milligrams per liter (mg/L), or nanograms per liter (ng/L). Tritium, ^3H, concentrations are given in tritium units (T.U.), where 1 T.U. is equal to 1 atom of tritium for every 1,018 atoms of hydrogen in water.

Specific conductance (SC) of water is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C). The unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), a unit formerly used by the U.S. Geological Survey.

Additional abbreviations:

inches (in)
millimeter (mm)
micromolar (µM)
milliliter (ml)
grams per year (g/yr)
inches per mile (in/mi)
ohm-meters (ohm-m)
disintegrations or atoms per minute (dpm)

Surface-Water and Ground-Water Interactions in the Central Everglades, Florida

By Judson W. Harvey[1], Jessica T. Newlin[1], James M. Krest[1], Jungyill Choi[1], Eric A. Nemeth[1], and Steven L. Krupa[2]

Abstract

Recharge and discharge are hydrological processes that cause Everglades surface water to be exchanged for subsurface water in the peat soil and the underlying sand and limestone aquifer. These interactions are thought to be important to water budgets, water quality, and ecology in the Everglades. Nonetheless, relatively few studies of surface water and ground water interactions have been conducted in the Everglades, especially in its vast interior areas. This report is a product of a cooperative investigation conducted by the USGS and the South Florida Water Management District (SFWMD) aimed at developing and testing techniques that would provide reliable estimates of recharge and discharge in interior areas of WCA-2A (Water Conservation Area 2A) and several other sites in the central Everglades. The new techniques quantified flow from surface water to the subsurface (recharge) and the opposite (discharge) using (1) Darcy-flux calculations based on measured vertical gradients in hydraulic head and hydraulic conductivity of peat; (2) modeling transport through peat and decay of the naturally occurring isotopes ^{224}Ra and ^{223}Ra (with half-lives of 4 and 11 days, respectively); and (3) modeling transport and decay of naturally occurring and "bomb-pulse" tritium (half-life of 12.4 years) in ground water. Advantages and disadvantages of each method for quantifying recharge and discharge were compared. In addition, spatial and temporal variability of recharge and discharge were evaluated and controlling factors identified. A final goal was to develop appropriately simplified (that is, time averaged) expressions of the results that will be useful in addressing a broad range of hydrological and ecological problems in the Everglades. Results were compared with existing information about water budgets from the South Florida Water Management Model (SFWMM), a principal tool used by the South Florida Water Management District to plan many of the hydrological aspects of the Everglades restoration.

A century of water management for flood control and water storage in the Everglades resulted in the creation of the Water Conservation Areas (WCAs). Construction of the major canals began in the 1910s and the systems of levees that enclose the basins and structures that move water between basins were largely completed by the 1950s. The abandoned wetlands that remained outside of the Water Conservation areas tended to dry out and subside by 10 feet or more, which created abrupt transitions in land-surface elevations and water levels across the levees. The increases in topographic and hydraulic gradients near the margins of the WCAs, along with rapid pumping of water between basins to achieve management objectives, have together altered the patterns of recharge and discharge in the Everglades. The most evident change is the increase in the magnitude of recharge (on the upgradient side) and discharge (on the downgradient side) of levees separating WCA-2A from other basins or areas outside. Recharge and discharge in the vast interior of WCA-2A also likely have increased, but fluxes in the interior wetlands are more subtle and more difficult to quantify compared with areas close to the levees.

Surface-water and ground-water interactions differ in fundamental ways between wetlands near WCA-2A's boundaries and wetlands in the basin's interior. The levees that form the WCA's boundaries have introduced step functions in the topographic and hydraulic gradients that are important as a force to drive water flow across the wetland ground surface. The resulting recharge and discharge fluxes tend to be unidirectional (connecting points of recharge on the upgradient side of the levee with points of discharge on the downgradient side), and fluxes are also relatively steady in magnitude compared with fluxes in the interior. Recharge flow paths are also relatively deep in their extent near levees, with fluxes passing entirely through the 1-m peat layer and interacting with a substantial portion (greater than 30 m) of the ground water in the underlying sand and limestone aquifer. The recharged water flows beneath the levees and is discharged in an adjacent

[1] U.S. Geological Survey, Reston, Virginia

[2] South Florida Water Management District, West Palm Beach, Florida

basin or outside the Everglades, and therefore contributes to the basin-scale water balance in WCA-2A.

Unlike recharge and discharge near levees, fluxes in the interior areas of WCA-2A are highly unsteady in magnitude and frequently undergo reversals in direction. Because of the highly transient nature of these fluxes, the depth of exchange between surface water and ground water in the wetland interior was not as deep (< 8m) as locations in the vicinity of levees. In contrast to levee-driven fluxes, the fluxes in the interior of WCA-2A probably are only important to seasonal (or shorter) timescale variations in the basin-scale water balance. This is because recharge and discharge in the interior of WCA-2A are too shallow and too far from levees to cause a net exchange with areas outside the basin. Although the recharge and discharge fluxes in WCA-2A's interior are smaller on a per unit area basis compared fluxes near levees, they are nevertheless the dominant interaction between surface water and ground water in WCA-2A when considered as a whole. Dominance of surface-water and ground-water interactions in the interior wetlands results from the very large ratio of wetlands in the interior compared with wetlands close to the levees.

A simple hydrogeological model accurately predicted the effect of water-level differences across levees on recharge and discharge, but the model was insufficient to explain why recharge and discharge were also significant in the wetland interior. The pattern of recharge and discharge fluxes was at a maximum near the levee (approximately 2 cm/day), and decreased exponentially with distance until modeled fluxes became insignificant. Agreement between modeled and measured results deviated beyond a distance of 600 m, with the model predicting that recharge and discharge fluxes would decline to insignificance while measurements in the WCA-2A interior (based on head measurements and Darcy-flux calculations) showed that recharge and discharge fluxes remained significant throughout the basin (ranging generally between 0.2 and 1 cm/day, or approximately a factor of two to ten times smaller than the maximum flux near levees). These interior fluxes are the dominant interaction between surface water and ground water in WCA-2A because of the large ratio of interior wetland area compared to wetland area near levees.

Recharge and discharge in the WCA-2A wetland interior reversed in direction on weekly, monthly, and annual timescales according to a 5-year time series (1997-2002) of hydraulic data. Ground-water discharge tended to occur during average to moderately dry conditions when local surface-water levels were decreasing. Recharge tended to occur during moderately wet periods or during very dry periods just as water levels began to increase. The cyclic variation in recharge and discharge is driven by the differential responses of surface water and ground water to annual, seasonal, and weekly trends in precipitation and operation of water-control structures. For example, a meteorological event such as heavy rainfall in one area of the Everglades causes fluctuations in the surface-water level that are transferred to other nearby areas. The surface-water and ground-water systems have different response times to these perturbations. It is these differential response times to perturbations in water level that, along with hydraulic conductivity of peat soil, determine the magnitude and direction of vertical fluxes across the wetland surface. One of the unintended effects of water management involves the growing number and capacities of water pump and spillway operations. These operations have increased the range of surface-water level fluctuations in the interior areas of the water conservation areas relative to the predrainage Everglades. Following major releases of surface water between basins, gravity waves move toward the central parts of the basin that cause relatively high frequency fluctuations in surface-water levels and ground-water hydraulic heads. Since head fluctuations are not instantaneous (and propagate at different rates in the surface water and ground-water systems), there are concomitant fluctuations in vertical hydraulic gradients which cause the magnitude and direction of vertical fluxes to alternate between recharge and discharge as the gravity waves move toward the center of the WCAs.

The highly transient nature of surface-water fluctuations and ground-water responses in the interior parts of the wetland interior causes fluctuations in recharge and discharge on a variety of timescales. Quantifying the time-averaged behavior of recharge and discharge was an important goal of the present study, and environmental solute tracers were potentially well suited to accomplishing that task. Comparison between results gained using short-lived radium isotopes as a tracer in peat pore water, and tritium in ground water, showed that most recharged water in the Everglades only moves through relatively shallow flow paths in the peat before being discharged back to surface water. Only a small proportion of the total amount of recharged water (a few percent) enters the deeper flow paths that pass through the sand and limestone aquifer. The exceptions are wetlands within a half kilometer or so of levees, where the percentage of recharged water flowing through the sand and limestone aquifer is considerably higher (50% or more).

A comparison with Darcy-flux calculations demonstrated the advantage of environmental solute tracers in avoiding the problem of accurately estimating hydraulic conductivity in the sediments. Tracer methods also have challenges, in particular the problem of differing sensitivities of various tracers. Due to the relatively narrow range of sensitivity each tracer has to a particular timescale of recharge and discharge, a single tracer will generally only will be appropriate for characterizing a subset of the total recharge and discharge fluxes. This is the result of the differential detection capability of the various tested tracers across the very broad distribution of residence timescales of recharged water. The flux estimates acquired by tracers in the present study varied over two orders of magnitude (0.01–2 cm/d), with the differences reflecting the portion of total recharge that a particular tracer is sensitive to.

It is important to note that there is no measurement of recharge and discharge (tracer based or hydraulic) that is not affected by issues of scale dependence. For example, the Darcy-flux calculations discussed earlier also produce results that are scale dependent, as illustrated by a comparison between estimates for WCA-2A that were averaged for two different timescales (daily and annually) and estimates that were averaged spatially for two different spatial scales (meters and kilometers). Thus, there is no single measure of recharge and discharge in the wetland interior that can be scaled to all possible problems of interest. Understanding scale dependence is beneficial to a comparison of the results of this study with the results of the South Florida Water Management Model (SFWMM), a hydrological model used extensively by the South Florida Water management District (SFWMD) to design many of the hydrological aspects of the Everglades restoration. Because the SFWMM is spatially discretized on a 2-mile by 2-mile square grid, and because recharge and discharge are often estimated from modeling results by averaging on annual or longer timescales, the SFWMM also is subject to scale dependence in its results. Like tritium modeling, longer runs of the SFWMM generally provide results that reflect longer timescale and deeper subsurface interactions between surface water and ground water. For example, a decadal timescale run of the SFWMM (1979–1990 “calibration” simulation) produced an estimate of recharge and discharge (0.03 cm per day) that was consistent with tritium modeling (0.01 cm per day). Decreasing the length of a model run for the SFWMM appears to increase its sensitivity to shorter term interactions between surface water and ground water. For example, a shorter (5-year) run of the SFWMM (1991–1995 “verification” simulation) produced an estimate of recharge and discharge that was consistent with Darcy-flux calculations in this investigation (0.1 compared with 0.2 cm per day for the Darcy-flux calculations, respectively).

The scale dependence of measurements of recharge and discharge requires that investigators choose a technique that is appropriately matched to spatial and temporal scale of the questions being addressed. For example, studies considering transport of contaminants and chemical reactions in surface water of the Everglades will need to pay particular attention to fast-timescale water exchange with pore water in the peat. On the other hand, studies concerned with questions about long-term recharge in the Everglades and its role in supplying water to well fields will need to pay attention to longer term exchanges between surface water and ground water in the sand and limestone aquifer, both beneath the immediate area of interest and outside the basin. Investigators can be most confident in their estimates of surface-water and ground-water interactions if a combination of hydraulic methods and more than one tracer with differing sensitivities to long and short timescale processes are used. Using what has been learned about the differing sensitivities of each method, the results can be combined to characterize the full distribution of timescales involved in exchange between surface water and ground water in the Everglades.

Introduction

The Everglades is a subtropical coastal wetland that extends 160 km from Lake Okeechobee to Florida Bay in southeastern Florida (fig.1). Before water management began in the Everglades, large quantities of fresh surface water moved southward by overland sheet flow through the broad wetland system, ultimately discharging to the Atlantic Ocean, Florida Bay, or the Gulf of Mexico, depending on the particular flow path through the wetlands. Beneath the wetlands is ground water flowing in limestone and sand sediments of the Biscayne and Gray Limestone aquifers, known collectively as the surficial aquifer system (fig. 1b).

Beginning about 1910, construction of canals began in the Everglades initially for the purpose of drainage and flood control. The early canals extended southeast from Lake Okeechobee to the Atlantic Ocean (Light and Dineen, 1994). With the passage of time came growing concerns that the Everglades needed to be managed for water supply in addition to being managed for flood control. Beginning in the 1950s, additional systems of canals and levees narrowed the main flow-way and completely encircled parts of the Everglades, creating a series of enclosed basins called Water Conservation Areas (WCAs). The purpose of the WCAs went beyond just flood control, and included water storage for later delivery to the growing population of the lower east coast of Florida as well as to Everglades National Park. The construction and management of the WCAs (and the associated drainage and subsidence of areas outside) have altered the Everglades ecosystem in profound ways. Decreasing surface-water flows and deteriorating water quality are blamed for declines in wading bird populations, disappearance of tree islands, and replacement of native plant communities by cattails (Jensen and others, 1995; McCormick and others, 1998; Rutchey and Vilchek, 1999). In the past 20 years, these concerns have fueled wide-ranging discussions on how to improve water management in the Everglades. In 2000, Congress approved the Comprehensive Everglades Restoration Plan (CERP), with the goal to restore (to the extent possible) predrainage conditions in the central Everglades.

Evaluating the success of restoration efforts depends on reliable hydrologic information, including quantification of interactions between surface water and ground water. Surface water and ground water in the Everglades are exchanged across the wetland ground surface by processes known as recharge (flow from surface water to ground water) and discharge (flow from ground water to surface water). Recharge and discharge are generally assumed to have been relatively small under the predrainage conditions in Everglades, as a result of the small natural topographic gradients and the wide expanse of wetland available for dissipation of floodwater. The principal topographic features in the central part of the predrainage Everglades are related to the ridge and slough topography, which gave the Everglades a corrugated appearance by alternating between sawgrass ridges and sloughs on

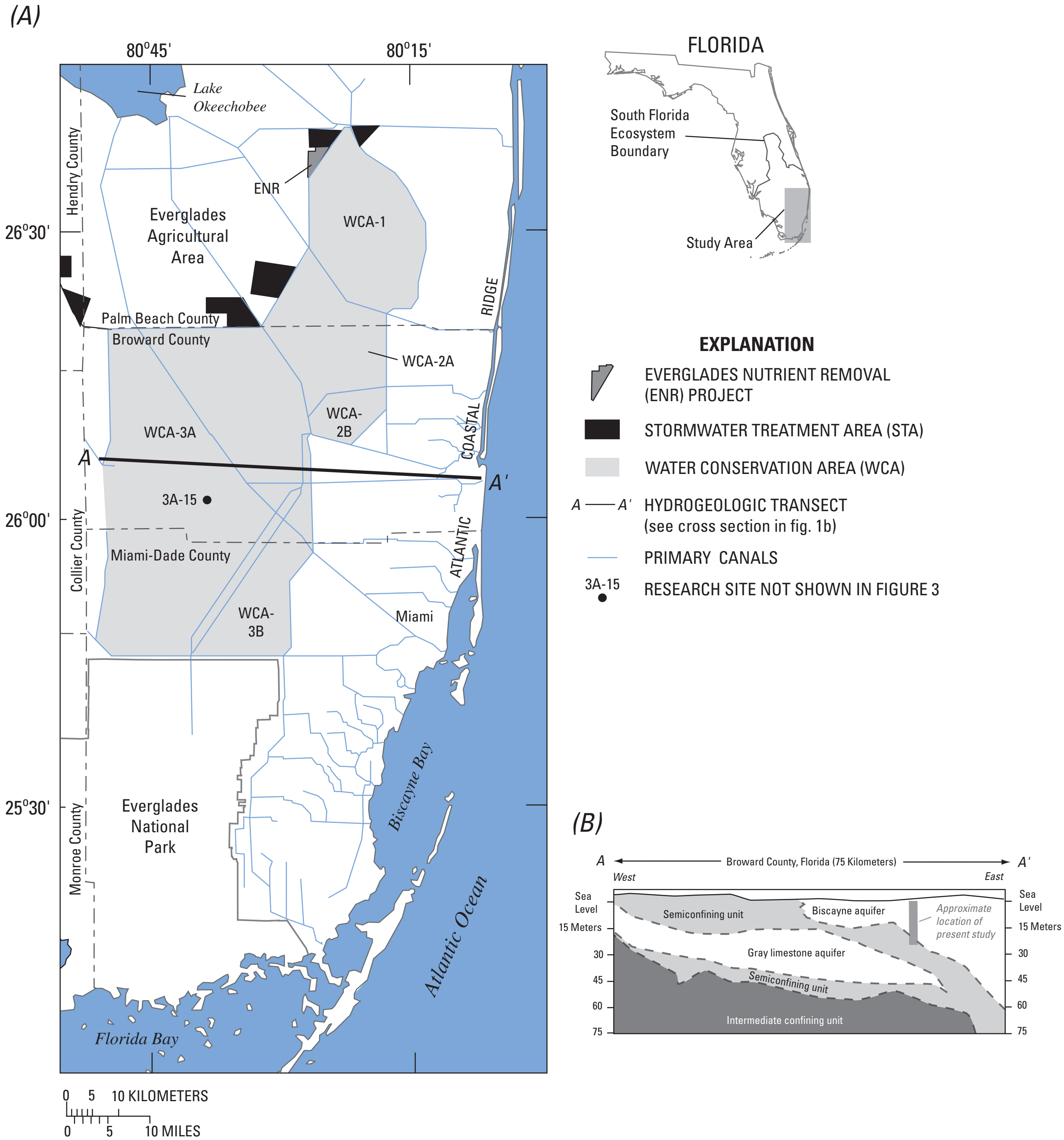


Figure 1. Central Everglades and adjoining areas, south Florida, showing in *(A)* locations of Water Conservation Areas (WCA), Everglades Nutrient Removal (ENR) project, and Stormwater Treatment Areas (STA) and showing in *(B)* generalized hydrogeologic features across Broward County, in the central Everglades, South Florida.

spatial scales of hundreds of meters. Only recently has there been speculation about how the topography of ridges and sloughs, and tree islands, may have evolved, and presently be maintained, due to the complex feedbacks between hydrologic driving forces, sediment transport and accumulation, carbon and nutrient dynamics, and plant performance (National Research Council, 2003, Science Coordination Team, 2003). The earliest observations that interactions between surface water and ground water could be important to Everglades hydrology began in the 1950s with concerns raised about large amounts of “seepage” (or ground-water underflow) that began to occur beneath the eastern boundary levee that separated the remaining wetlands of the Everglades from the growing urban population to the east (U.S. Army Corps of Engineers, 1952). Although still a major concern for water managers, seepage is not the only issue requiring a better understanding of surface-water and ground-water interactions. For example, the deeper ground water beneath the Everglades is high in dissolved salts due to its origin as entrapped sea water during higher sea level stands in an earlier geologic time period. Increased recharge and discharge is bringing more dissolved salts into surface water, and the increasing load of salts is contributing to an upset of subtle biological and geochemical dependencies that influence plant community structure in this unique ecosystem (McCormick and others, 1998). Furthermore, changes in surface-water and ground-water interactions may be involved in storing phosphorus and other surface-water contaminants that are currently entering the Everglades. A thorough understanding of surface-water and ground-water interactions is essential to understanding how long this legacy of contamination could last, and how far it could be transported downstream in the Everglades under “restored” flows. Concerns are not just for the ecosystem. For example, municipal water budgets indicate that an important source of drinking water comes from recharge of central Everglades water in into the Biscayne aquifer (particularly in WCA-3A) and eastward movement toward domestic well fields. There is relatively little understanding, however, of the source areas, flow paths, and travel times required for Everglades surface water to reach domestic water-supply well fields. There is also little understanding of the role of ground-water discharge in sustaining sensitive wetland ecosystems during drought.

From the standpoint of water quality, surface-water and ground-water interactions could be important in affecting much more than just transport and storage of phosphorus. More information is needed about how pore water in Everglades peat and shallow ground water functions as a reservoir not only for phosphorus, but for a host of surface-water contaminants including sulfate from agricultural drainage, atmospheric-derived mercury, dissolved organic carbon, dissolved salts from discharge of deep ground water of marine origin with relatively high sulfate and chloride concentrations, and volatile organic carbons of uncertain origin (Krabbenhoft and others, 1998; Bates and others, 2002; Harvey and others, 2002). Increasingly contaminated Everglades surface waters are cycled back and forth between wetland surface water and the shallow ground-water system by the processes of recharge and discharge. Over time, that exchange of water between the surface and subsurface is having the effect of replacing what was previously a layer of very high-quality, fresh ground water near the top of the aquifer with contaminated surface water (Harvey and others, 2002). Both the physical mechanism of contaminant storage in the aquifer and the chemical reactions that occur there may affect contaminant mobility. Contaminants stored in ground water potentially can return to surface water with discharging ground water long after restoration management improvements have been implemented. As stated above, little is known about how the current distribution of contaminants in Everglades waters and soils will spread under higher “restored” flows. The potential for these legacies of contamination to affect future water quality in the Everglades is significant, and predicting those effects requires a better understanding of how to quantify surface- and ground-water interactions, and how to determine the processes controlling the magnitude of those interactions.

A previous USGS Open-File report (Harvey and others, 2000) describes many the methods and materials used in the overall investigation in great detail, including all of the specifics regarding borehole drilling methods, geophysical measurements, sampling of ground-water geochemistry, and design and operation of shallow piezometers and seepage meters. That report provided appendixes that include all of the data collected prior to September 1998. Another recent report by Harvey and others (2002) documented hydrogeologic and ground-water geochemical patterns in the central Everglades and used that information to explain the occurrence and fate of mercury in Everglades ground water.

In an effort to improve understanding of interactions between ground water and surface water in the Everglades and its consequences for water quality, the U.S. Geological Survey (USGS), began a second cooperative research investigation in 1999 with the South Florida Water Management District (SFWMD). Together, those organizations conducted a detailed investigation of hydrologic interactions between surface water and ground water in Water Conservation Area 2A (WCA-2A), a 42,492-ha basin in the central Everglades. Fieldwork for the investigation was completed in 2002.

Purpose and Scope

This report presents the results of an investigation to develop reliable methods of quantifying surface- and ground-water interactions in the central Everglades, south Florida. The focus of the investigation is Water Conservation Area 2A (WCA-2A), with additional information presented from the Everglades Nutrients Removal (ENR) Project, and from single sites in WCA-2B and WCA-3A (fig. 1). In this investigation, three new methods were used to quantify recharge and discharge in the interior wetland areas of the central Everglades. These methods were (a) the Darcy-flux calculation approach, based on measured vertical gradients in hydraulic head and hydraulic conductivity of peat, to calculate vertical fluxes between ground water and surface water; (b) modeling the vertical transport and decay of the naturally occurring short-lived radium isotopes ^{224}Ra and ^{223}Ra through peat; and (c) modeling the transport and decay of naturally occurring and "bomb-pulse" tritium (^{3}H) in surface water and ground water. The report includes discussion of the physical factors that affect recharge and discharge in the central Everglades, including effects of geologic materials and their hydrogeologic properties; seasonal and interannual climate fluctuations; and effects of water management, including ponding of water at different elevations across levees, as well as the release of large pulses of surface water between WCAs through water-control structures.

One purpose the report is to compare results acquired by testing different methods of quantifying recharge and discharge side by side in WCA-2A wetlands. Several of the new methods are based on modeling the distribution of naturally occurring solute tracers (radium, tritium, and tritium-helium ratios) that are transported with water in the central Everglades. Cross-comparisons between those estimates and other independently acquired estimates based on hydraulic measurements provide insight about advantages and limitations of each method, and about the effect of differences in the spatial and temporal averaging of each method on overall results. To help place the new recharge and discharge estimates in the perspective of previous understanding in the Everglades, the new estimates were also compared with recharge and discharge estimates from the South Florida Water Management Model (South Florida Water Management District, 1999).

In addition to the above-stated research purposes, the present report also functions as an outlet for data sets not previously published in the prior reports. Appendix 1 provides detailed locations of research sites and additional information about wells and piezometers. Appendix 2 expands previously published data sets on hydraulic conductivity in peat and in sediments that are transitional to the underlying aquifer. Appendix 3 reports hydraulic-head calibration data collected at surface-water recorders and wells. Appendixes 4–17 illustrate the measured water levels in surface water and wells for a period of record that is typically 1998–2002. Appendixes 18–21 report all of the geochemical data collected in WCA-2A after 1998.

In the next several sections background information is given about hydrologic setting, hydrogeology, and a summary of previous investigations of interactions between surface water and ground water in the Everglades.

Pre- and Post Drainage Hydrologic Setting

Although some of the northern parts of the WCA wetlands occasionally dry out, they are normally inundated by surface water to depths ranging between 5 cm to 1.2 m. Beneath the surface water is a ground surface composed of an organic peat soil that is approximately 1 m thick in WCA-2A. Peat in the central Everglades was formed from the incomplete decomposition of sawgrass, water lilies, and other emergent plants. The peat is fibrous with a low mineral or ash content, usually less than 10 percent (Gleason and Stone, 1994). The peat is underlain by a relatively thin (< 1 m) and often discontinuous layer of layer of transitional freshwater marl and sand. Beneath those layers is the 60-m thick surficial aquifer composed of layers of sand and limestone.

Hydrogeology

The surficial aquifer in southeastern Florida underlies Miami-Dade County, Broward County, and eastern Palm Beach County (fig. 1b) beneath the Atlantic coastal ridge system and extends farther west beneath the Everglades. It is composed mainly of shallow-water marine facies, including coral limestones, beach and offshore sandbar complexes, lagoonal limestones, and an oolitic ridge along the coast of Miami (Perkins, 1977). The aquifer thins to approximately 60 m thick beneath the study area in WCA-2A (fig. 1b). To the east the surficial aquifer encompasses the highly transmissive Biscayne aquifer, which is a principal source of fresh drinking water in south Florida. Beneath the surficial aquifer is an aquitard generally referred to as the Intermediate Confining unit that restricts hydrologic communication with the deeper Floridan aquifer (fig. 1b). Stratigraphy and hydrogeology of the surficial aquifer beneath the Everglades is only briefly summarized here. Since geological interpretation was not a major component of the present study, readers are referred to more complete discussion in the cited references.

A subset of the surficial aquifer, the Biscayne aquifer, is thickest to the east of the Everglades and thins toward the west, disappearing completely beneath the central Everglades. Because of the presence of the Biscayne aquifer, the hydraulic conductivity is relatively high in the eastern part of the surficial aquifer and it declines to the west beneath the Everglades. Investigations in the surficial aquifer that underlies the Everglades have assessed its potential as a source of fresh drinking water. Hydrogeological investigations by Howie (1987), Fish (1988), and Reese and Cunningham (2000) found that this more western part of the surficial aquifer system generally has lower transmissivities and higher total dissolved solids (Howie, 1987; Fish, 1988; Reese and Cunningham, 2000) than the Biscayne aquifer to the east. The marked decrease in hydraulic conductivity from east to west in Palm Beach County is caused by the change from high porosity limestones and coarse sands in the east to limestone with more variable degrees of cementation and finer sands in the western part of the Everglades. Harvey and others (2002) found that although the hydraulic conductivity of the surficial aquifer throughout most of its depth was relatively low beneath WCA-2A, the hydraulic conductivity in the top 10 meters beneath WCA-2A was not substantially less compared with areas to the east of the Everglades.

Miller (1988) illustrated some of the effects of water management on ground-water levels in the central Everglades.

The geology and hydraulic properties of the surficial aquifer beneath the northern WCAs were recently characterized in greater detail than previously available (Harvey and others, 2002; summarized in table 1). Detailed hydraulic conductivity data are presented in this report for wetland peat and underlying transitional layers in the top 2 m beneath the ground surface of WCA-2A. Other than the studies cited above, little detailed information is available about the hydrogeology of the central Everglades in western Palm Beach and Broward Counties.

Historical Changes in Surface-Water and Ground-Water Flow Patterns

A thorough investigation of the present-day hydrology of the central Everglades requires an understanding of the predrainage hydrologic system. The predrainage Everglades received water primarily from direct rainfall, periodic overflow from Lake Okeechobee, and runoff from surrounding pine flatwoods and other upland systems (Gleason and Stone, 1994). In addition, the slough systems of the Everglades probably received ground-water discharge from the surficial aquifer and runoff derived from the adjacent low-lying pinelands.

The driving force for water flow in the Everglades is the gravitational effect on a sloping water-surface, which is controlled by the regional topographic gradient. In the predrainage Everglades, the north to south topographic gradient was a relatively consistent 3.2 centimeters per kilometer (cm/km), with only minor undulations of the natural landscape affecting water flow. The slight topographic gradient suggests that recharge and discharge were low or moderate in the predrainage system. Sources of water and flow directions were controlled in part by topographic variation across the approximately 80-km width of the predrainage Everglades. A major slough system on the northwestern side of the Everglades graded into a broad sawgrass plain in the north-central area and back into another major slough system on the northeast side. Finer-scale topographic variation consisted of alternating ridge and slough systems with typical spacing of approximately 300 m (Science Coordination Team, 2003; Christopher W. McVoy, South Florida Water Management District, written commun., 2003).

Changes in topography caused by subsidence or construction of levees, and changes in water levels caused by canal drainage, have been some of the most important factors that have perturbed the direction of water flow in the Everglades. Beginning about 1912, canal construction and drainage began to modify water levels and topography substantially in the northern and north-central parts of the Everglades. Initially, four major north-south canals were constructed to drain water to the Atlantic Ocean. Early canal drainage in the Everglades Agricultural area (EAA) led to excessive oxidation of the peat in the vast sawgrass plain and swamp forest south of Lake Okeechobee. Over the past century, drainage and oxidation have caused between 0.9 and 3 m of subsidence in the agricultural area. Subsidence and continual pumping in the EAA to keep agricultural fields dry have reversed the horizontal direction of ground-water flow in some areas of the Everglades. For example, in areas of western WCA-1, ground water once flowed toward the southeast but now flows northwest toward areas of subsidence in the agricultural area (Miller, 1988; Harvey and others, 2002).

As a result of the conversion of wetlands to agricultural areas, the northern part of the Everglades is approximately one-third its predrainage width (Science Coordination Team 2003; illustrated schematically in fig. 2). By the 1950s, it was apparent that the canals were too effective in draining the remaining wetlands. It became increasingly apparent that those wetlands were critical for sustaining water supply to the newly formed Everglades National Park, and to the growing population along the Florida Atlantic Coast. In an attempt to counteract the deleterious effects of drainage, more levees were constructed during the 1950s and early 1960s as a means

Table 1. Summary of hydrogeologic properties of the Surficial aquifer, central Everglades, south Florida. Modified from Harvey and others, 2002.

[m, meters; *K*, hydraulic conductivity; cm/d, centimeters per day; >, greater than]

Average thickness (m)	Primary lithology	Common formation/group name	Geologic time scale	Hydraulic conductivity, *K* (cm/d)
1	Peat	Undifferentiated deposits	Holocene	60
1	Freshwater Marl/Sand	Undifferentiated deposits	Holocene	50
4.5	Sand	Fort Thompson	Pleistocene	2,500
4	Limestone with sand stringers	Fort Thompson	Pleistocene	9,000
7.5	Sand	Fort Thompson	Pleistocene	5,000
9	Sand with fine sand layers	Tamiami	Pliocene	4,000

of completely enclosing the large basins that are now known as the WCAs.

Compartmentalization of the Everglades into enclosed basins narrowed the surface water flow-way even further Subsidence, canal drainage, and ground-water withdrawals on former wetlands to either side of the Everglades contributed to an increased driving force for recharge near levees (Miller, 1988; see schematic representation in fig. 2b). Along a north-south axis, the retention of surface water in the enclosed basins created a “stair-step” of water levels, causing recharge on the upgradient side and discharge on the down gradient side of levees (fig. 2c). This situation contrasts with conditions before water management, when it was common for surface flow in the central Everglades to be augmented by seasonal runoff from the surrounding uplands, lake drainage, and local rainfall. Currently, with water levels generally lower outside of the Everglades, flow of ground water beneath the levees to areas outside of the Everglades is now a critical component of Everglades water budgets.

Drainage canals continue to be a primary component of water management in the north-central Everglades. During excessively wet conditions, the major drainage canals carry excess water from Lake Okeechobee or the EAA to the Atlantic Ocean. Under more typical wet-season conditions, runoff from the EAA into drainage canals and the operation of pump stations and opening of spillways into WCAs cause the release of large “pulses” of surface water that move southward. East of the Everglades, the canals have various functions, including drainage of the low-lying pinelands and aquifer recharge to balance losses by ground-water pumping.

The controls on recharge near levees include the difference in water levels across the levees, presence and management of water levels in the canals that are present on either or both sides of the levee, and the hydraulic properties of Everglades peat, underlying aquifer materials, and natural sealing layers of organic materials that have settled to the bottom of canals. The large amount of seepage along the northwestern border of the Everglades has been exacerbated by 80 years of subsidence and drainage that lowered water levels by as much

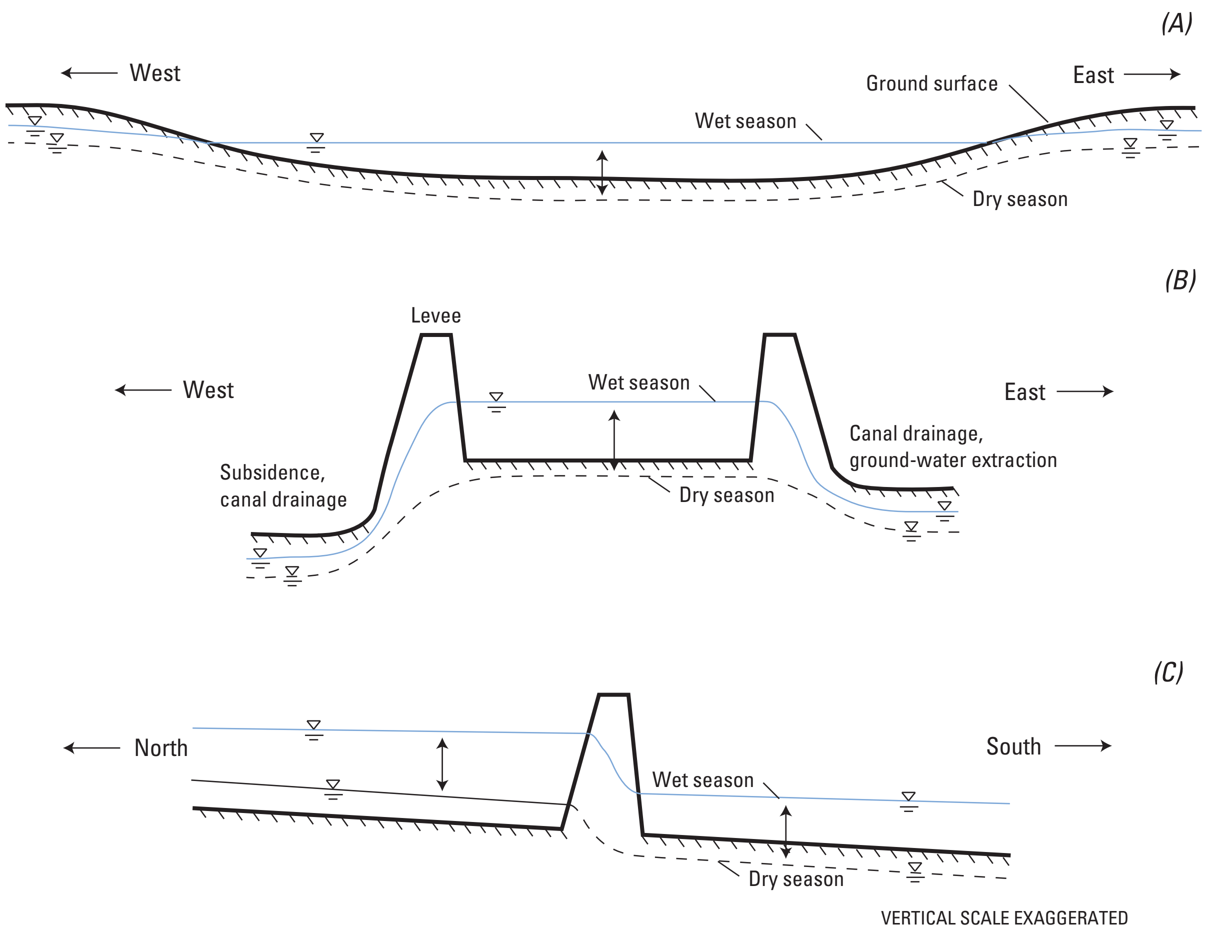


Figure 2. Schematic diagrams of topography, surface-water levels, and ground-water levels in predrainage *(A)* and present-day *(B and C)* hydrologic systems, central Everglades, south Florida.

as 3m in some areas of the neighboring EAA. There are also critical areas of concern for seepage along much of the eastern boundary levees of the Everglades. In those areas the complicating factor is that there is a desirable level of seepage along those levees to replace ground water pumped from the well fields for potable water to supply the needs of the growing communities of the lower east coast of Florida.

The effects of seepage beneath levees were detected early in the process of levee construction in the central Everglades (U.S. Army Corps of Engineers, 1952). Initially, levee seepage was of concern mainly to land users in the immediate vicinity of the WCAs that experienced drainage problems. Over the past 50 years, the effects of levee seepage on Everglades ecology, especially water budgets, have been widely investigated (Klein and Sherwood, 1961; Swayze, 1988; Harvey, 1996; Genereux and Guardiario, 1998; Choi and Harvey, 2000; Nemeth and Solo-Gabriele, 2001; Sonenshein, 2001). Seepage that occurs beneath the levees that separate WCAs and within the interior of the WCAs also has been studied (Harvey and others, 2002). Seepage losses are considered one of the most important unintended side effects of water management in the central Everglades.

Investigations of Surface-Water and Ground-Water Interactions

Although a connection between ground water and surface water is generally recognized in the Everglades, there is uncertainty about the locations of recharge and discharge sites, the volumes of water exchanged, and the principal driving forces. Past investigations of recharge and discharge were conducted primarily on wetland areas near levees and canals (Klein and Sherwood, 1961; Miller, 1978; Swayze, 1988; Chin, 1990; Genereux and Slater, 1999; Genereux and Guardiario, 1998; Rohrer, 1999; Nemeth and Solo-Gabriele, 2001; Bolster and others, 2001; Sonenshein, 2001). In part due to logistical constraints, there have been few investigations of surface- and ground-water interactions in the vast interior areas of the Everglades.

Estimates of recharge and discharge in the Everglades that represent average conditions throughout entire WCA basins have previously been calculated by means of mass-balance techniques (South Florida Water Management District, 1999; Choi and Harvey, 2000). A related approach is the coupled modeling of surface-water and ground-water flow that was accomplished with the South Florida Water Management Model (SFWMM) (South Florida Water Management District, 1999). Previous estimates were computed as ”net” estimates averaged over very large areas (50,000-ha or larger) and long time periods (annual or longer) as part of regional surface-water budgets (Fennema and others, 1994). Disadvantages of the regional water budget approach include (1) the difficulty of distinguishing between vertical fluxes that occur near levees compared to the interior areas of the basins; and (2) the effect of averaging over time recharge and discharge fluxes that nearly balance in the long term, which can significantly misrepresent the effects that short-term imbalances that favor recharge or discharge can have in transporting dissolved chemicals between surface water and ground water. Greater spatial and temporal resolution in sampling, and incorporating a chemical component to mass balances can help in overcoming these problems. Recharge and discharge were estimated in a smaller Everglades basin (the Everglades Nutrient Removal Project area) using mass-balance calculations based on surface-water and chloride budgets (Choi and Harvey, 2000), but that work required an exceptionally dense network of instrumentation and frequent hydrologic and chemical measurements. One barrier to progress has been the lack of instrumentation in the central areas of the larger basins of the Everglades (fig. 1). Because the relative area is so large in the interior of these basins, even relatively small recharge or discharge fluxes in the wetland interior could have large effects on overall water or chemical budgets. As a result, there is an increasing need for information about recharge and discharge in the interior wetlands of the central Everglades.

Vertical mixing between surface water and ground water in the central Everglades appears to be limited to shallow depths in the aquifer, generally less than 10 m. The primary evidence for shallow interactions is segregation of water types: fresh ground water is restricted to primarily the top 10 m of the aquifer, a brackish mixing zone exists between 10 and 30 m, and the lower 30–40 m of the surficial aquifer contains relict seawater that entered the aquifer during a time of higher sea level stand (Harvey and others, 2002). For example, canals at the margins of the Everglades show clear signs of vigorous vertical mixing, as evidenced by higher concentrations of chloride in canal waters compared with surface waters in the interior wetlands (Harvey and others, 2002). Chemical signals of vertical mixing are more subtle in the interior wetland areas of the central Everglades, which is suggestive of lower recharge and discharge rates in those areas compared with sites near canals and levees. Interactions between surface water and ground water can therefore potentially be quantified from the chemical signals of vertical mixing.

Description of the Research Sites and Their Instrumentation

In addition to research conducted in WCA-2A, some research was conducted in the Everglades Nutrient Removal Project (ENR) area, and in WCAs 1, 3A, and 2B. Land-use, previous research, and other background information about research sites is given in the present section.

Everglades Nutrient Removal Project

The Everglades Nutrient Removal Project (ENR) area is a 1,545-ha wetland that was formerly part of the Everglades (fig. 3). The ENR was drained and farmed beginning in the mid-1900s and was converted back to a wetland in 1994 to be a prototype to test the capacity of larger constructed wetlands, called Stormwater Treatment Areas (STAs), to remove nutrients from agricultural drainage waters (fig. 3). ENR was expanded during 1999 and 2000 into a working STA, referred to as STA-1W (2,700 ha). Only data collected in ENR prior to its expansion into STA-1W are discussed in this report. The source of surface water to ENR is pumpage from agricultural land to the west and surface water from Lake Okeechobee.

ENR's location affects surface- and ground-water interactions in the Everglades. To the east of ENR is WCA-1, where water surfaces are maintained at relatively high elevations compared with the rest of the Everglades. West of the ENR is the EAA, where subsidence and canal drainage have substantially decreased the ground elevation and water table relative to WCA-1 and ENR. The ENR water budget is affected by its proximity to the agricultural area, with recharge in ENR accounting for 30 percent of the pumped inflow (Choi and Harvey, 2000).

Water Conservation Area 2A

Located 10 km to the south of ENR, WCA-2A is 25 times larger in area (42,525 ha) (fig. 3). Studying WCA-2A is a logical complement to investigations in ENR, because of the much larger area and much longer history of nutrient pollution (Urban and others, 1993; Jensen and others, 1995). The present investigations were conducted primarily at hydrological research sites in the northeastern and central part of WCA-2A (fig. 3). WCA-2A shares boundaries with WCA-1 and the EAA to the north, lands developed for light industry and residential areas to the east, and WCA-3A to the southwest. In the 1950s, construction began on a new system of levees and canals to connect the canal and levee systems that bordered WCA-2A to the north and south (Light and Dineen, 1994). By about 1963, WCA-2A was completely surrounded by levees and canals (fig. 3).

Researchers started investigating the ecology of WCA-2A beginning about 1975, documenting, for example, the loss of tree islands and a transition from a sawgrass-dominated wetland to one affected by extensive cattail growth in some areas (Jensen and others, 1995). Possible causes for those ecological changes are excess nutrients from agricultural runoff, and excessive periods of drying and wetting due to water-management practices.

The water-surface slope in the northeastern and central parts of WCA-2A is similar to or slightly greater than the average land-surface slope in the central Everglades (Harvey and others, 2002), with precise water-slope directions ranging between southwest and south-southeast depending on water releases from nearby hydraulic structures (Romanowicz and Richardson, 2000). The land slope in WCA-2A (3×10^{-5} south-southeast) is similar to predrainage conditions and flows are typically toward the south. On transect B-B' (fig. 3), there is a transition from north to south in major vegetative communities that has been extensively studied in the past 20 years (Jensen and others, 1995; McCormick and others, 1998; Rutchey and Vilchek, 1999). The northernmost part of the transect is dominated by cattail vegetation, the middle part of the transect has large patches of mixed cattail and sawgrass vegetation as well as smaller distinct patches of cattail, sawgrass, and wet prairie vegetation, and the south part of the transect (in central WCA-2A) is dominated by sawgrass and wet prairie vegetation. Vegetation sampling along the transect in September 1999 (Rybicki and others, 2002) provided detailed information on species composition, vegetation characteristics, and biomass.

Interactions between surface water and ground water in WCA-2A have been affected by levee construction, subsidence, and ground-water pumping at the margins and outside of WCA-2A (Harvey and others, 2002). The effects of managing surface-water levels within WCA-2A may also be important. Several times each year, surface water is released from WCA-1 through the S10 control structures, which quickly move large quantities of water into WCA-2A. These sudden releases generate a gravity wave that is occasionally as high as 1.2 m that propagates southward through WCA-2A. Most of the WCA-2A wetland maintains at least a partial coverage of surface water at most times of the year in WCA-2A. Annual fluctuations in surface-water levels typically range up to 0.9 m. The operation of control spillways that release water from WCA-1 into WCA-2A affect water levels and the direction of water flow. A man-made levee on the WCA-2A side of the "tailwater" canal has an important effect on water flow directions during relatively dry condition, tending to cause water flow toward the northeastern corner of WCA-2A before the flow spreads out into the wetland. Hydrologic simulations using the SFWMM and Natural System Model (NSM) suggest that the average annual range of surface-water fluctuations in the WCA-2A may have increased by as much as 50 percent or more since predrainage times, from approximately 0.6 m to 0.9 m (Tarboton and others, 1999; South Florida Water Management District, 2003).

Measurement Locations

The locations of all measurements discussed in this report are shown in figures 3 and 1. Site locations are provided in geographic coordinates in Appendix 1. Sites in WCA-2A are roughly oriented with a research transect established for ecological studies in the 1980s and instrumented for hydrological studies in the 1990s (Harvey and others, 2002). The transect is often referred to as the "nutrient-threshold" transect because the value of measurements made along the transect to establishment of a phosphorus criteria for drainage waters entering the Everglades. The nutrient-threshold research sites are roughly aligned on a transect that extends from the northeastern edge of WCA-2A (where extensive ecological changes have occurred due to inputs of water with high phosphorus concentrations), into the central part of WCA-2A where ecological changes are less pronounced (transect B – B' in figure 3). Measurement locations in WCA-2A include seven sites in the interior part of the wetland at locations far from

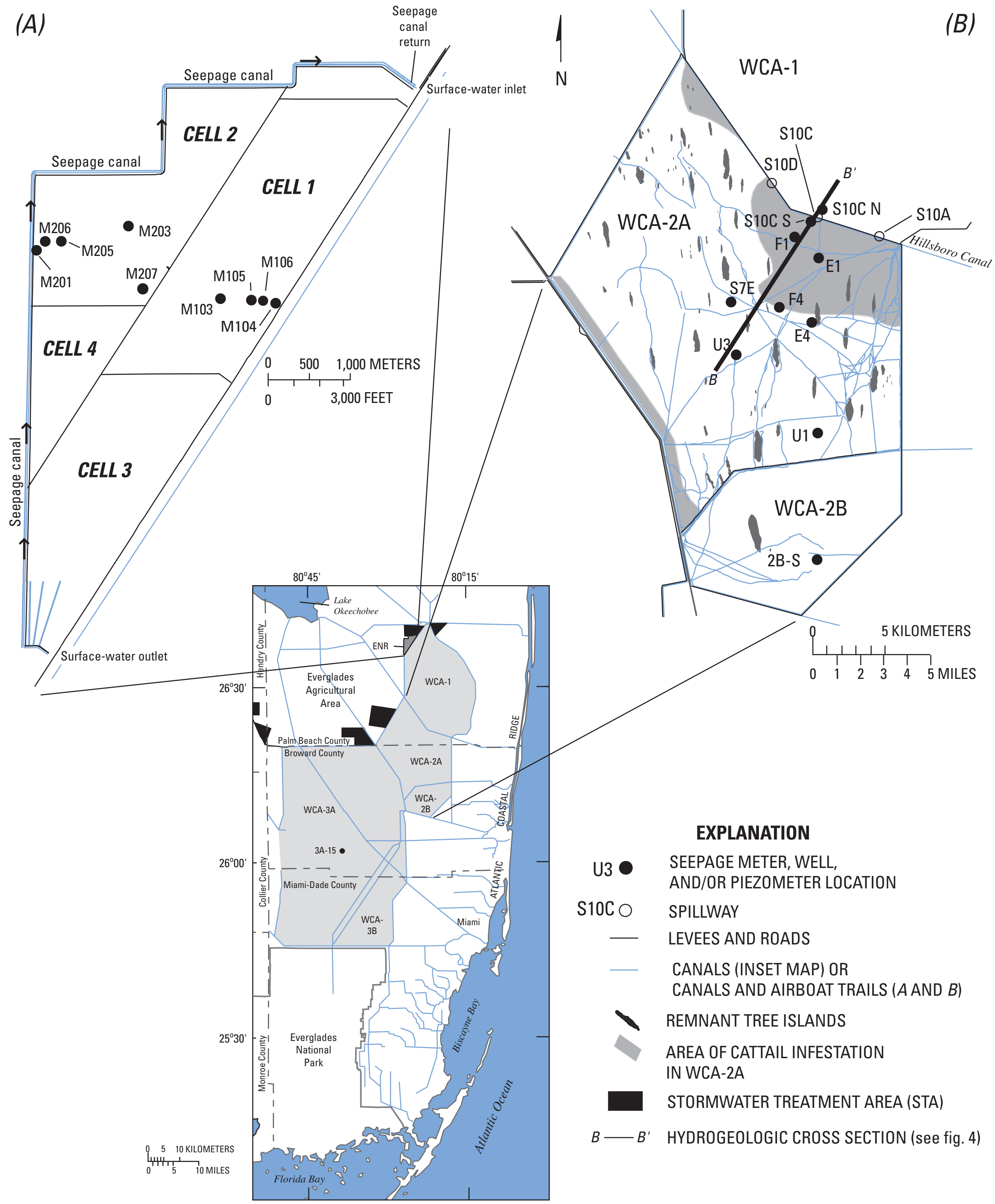


Figure 3. Research sites, instrumentation, and natural and man-made features in Everglades Nutrient Removal (ENR) project *(A)* and Water Conservation Area 2A (WCA-2A) *(B)*, central Everglades, south Florida.

levees (F1, F4, E1, E4, U3, U1, and S7E). Research platforms and surface-water stage recorders had previously been setup at most of these sites (except S7E), as well as other sites, as a part of the South Florida Water Management District's investigation of water quality in the central Everglades during the 1980s and 1990s. A seventh interior site (S7E) was selected to supplement the nutrient-threshold sites, to increase coverage of ground-water sites at interior locations in WCA-2A. In addition to selecting six of the original six sampling sites in the interior and adding a seventh, an eighth site was selected on the Hillsboro Levee. This new site, referred to as S10C, is located at what is essentially the upstream end and source of much of the surface water flowing along the nutrient-threshold transect. Located on the Hillsboro levee that separates northern WCA-2A from southern WCA-1, the S10C site is very close to the S10C water control structure, which permits surface flow from WCA-1 into WCA-2A. Surface-water stage recorders were previously installed near the S10C structure, and had previously measured surface-water stage on both the "headwater" (WCA-1) and "tailwater" (WCA-2A) side of the Hillsboro levee.

In addition to sites in ENR and WCA-2A, additional hydrological and chemical measurements were made in three adjoining WCAs, specifically at site S10C N in WCA-1, site 3A-15 in WCA-3, and site 2B-S in WCA-2B (figs. 1 and 3).

Instrumentation

A brief overview of research site instrumentation is presented here, including types of instrumentation, emplacement, and other information about materials and methods. More complete information is available in Harvey and others (2000), including information on methods of drilling, core recovery, core logging, well construction and completion; well development; and materials and methods for constructing, installing, and operating other instrumentation such as seepage meters and piezometers. Additional information information about research sites and instrumentation is found in Harvey and others (2002). Note that research-site information is only discussed for sites in WCA-2A. For information about other research sites in the central Everglades (that is, ENR Project, WCA-2B, and WCA-3A), all of the necessary background and details about instrumentation has previously been published in the references cited above.

The USGS and SFWMD began a cooperative effort in late 1996 to emplace monitoring wells in the sand and limestone of the surficial aquifer, and piezometers in the wetland peat at sites in ENR and WCA-2A (fig. 3). Wells and piezometers were used to measure vertical gradients in hydraulic head, from which the direction and flow rate of recharging or discharging water could be determined. Estimates of the hydraulic conductivity of the peat and aquifer sediments, a necessary component of Darcy-based flux estimates, were made within these same instruments. The wells and piezometers were used to determine chemical composition of water at various levels in the aquifer and peat by removing small-volume water samples that were returned to the laboratory for chemical analysis. Seepage meters were emplaced on the surface of the wetland peat and operated for time periods varying from a few hours to a few weeks to provide measurements of the vertical flux of water between the surface and subsurface water. In total during the years 1997 to 2000, there were 25 research wells, 90 piezometers, and 10 seepage meters emplaced in WCA-2A. Between 2 and 6 research wells were emplaced at each of the WCA-2A sites at depths ranging between 5 and 115 ft in the underlying limestone and sand aquifer. Replicate seepage meters were emplaced at all but sites S10C, S7E, and U1. Between 1 to 15 piezometers were installed in the peat at depths ranging between 50 to 220 cm. Two piezometer-only sites were established near site S10C at distances approximately 300 m away from the levee on the north side (S10C N) and 100 m away from the levee on the south side (S10C S). At those sites, between 18 to 35 piezometers were installed in peat at depths ranging between 10 and 270 cm.

Addition of the new instrumentation began with an exploratory program to drill shallow wells in the interior of WCA-2A at six sites (F1, F4, E1, E4, U3, U1). Those wells were drilled to depths of 6 ft and 25 ft below ground surface at six sites. A portable tripod drill rig with rotary coring capabilities (Shinn and others, 1984) was used to emplace those wells. Surface water was used as the drilling fluid by pumping it down the annular space with hydraulic pumps. The depth of drilling under these conditions was limited by "running sands" in the aquifer, the flow of which eventually equaled the flushing capacity of the pump causing drilling to be terminated. Upon completion of the borehole, a 1.5-in-diameter (nominal) well was installed with a 2-ft screen (0.010-in slotted PVC) at the bottom.

To accommodate the need for a deeper set of research wells, a more traditional mud-rotary method was used with drilling equipment mounted conventionally on a truck trailer or on a specialized floating drilling barge. Deeper boreholes were drilled at the S10C levee site, and at three of the seven sites in the WCA-2A interior (E4, U3, and S7E). Three boreholes were drilled at the levee site (30, 60, and 90 ft) and two boreholes were drilled at the interior sites (60 and 120 ft). Wells that were emplaced in the deeper boreholes were 2-in diameter (nominal) with 2-ft screens (0.010-in slotted PVC) at the bottom. At sites U3, E4, and S7E, 2 wells were emplaced in each of two boreholes, at depths of 11 and 28 ft in the shallower borehole, and 60 and 120 ft in the deeper borehole. The relation of the wells emplaced in WCA-2A to hydrogeological information that is detailed in Harvey and others (2002).

Piezometers were installed in peat and in underlying sediments (organic–marl–sand) that are transitional to the sandy limestone sediments of the aquifer. These piezometers were constructed either of 1-cm stainless steel drivepoints with 1-cm vertical slots (0.035-cm slot thickness) near the bottom, or 1.5-cm schedule 40 PVC pipes with 5 cm of horizontal slots (0.025-cm thickness), or either 3.2- or 3.8-cm schedule 40 PVC pipes with 15 cm of horizontal slots (0.025-cm thickness). Piezometers were emplaced by hand-pushing to depth.

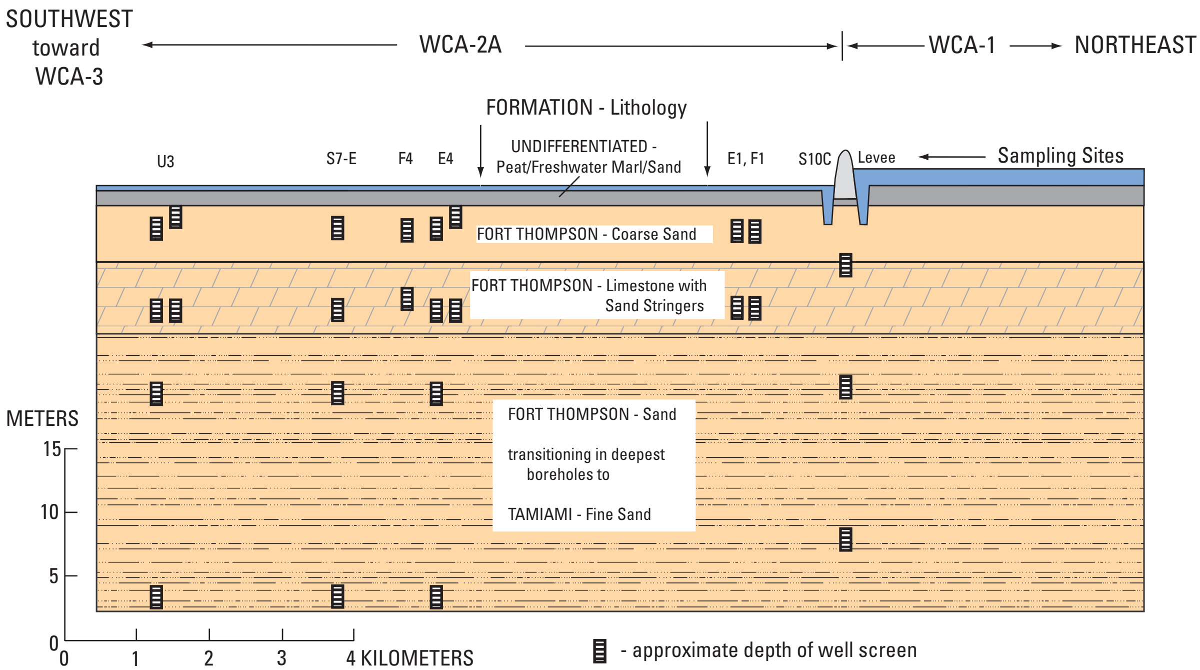


Figure 4. Hydrogeologic cross section *B–B′* in Water Conservation Area 2A (WCA-2A), central Everglades, south Florida. Cross section shows relation of reseach wells to formations and lithology of the aquifer. See figure 3B for location of cross section.

Several of the deepest piezometers in the transitional sediments required hand-augering of a guide hole with a 2.5-cm auger before emplacement.

NOTE: The present report is interdisciplinary in nature, serving hydrogeologists, surface-water hydrologists, and landscape ecologists and geomorphologists. Each of those scientific fields uses customary scientific units. The decision was made to be consistent with the use of customary units used by several disciplines although it results in use of mixed units in the report. Metric units are mostly used, but the report adheres to a customary use of English units in the field of engineering hydrogeology. This convention is upheld by the South Florida Water Management District, the cooperator for this investigation. Choice of which units to use in a given instance was made by the authors using best judgment about the needs of different report users. A conversion table can be found near the beginning of the report.

Recharge and Discharge Estimates Determined by Independent Techniques

Each of the following sections details the use of one technique to estimate recharge and discharge in WCA-2A. Each technique has is strengths and weaknesses in terms of cost and sophistication of analyses and modeling. The comparison between techniques reveals that the problem of estimating recharge and discharge in the Everglades is a scale dependent one. Each technique has a differing level of sensitivity, and thus detection capability, for determining the shorter or longer timescale components of recharge and discharge. Results of each approach are reported in sequence and then all results are compared in a final section.

Estimates from the South Florida Water Management Model

Even though the South Florida Water Management Model (SFWMM) is one of the most important tools being used to understand the hydrology of the Everglades, it has not often been used to specifically investigate recharge and discharge in the WCAs (South Florida Water Management District, 1999). Recharge and discharge in the central Everglades are considered by the SFWMM, but these values are not reported in a format that is directly interpretable as such in the standard output of the SFWMM (Ken Tarboton, South Florida Water Management District, written commun., 2003). Water-balance results from the SFWMM mainly report fluxes in surface water and ground water that cross basin boundaries. A simple estimate of recharge and discharge is possible using the water balance results directly, but the result would be an underestimate because recharge fluxes in the interior part of the wetland are not necessarily considered.

In the present study recharge and discharge were estimated for WCA-2A using the results of the SFWMM in a new interpretive framework. Individual mass-balance equations for surface water and ground water were written based on the SFWMM. Terms and numerical values were then inserted for WCA-2A as supplied from SFWMM results for certain specific time periods. The mass balance equations were then solved for recharge and discharge. Since these recharge and discharge estimates should be sensitive to fluxes in the interior part of WCA-2A, they can be compared with other estimates of recharge and discharge described later in this report.

Mean annual water-balance fluxes for WCA-2A were obtained (based on SFWMM version 3.5) representing the periods 1979–1990 (calibration run), 1991–1994 (verification run), and 1965–1995 (base simulation). Using those results and the SFWMM documentation (South Florida Water Management District, 1999), time-averaged mass-balance equations for WCA-2A were written individually for surface water and ground water. The new equations included complete expressions for vertical fluxes of water across the sediment surface. The terms in these mass-balance equations are illustrated in figure 5. Equation 1 is a mass balance equation for surface water, equation 2 is a mass balance equation for ground water (used mainly as a check on the first equation), and equation 3 computes a net flux between surface water and ground water by summing total recharge and discharge.

0 = STQSIN + RAINFALL + LSPGIN – STQSOUT – ETP – LSPGOUT – STOCH – PERCOLATION – SW-GW_RESIDUAL, (1)

0 = GWIN – GWOU T – ETS – GWSTOCH + PERCOLATION + SW-GW_RESIDUAL, (2)

NET EXCHANGE = Recharge – Discharge = LSPGOUT + PERCOLATION + SW-GW_RESIDUAL – LSPGIN. (3)

where STQSIN and STQSOUT are surface water flows through water control structures entering or leaving the basin, respectively;

RAINFALL is the rainfall on the basin;

ETP and ETS are evaporation and/or transpiration leaving the basin from ponded surface water and saturated subsurface zones, respectively;

SWSTOCH and GWSTOCH are the changes with time in water storage in surface water and ground water of the basin, respectively;

GWIN and GWOUT are the water fluxes entering and leaving ground-water basin by regional ground-water flow, respectively;

LSPGIN and LSPGOUT are the water fluxes entering or leaving the surface-water basin by shallow ground-water flow beneath selected levees, respectively;

PERCOLATION is a regional-scale computation of water movement across the wetland sediment surface based on (2 x 2 mi grid cell) data for a specified domain;

SW-GW_RESIDUAL is a residual (an unmeasured quantity) associated with both the surface-water and ground-water balance equations. Its magnitude can be calculated by difference using either equation 1 or 2. Since this residual term is comparable in magnitude to the other water balance fluxes, it is used to account for vertical fluxes not specifically accounted for by LSPGIN, LSPGOUT, or PERCOLATION. A positive value indicates recharge and a negative value indicates discharge.

All of the variables are positive numbers except for SWSTOCH, GWSTOCH, PERCOLATION, and SW-GW_RESIDUAL, which can be positive or negative depending on the direction of the flux. Changes in storage variables are positive if water storage increases, and negative if water storage decreases. Vertical exchange fluxes (PERCOLATION and SW-GW_RESIDUAL) are positive if recharge occurs and negative if discharge occurs.

Although equations 1–3 are not documented as part of the SFWMM, the variables are exactly as represented in the documentation, both in name and in magnitude (South Florida Water Management District, 1999, p. 12-56). However, recasting the mass balance equations in terms that are most relevant to recharge and discharge did require the definition of one new variable, SW-GW_RESIDUAL, in order to compute residual terms for the equations 1 and 2 by difference. Residual terms that are specific to surface water and ground water have not previously been computed or interpreted by the SFWMD, yet the magnitude of those residuals was found to be large, which has important implications for the estimation of recharge and discharge.

The surface-water mass balance for WCA-2A included all surface-water inflows and outflows from the SFWMM water balance, including a calculation of "percolation" (South Florida Water Management District, 1999, p. 37). According to Ken Tarboton of SFWMD (written commun., 2003), the PERCOLATION flux is calculated for areas of the Everglades where ponded surface water occurs (which generally includes the majority of WCA-2A) by determining the vertical flux of that water across the wetland sediment that must occur to maintain a hydrostatic distribution of pressure head in surface water and ground water. PERCOLATION tends to be relatively large in magnitude and negative in sign in WCA-2A, which defines it as a discharge flux that transfers water from ground water into WCA-2A surface water. The SW-GW_RESIDUAL computed in the present investigation is also relatively large but positive in sign. The SW-GW_RESIDUAL flux should not be confused with RESIDUAL, which is defined in standard SFWMD water-budget reports. The RESIDUAL term is computed by summing all surface-water and ground-water balance terms (which results from combining equations 1 and 2). RESIDUAL fluxes reported by SFWMD for WCA-2A tend to be more than an order of magnitude smaller than the SW-GW_RESIDUAL fluxes

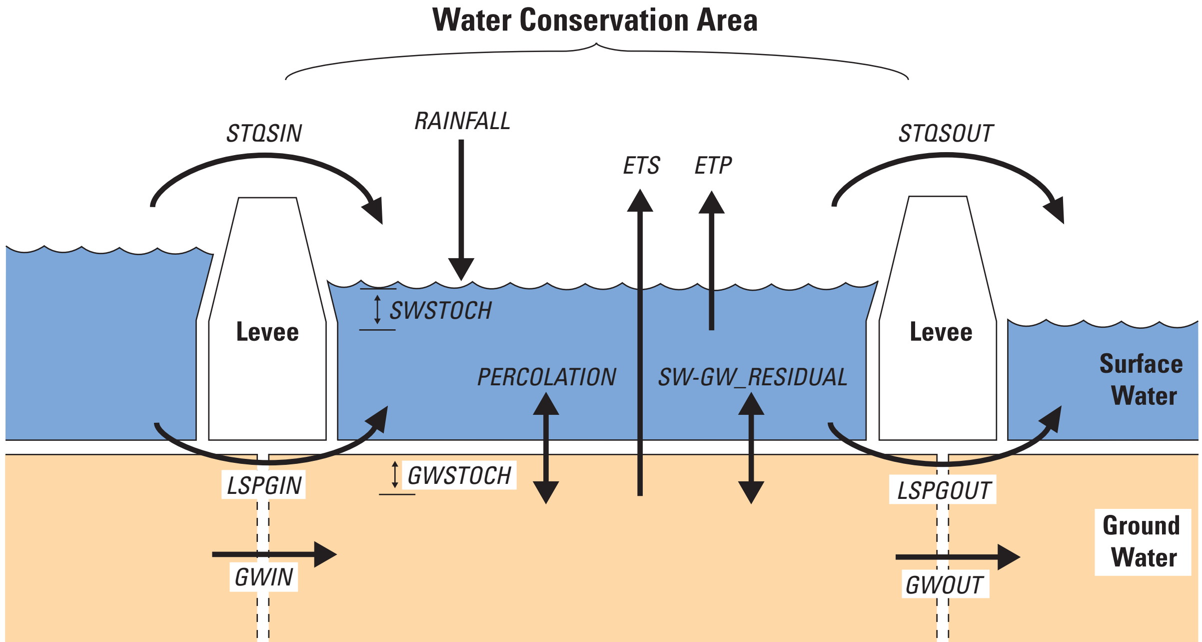


Figure 5. Schematic diagram showing hydrologic fluxes of the South Florida Water Management Model in an application to the water budget of a Water Conservation Area, central Everglades, south Florida. (Modified from South Florida Water Management District, 1999). STQSIN and STQOUT are surface water flows through water control structures entering or leaving the basin, respectively; RAINFALL is the rainfall on the basin; ETP and ETS are evaporation and/or transpiration leaving the basin from ponded surface water and saturated subsurface zones, respectively; SWSTOCH and GWSTOCH are the changes with time in water storage in surface water and ground water of the basin, respectively; GWIN and GWOUT are the water fluxes entering and leaving ground water in the basin by regional ground-water flow, respectively; LSPGIN and LSPGOUT are the water fluxes entering or leaving the surface-water basin by shallow ground-water flow beneath selected levees, respectively; PERCOLATION is a regional-scale computation of water movement across the wetland sediment surface based on (2X2 mi grid cell) data for a specified domain; SW_GW_RESIDUAL is a residual (an unmeasured quantity) associated with both the surface-water and ground-water balance equations.

reported here, likely because SW-GW_RESIDUAL accounts for unmeasured fluxes of water across the interface between surface water and ground water. In the case of WCA-2A, the SW-GW_RESIDUAL flux accounts for an unmeasured component of recharge greater than the estimate for levee seepage expressed as the LSPGOUT term in equation 1.

In order to estimate recharge in WCA-2A, the positive vertical fluxes across the interface (LSPGOUT, SW-GW_RESIDUAL, and sometimes PERCOLATION) were summed. Likewise, discharge was computed by summing the negative vertical fluxes (LSPGIN and, usually, PERCOLATION). The sum of all these vertical fluxes is the NET EXCHANGE (equation 3), which was usually positive in WCA-2A. A small positive NET EXCHANGE suggests that a small amount of recharge tends to occur on a net basis in WCA-2A.

The calculations of recharge and discharge for WCA-2A based on SFWMM version 3.5 are given in table 2. The results of the 1991-1995 “verification” run and 1979-1990 “calibration” run each have the expected characteristic that the “exchange” fluxes, recharge and discharge, are similar in magnitude with only a small difference which represents a net flux due to recharge in the central area of WCA-2A (table 2). Beyond the general pattern of similarity between recharge and discharge fluxes, there was not particularly good agreement between the two different simulations. The shorter of the two model runs, the 1991–1995 “verification” run, produced estimates of recharge and discharge that are 3 to 4 times larger compared with the longer 1979–1990 “calibration” run. There is no obvious explanation for these differences. That recharge and discharge fluxes should be linked in the interior areas of WCA-2A is supported by detailed measurements in WCA-2A. For example, on the basis of a 5-year record of daily calculations of recharge and discharge, Harvey and others (2004) showed alternating periods of recharge, discharge, and neutral flux conditions in WCA-2A. Peak magnitudes and time periods dominated by recharge and discharge were comparable, with reversals on various time scales ranging from weeks to months. Those detailed results support the general pattern of equality illustrated by recharge and discharge results from the SFWMM. A more detailed comparison between all estimates of recharge and discharge is given later in the report.

Table 2. Calculations of vertical fluxes in WCA-2A, central Everglades, south Florida, based on results from South Florida Water Management Model (SFWMM) Version 3.5.

[Positive numbers are recharge fluxes and negative numbers are discharge fluxes ; cm/d, centimeters per day]

SFWMM run	Recharge flux (cm/d)	Discharge flux (cm/d)	Net exchange flux (cm/d)
1979–1990 calibration run	0.055	-0.032	0.023
1991–1995 verification run	.150	-.129	.021

Estimates from Darcy-Flux Calculations

Recharge and discharge were estimated at 15 sites throughout the ENR Project and WCA-2A. Spatial and temporal patterns of those fluxes were delineated using hydrologic data collected from 1997 through 2002. A simple hydrogeologic simulation was used to assess the driving forces for recharge and discharge, including levee seepage. Other factors that were assessed include inter-annual and seasonal climate variation, as well as surface-water "pulses" released through the S10 water-control structures into WCA-2A.

Measurements of Hydraulic Conductivity

Hydraulic conductivity of the sand and limestone aquifer beneath WCA-2A and ENR was estimated as part of a previous research investigation (Harvey and others, 2000). Hydraulic conductivities of Everglades peat and the organic/marl/sandy sediments immediately underlying the peat were determined as part of the present investigation at 11 sites. In the WCA-2A interior, 18 measurements of hydraulic conductivity in peat and 8 measurements in transitional sediments were made at 4 sites in the wetland interior (F1, F4, U3, E4). At site S10C N near the WCA-2A levee, 4 measurements were made in peat and 7 measurements were made in transitional sediments. In ENR, 12 measurements in peat and 5 measurements in transitional sediments were made at 6 sites (M104, M105, M106, M201, M203, and M207).

Either a constant-head, pump-out method (Tavenas and others, 1990; Brand and Premchitt, 1980) or a bail-test method (Luthin and Kirkham, 1949) in piezometers was used to measure hydraulic conductivity. Single-well hydraulic tests are usually thought to be more sensitive to horizontal hydraulic conductivity, which could bias results if used to compute a vertical flux. However, heterogeneities in peat are not necessarily layered horizontally, as is often the case in granular sediments, because vertically oriented channels created by roots sometimes promote faster vertical flow. Therefore, even though single-well hydraulic test results from granular sediments are usually not accepted as estimates of vertical hydraulic conductivity, this investigation used test results from Everglades peat as estimates of vertical hydraulic conductivity. In addition to presenting the data in summarized table form in the present section, all of the individual data are presented in Appendix 2. (To be consistent with recharge and discharge estimates, all hydraulic conductivity values are reported in units of cm/d.)

Estimating Recharge and Discharge using Hydraulic Data

Daily-averaged measurements of surface- and ground-water levels were combined with estimates of peat hydraulic conductivity to compute recharge and discharge in WCA-2A. The entire record of daily measurements of surface-water stages and ground-water levels collected over nearly 5 years (1998–2002) from WCA-2A sites are shown graphed in appendixes 4–17. The vertical hydraulic gradient was estimated from those data as the difference between the surface-water stage and the ground-water level in the shallowest monitoring well (approximately 2 m below the peat surface). The average hydraulic conductivity of peat at a site was multiplied by the vertical hydraulic gradient measured at that site. Using the thickness of peat as the denominator in the hydraulic gradient is justified based on the assumption that head changes linearly through the peat and that the head measurement in the well is a good estimate of head at the base of the peat. The sign conventions are a positive flux and negative hydraulic gradient when discharge occurs (upward flow from ground water to surface water) and a negative flux and positive hydraulic gradient when recharge occurs (downward flow from surface water to ground water). Another assumption was that head changes in surface water or ground water are rapidly transmitted through the peat without significant time lag, thus maintaining the linear head distribution assumed by Darcy's law. That assumption is justified by the relative time scales involved, that is, the time scale for pressure propagation through the peat is minutes compared to days to weeks for changing surface-water levels (which control head at the peat surface). The characteristic time of pressure propagation through the peat, t_p, was estimated using the equation $t_p = ½ \times L^2 \times S_s/K_{peat}$, where L is the approximate thickness of the restricting layer (1 m), S_s is the specific storage of peat (0.001/m), and K_{peat} is the approximate hydraulic conductivity of the restricting layer (0.3 m/d) (Thibodeaux, 1996).

Seepage meters were used to obtain direct estimates of vertical water fluxes (recharge and discharge) through the peat at the sites in ENR. The seepage meters were somewhat larger than the Lee-type meter (Lee, 1977) and include a conical dome made of 0.64-cm-thick, high-density polyethylene (HDPE). Simultaneous seepage-meter measurements using replicate meters at a single site had an average uncertainty of plus-or-minus 50 percent. A more limited data set on recharge and discharge was collected using seepage meters at sites WCA-2BS and WCA-3A-15 (fig. 3). More detailed information on seepage meters, including design and construction, emplacement and operation, and precision and limit of detection, is in Harvey and others (2000). Because of limited access to more remote wetland sites in WCA-2A, seepage meters could not be used to estimate recharge and discharge fluxes at those sites.

Hydrogeologic Simulation

Factors affecting recharge and discharge were examined using a simple hydrogeologic model of ground-water flow for a “leaky” aquifer overlain with a thin aquitard adjacent to a canal. Barlow and Moench (1998) provide a solution based on a one-dimensional (horizontal) flow assumption through the aquifer with uniform hydrogeologic properties, with vertical leakage across the aquitard (envisioned as Everglades peat in this investigation). Because of one-dimensional flow, the head at the left boundary of the aquifer (in contact with the canal) is equal to the canal water level and is constant with depth. That boundary condition represents the hypothetical situation where the canal fully penetrates the aquifer, which is not the situation in WCA-2A where the surficial aquifer is approximately 60 m thick and the canal is approximately 4 m in depth. The fully penetrating assumption was judged sufficient, however, because of its simplicity and because it has been used successfully in the past as a first-order approximation of boundary conditions for situations that are in reality more complicated (Barlow and Moench, 1998).

The governing equations for the model are as follows,

$$\frac{\partial^2 h}{\partial x^2} = \frac{S_s}{K_x}\frac{\partial h}{\partial t} + q', \quad (4)$$

$$\frac{\partial^2 h'}{\partial z^2} = \frac{S'_s}{K'}\frac{\partial h'}{\partial t} \text{ for the domain } b \le z \le (b + b'), \text{ and} \quad (5)$$

$$q' = -\frac{K'}{K_x b}\left(\frac{\partial h'}{\partial z}\right)_{z=b}. \quad (6)$$

where h and h’ are hydraulic heads in the aquifer and aquitard (peat) [m], respectively;

x is horizontal distance from a canal boundary [m] in the domain $x_o \le x \le \infty$;

S_s and S_s’ are specific storage of the aquifer and aquitard, respectively [1/m];

K_x and K’ are the horizontal hydraulic conductivity of the aquifer and vertical hydraulic conductivity of aquitard, respectively [m/s];

z is vertical distance [m];

b and *b’* are the thicknesses of the aquifer and aquitard, respectively [m]; and

q’ is the volumetric flux to or from the aquifer per unit volume of aquifer divided by the aquifer hydraulic conductivity (Barlow and Moench, 1998).

The initial conditions for the model are:

$h(x, 0) = h_i$, and

$h'(z, 0) = h_i$,

where h_i is the initial head in the aquifer. Boundary conditions in the aquifer are:

$h(0, t) = h_o$

$h'(\infty, t) = h_i$,

where h_o is the new head at the canal-aquifer interface achieved after an instantaneous step change. Boundary conditions in the aquitard are:

$h'(x, z=b, t) = h(x, t)$,

$h'(x, z=b+b', t) = h_i$.

The equations were solved using the numerical code STLK1 (Barlow and Moench, 1998).

The simple hydrogeologic simulation described above was used to isolate the effect of the levee boundary on discharge in the wetland. The stress applied to the model was a sudden 1-m increase in head at the left boundary (representing an increase in the water level of a canal that is separated from the wetland by a levee). Other possible influences were ignored, such as climatic factors, surface-water pumping and operation of water-control structures, and the slight slope of the wetland ground surface and water-level surface. Assuming that the surface-water level in the wetland is constant presumes quick drainage of recently discharged ground water away from the levee. Constant surface-water level was implemented using the “source bed” option of the STLK1 model, which holds the hydraulic head constant at the top of the aquitard (restricting layer of peat). Aquifer and restricting layer thicknesses, aquifer hydraulic conductivity, and head change at the boundary were set on the basis of field estimates and held constant for all simulations. Hydraulic conductivity of the restricting layer was initially set to 30 cm/d, an intermediate value of K_{peat} that was representative of vertical hydraulic conductivity in both ENR and WCA-2A. A value of specific storage for both peat and aquifer (0.001 m) was selected based on literature values. Other parameter values used in model simulations included aquifer depth of 60 m; peat depth of 1 m; and $K_{aquifer}$ of 3,000 cm/d. To test sensitivity to the value of K_{peat}, two additional simulations were run using values of K_{peat} of 0.3 and 3,000 cm/d.

Spatial and Temporal Variability of Hydraulic Conductivity and Recharge and Discharge Fluxes

This section reports on the spatial variability of hydraulic conductivity of peat and the underlying transitional sediments, and compares results of the hydrogeologic simulation with field estimated computations of recharge and discharge. Temporal trends in recharge and discharge are also discussed.

Hydraulic Conductivity

Hydraulic conductivities of peat (K_{peat}) are reported as geometric means for three areas of the central Everglades. No obvious pattern was seen in the vertical distribution of K_{peat} estimates (fig. 6), which supports the use of the geometric mean of all K_{peat} estimates from a site to characterize vertical hydraulic conductivity at the site (table 3). Values of K_{peat} tended to be higher in the WCA-2A interior (geometric mean of 59 cm/d) compared with ENR (6 cm/d). The average value of K_{peat} (26 cm/d) at a site near the Hillsboro levee (which separates WCA-1 and WCA-2A) in WCA-1 was intermediate between values in the interior WCA-2A and in ENR. Lower K_{peat} values in ENR may be the result of irreversible compaction of peat that probably occurred due to decades of drainage and farming before the site was reconverted to a wetland (Harvey and others, 2002). That interpretation is consistent with bulk density measurements, which indicate that peat sediments in ENR are denser by a factor of 3 than in the WCA-2A interior. The finding that K_{peat} values are lower near the WCA-2A levee than in the WCA-2A interior is consistent with the higher bulk density peat measurements near the levee (table 3), which may be the result of interactions with the nearby canal, where frequent overbank flooding over the past 30 years likely delivered large amounts of fine-grained mineral sediments into the wetlands. Interior areas of WCA-2A appear to have a higher K_{peat} that is more representative of predrainage conditions in the central Everglades, probably because these interior areas have been less disturbed by human activities (Gleason and Stone, 1994).

At some sites, hydraulic conductivity was estimated in the fresh water marl/sand layer immediately underlying the peat. Average hydraulic conductivities in the sand/marl/limestone layer at WCA-2A interior, WCA-2A levee, and ENR sites were 61, 6, and 18 cm/d, respectively (fig. 6 and table 3). K in the transitional layer therefore did not differ greatly from K_{peat} above. K values were 2,000 and 900 cm/d near the top of the surficial aquifer at WCA-2A and ENR, respectively (Harvey and others, 2000). The finding that hydraulic conductivity in the surficial aquifer is 1–2 orders of magnitude higher than in the peat or fresh water marl/sand transition layer indicates that the peat and the transitional matrix function together as

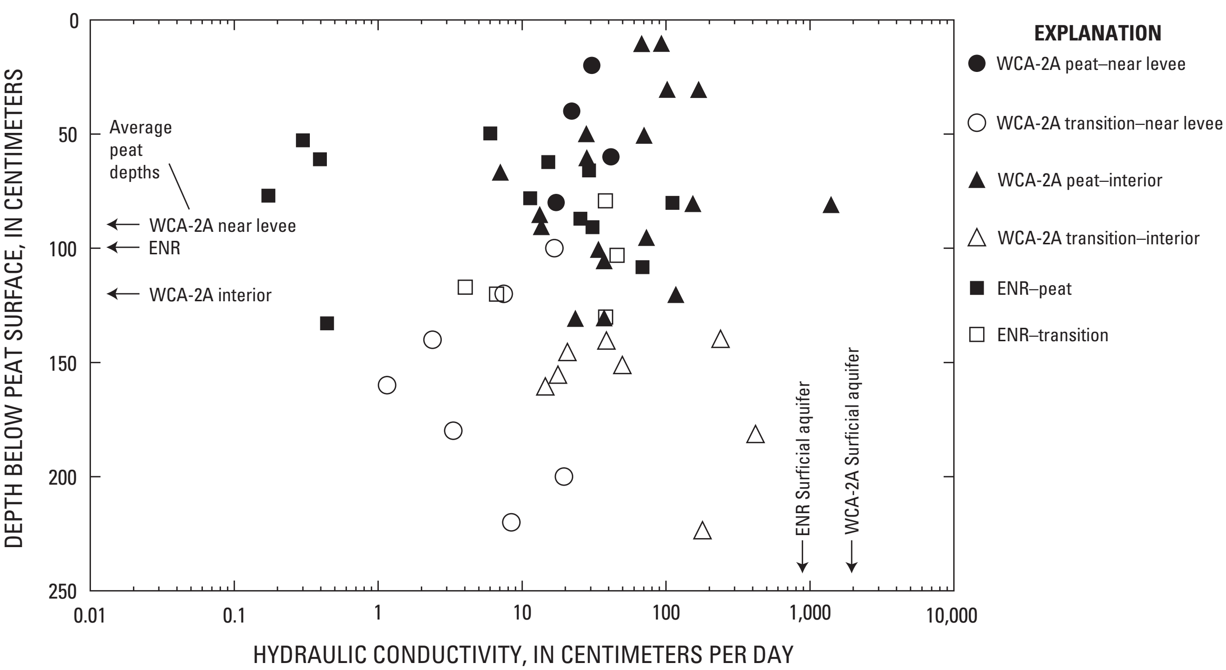


Figure 6. Hydraulic conductivities of wetland peat and fresh water marl/sand layers that are transitional to the underlying Surficial aquifer , which is composed of limestone and sand, Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), central Everglades, south Florida.

Table 3. Measured physical properties and hydraulic conductivities of peat and underlying transitional (fresh water marl/sand layers) sediments in Water Conservation Area 2A (WCA-2A) and Everglades Nutrient Removal (ENR) project, central Everglades, south Florida.

[means are geometric means; –, no data; cm, centimeters; cm/d, centimeters per day; g/cm^3, grams per cubic centimeter; >, greater than]

Location	Number of sites	Number of observations	Mean depth (cm)	Hydraulic conductivity (cm/d)			Bulk density (g/cm^3)
				Mean	Minimum	Maximum	
Peat							
WCA-2A interior	4	18	120	59	7	1,400	0.06
near WCA-2A levee	1	4	80	26	17	42	.09
ENR	6	11	110	6	0.2	110	.20
Transitional sediments							
WCA-2A interior	2	8	–	61	15	420	–
near WCA-2A levee	1	7	>100	6	1	20	1.1
ENR	5	5	–	18	4	46	1.1

a layer restricting vertical fluxes of water by recharge and discharge.

Recharge and Discharge Fluxes

Recharge and discharge fluxes were greater near levees compared with interior sites in wetlands (table 4 and fig. 7). Fluxes at the near-levee sites (within 600 m of levees) also tended to be unidirectional with time (that is, always recharge or discharge, depending on position upgradient or downgradient of a levee) (fig. 7a). At near-levee sites, the median (50th percentile) values of vertical fluxes ranged in magnitude from 0.07 to 3.3 cm/d. Highest values of discharge in WCA-2A and ENR occurred at sites close to the levee bordering WCA-1. For example, relatively high values of discharge occurred at ENR sites M104, M106, M105, and at site S10C in WCA-2A. The highest value of recharge occurred in ENR at the site that was closest to the levee bordering the agricultural area (site M201) (fig. 7a).

At wetland sites in the WCA-2A interior, the average behavior of vertical fluxes was better represented by the 25th and 75th percentile fluxes compared with the 50th percentile flux. The interior sites experienced reversals in the direction of vertical fluxes on a regular basis that tended to balance one another, resulting in a median near zero. The median (50th percentile) fluxes tended to be very small (less than 0.06 cm/d), and therefore the 25th and 75th percentile fluxes better represented the typical magnitudes of recharge and discharge (on the order of 0.5 cm/d). Interior sites at ENR had even smaller median fluxes (approximately 0.03 cm/d). Also, rather than experiencing changing directions of fluxes, vertical fluxes at the interior sites in ENR experienced recharge approximately 90 percent of the time (fig. 7c).

Hydrogeologic Simulation

Results of the hydrogeologic simulation suggest that surface-water level differences across levees can drive vertical fluxes across the peat surface as large as 10 cm/d near the levees, and that fluxes decline exponentially with distance and become negligible beyond 600 m (fig. 8). The model performed reasonably well simulating data collected near levees (within 600 m). All data collected near levees in ENR and WCA-2A plot within an envelope describing sensitivity of the model to a range of vertical values of K_{peat} (0.3 to 3,000 cm/d). Measured vertical fluxes in the interior of WCA-2A (up to 12,000 m away) were larger by several orders of magnitude than fluxes simulated by the model. The range of measured fluxes in the wetland interior is large, with 25th and 75th percentile fluxes being much larger in magnitude (0.1 to 1 cm/d) than their corresponding median fluxes (approximately 0.06 cm/d). The higher magnitudes of fluxes on the quartiles results from vertical fluxes switching between recharge and discharge at most sites, averaging to a net flux of approximately zero. The simulation results predicted a zero vertical flux at all times in the interior wetlands, which is a large underprediction of the observed recharge and discharge fluxes. These results suggest that a time-dependent factor drives alternating periods of recharge and discharge in the interior of WCA-2A.

Temporal Trends in Recharge and Discharge

During a five-year period the estimated recharge and discharge fluxes at site U3 in WCA-2A varied cyclically between recharge and discharge (fig. 9). The temporal record is based on daily calculations of Darcy-flux, which is based on measured surface-water levels and ground-water head at the site. A simple correlation is not evident, however, between the fluctuating pattern of recharge and discharge and measured fluctua-

Table 4. Vertical fluxes across the peat surface measured at wetland sites over a 5-year period in Water Conservation Area 2A (WCA-2A) and over a 2-year period in Everglades Nutrient Removal (ENR) Project, central Everglades, south Florida. Vertical fluxes in WCA-2A and ENR were estimated by Darcy-flux and seepage meter calculations, respectively.

[m, meters; cm/d, centimeters per day]

Site	Distance from levee (m)	Period of record	Number of estimates	Vertical flux[1] (cm/d) Percentile 10	25	50	75	90
				WCA-2A				
S10C S	50	9/97–11/02	1,651	1.5	2.3	2.9	3.7	4.0
E1	2,191	2/97–10/02	1,945	-0.9	-0.7	-0.03	0.3	0.6
E4	6,915	2/97–10/02	1,679	-1	-.4	.00	.4	.8
U1	14,447	2/97–10/02	1,741	-.8	-.4	-.06	.2	.6
F1	1,968	2/97–10/02	1,885	-.7	-.4	.04	.3	.4
F4	6,906	2/97–10/02	1,616	-1.0	-.8	-.5	-.08	.2
U3	11,075	2/97–10/02	1,955	-.3	-.1	.02	.2	.5
				ENR: East				
M104	50	10/96–4/98	110	.2	.3	.7	1.1	1.3
M106	132	3/97–4/98	43	.2	.2	.3	.8	4.7
M105	257	12/96–4/98	40	.1	.2	.4	2.3	4.7
M103	867	6/96–4/98	37	-.2	-.1	-.04	.01	.02
				ENR: West				
M201	50	8/96–4/98	68	-12	-9.6	-3.3	-2.3	-1.1
M206	180	3/97–4/98	14	-.7	-.1	-.07	-.06	-.04
M205	359	10/96–4/98	43	-.4	-.2	-.07	-.05	-.02
M203	1,027	6/96–4/98	53	-.2	-.06	-.03	-.01	.01

[1]Discharge fluxes are positive, and recharge fluxes are negative.

tions in surface water. Instead, the direction of vertical fluxes alternated on annual, monthly, and weekly timescales. On an annual basis, 1997 to 2002 were years of average wetness in WCA-2A with a slight (interannual) trend toward drying out over the five-year period (average rate of water-level decrease of 10^{-4} ft/day). The first half of the period of record, which followed a wetter period in the mid 1990s, was a time of average wetness during which the annual trend in fluctuation in the direction of vertical flux was weighted toward ground-water discharge rather than recharge. From 2000 to 2002, a time of transition to drier conditions in WCA-2A, recharge and neutral fluxes occurred more often than discharge (fig. 9).

On a monthly timescale, the most obvious patterns are the approximately 14 peaks in surface-water levels that lasted for several weeks to several months (fig. 9). A comparison of these peaks with the timing of spillway discharges suggests that most of those peaks (water levels above 3.8 m NGVD) resulted from the movement of a pulse of surface water from the spillways into the interior wetland (fig. 9). The approximately 8 smaller peaks (below 3.8 m NGVD) were not associated with surface-water pulses but with periods of heavy precipitation near the end of the dry season (fig. 9).

The weekly pattern of vertical flux begins with many missing values, and then is followed by several sharp spikes of recharge and discharge in late 1997, followed by a few months of recharge in early 1998. A discharge trend began in mid-1998 and continued through the rest of that year and into early 1999. Discharge in the summer of 1999 was interrupted by two short-lived reversals to recharge associated with peat rewetting events. The trend toward discharge continued through April 2000, when it transitioned to alternating periods of recharge and discharge for the remainder of the year. A brief period of neutral conditions (with approximately zero fluxes) followed, and then transitioned three months later to one of the longer periods of recharge in the record lasting through August 2001. During September and October 2001, the arrival of several large surface-water pulses drove alternating periods of recharge and discharge. Neutral flux conditions prevailed between November 2001 and February 2002. Recharge occurred throughout the remainder of the record, except for short-term reversals to discharge caused by precipitation (April 2002) and by the approach of a surface-water pulse in June 2002 (fig. 9).

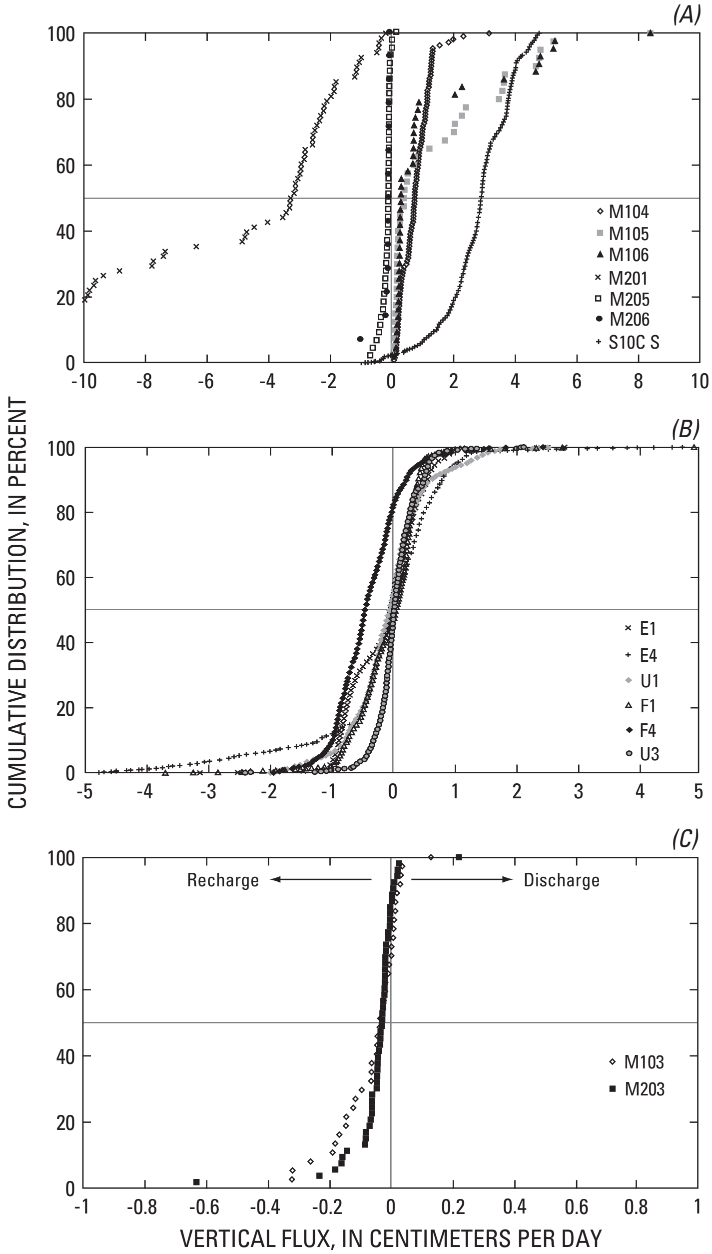


Figure 7. Cumulative distributions of vertical fluxes across the peat surface at wetland sites near levees *(A)*, interior sites in Water Conservation Area 2A (WCA-2A) *(B)*, and interior sites in Everglades Nutrient Removal (ENR) project *(C)*, central Everglades, south Florida. Vertical fluxes in WCA-2A and ENR were estimated by Darcy-flux calculations and seepage meter, respectively. X-axis exaggerated in *(B) and (C)*. Site locations are shown on figure 3.

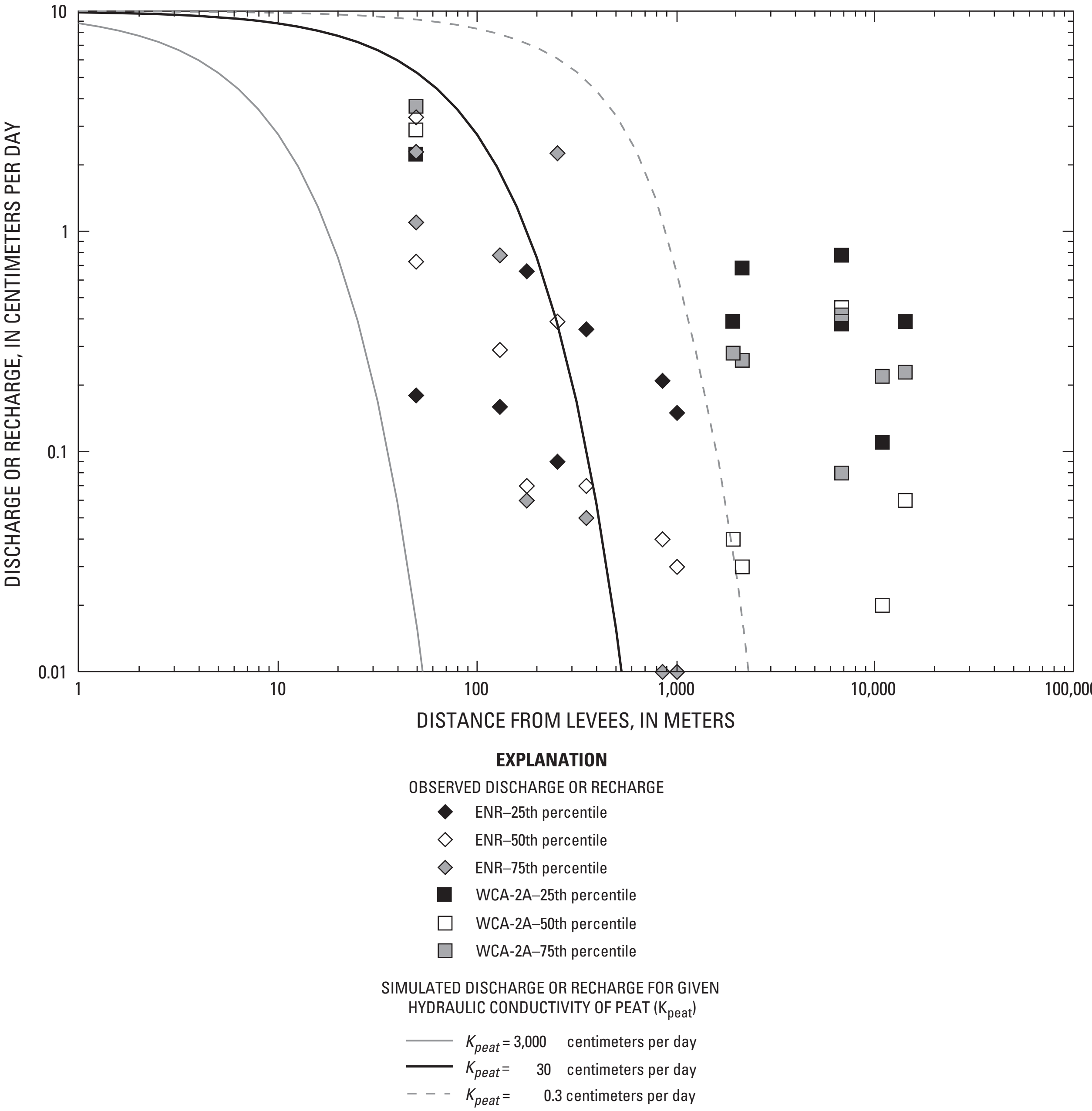


Figure 8. Magnitude of observed and simulated discharge and recharge fluxes in relation to hydraulic conductivity of peat and distance from levees in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), central Everglades, south Florida. Observed fluxes are from figure 7, this report.

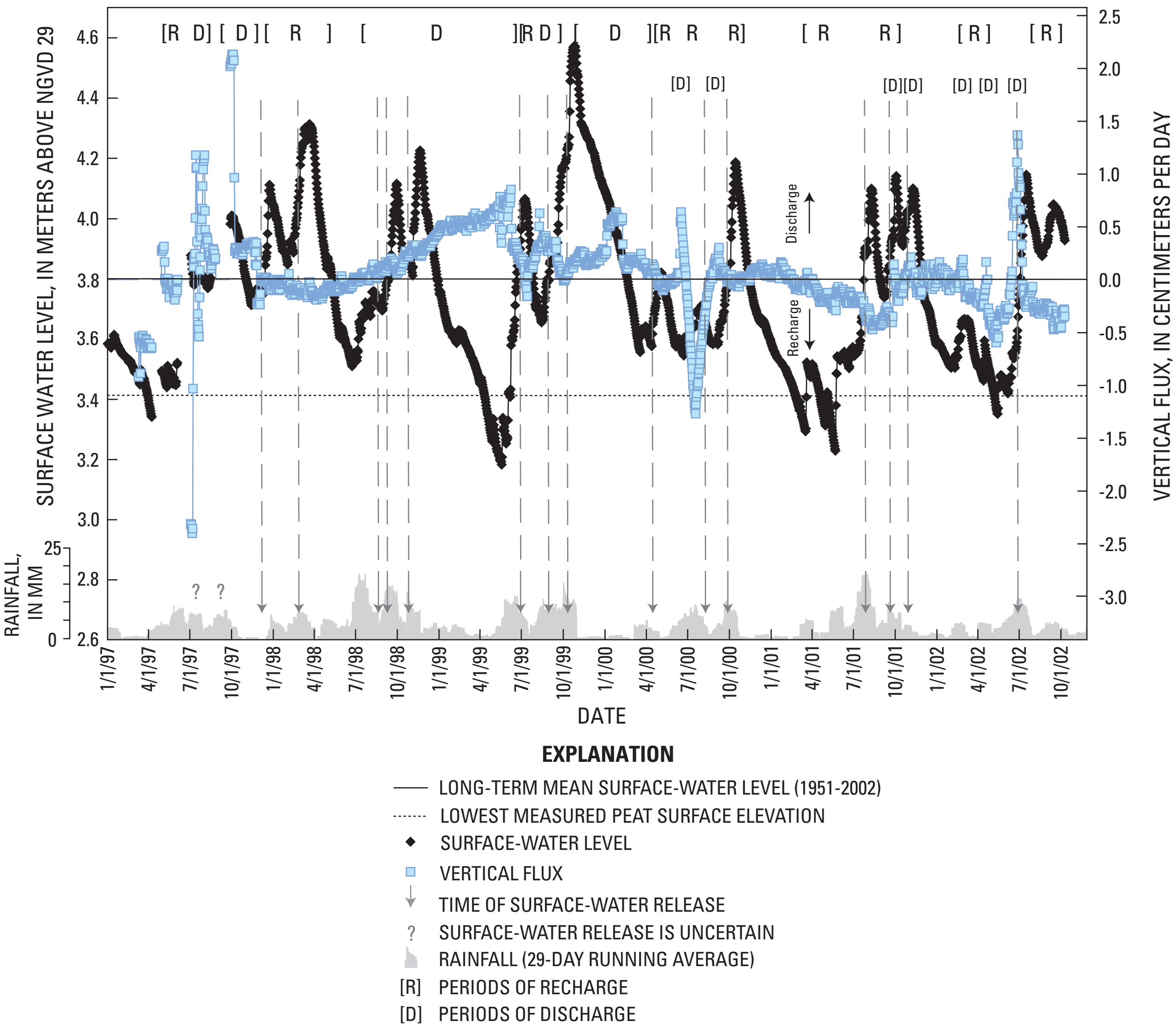


Figure 9. Surface-water levels and vertical fluxes (discharge and recharge) observed at site U3, and precipitation data from near U3 in the interior of Water Conservation Area 2A (WCA-2A), central Everglades, south Florida, 1997-2002. Precipitation data from recorders maintained by the South Florida Water Management District.

Controls on Reversals between Recharge and Discharge

Reversals between recharge and discharge were commonly associated with peat rewetting events. Peat rewetting occurs when unsaturated pore spaces are re-filled and the wetland is re-flooded following a dry period when ground-water levels have declined below the sediment surface. With a maximum drawdown of the water table of about 25 cm below the wetland surface, it is likely that the peat rarely dries out substantially, although surface cracking was observed in the late spring of 1999. Peat rewetting can either occur slowly, due to multiple precipitation events over a period of months, or rapidly, due to the sudden arrival of a large pulse of surface water. Peat rewetting probably involves a combination of processes, including ground-water discharge and infiltration of surface water flowing across relatively dry or variably saturated wetland sediment. The effects of peat rewetting at site U3 are most obvious from March through July 2001 and March through June 2002 (fig. 9).

Peat rewetting and fluctuations in surface-water levels in WCA-2A are affected by precipitation and evapotranspiration, and by spillway operations that release water from WCA-1. Precipitation and evapotranspiration are the primary controls on water levels when water-control structures are inactive. At those times, surface-water levels in the northern (higher elevation) area are usually similar to topographic slopes, whereas at the southern ends, surface water tends to be ponded (zero slope) (Romanowicz and Richardson, 2000). Three to four times a year, the S10 spillways at the northern levee of WCA-2A are opened for a period of weeks to months, releasing large amounts of surface water that flow in a wave-like manner (initially with an amplitude of 0.5 to 1 m) to the southwest toward the center of WCA-2A under the influence of gravity. The surface-water pulse often takes a week or more to travel south into the central area of the basin, and as it travels it becomes attenuated and dispersed.

These surface-water pulses potentially can influence surface- and ground-water interactions in the interior wetlands of WCA-2A. In particular, if surface-water levels increase faster than ground-water heads, a downward hydraulic gradient is expected that would drive ground-water recharge. Conversely, an upward hydraulic gradient and ground-water discharge are expected if surface-water levels decline faster than ground-water heads. This is referred to as the “ground-water lag” mechanism of driving vertical exchange. There is evidence for the ground-water lag mechanism in the five-year record at site U3, particularly in the many recharge events that occur simultaneously with peak surface-water levels (fig. 9). Conversely, discharge tended to occur both on the falling limb of surface-water levels and (for short periods of several weeks or less) prior to the arrival of the surface-water pulse (fig. 9). Although discharge on the falling limb of a surface-water peak is consistent with a ground-water lag in pressure heads, short-lived discharge preceding the arrival of a pulse of surface water is not. The data suggest that, under certain circumstances, ground-water heads propagate faster through the wetlands than the pulse of surface water. For example, in a wetland that is relatively dry or variably saturated (dry in some areas and wet in others), the pressure associated with a surface-water release at the spillway could potentially propagate faster toward the central wetland when moving through the aquifer than when moving with surface water across the top of the wetland. In fact, approximately seven times at site U3 in the interior of WCA-2A, a few days or weeks of discharge immediately preceded the arrival of a surface-water pulse (fig. 9). Pressure must have traveled faster in the aquifer to cause discharge (for even a short period) before the surface-water pulse arrived. This is referred to as the “ground-water pressure-wave” mechanism of driving vertical exchange. More field data and model simulations are needed, however, to confirm this interpretation.

Comparisons with Other Parts of the Central Everglades

A comparison of recharge and discharge estimates from a subset of sites in the central Everglades with average precipitation, evapotranspiration, and basin-averaged surface flows in the central Everglades (South Florida Water Management District, 1999) shows that recharge and discharge are greatest in the smaller basins (ENR and STAs) of the north-central Everglades (fig. 10). At some sites in ENR, recharge and discharge are larger than precipitation and evapotranspiration and large relative to surface flows (fig. 10). Choi and Harvey (2000) showed that recharge in ENR accounted for a flux of water equal to 30 percent of surface inflows. Farther south in the much larger WCAs the recharge and discharge fluxes are smaller when expressed per unit area, although the fluxes are still significant relative to other water-balance fluxes (fig. 10). The trend of decreasing vertical fluxes farther south in the central Everglades is probably the result of several factors, but all of those factors probably are related to the decreased effects of hydraulic perturbations at the levee and canal systems at the edges in larger basins. In that respect the interior areas of the larger basins are more likely to be similar to the predrainage Everglades in terms of the interactions between surface water and ground water.

Estimates from Modeling Radium Transport and Decay in Peat Pore Water

The approximately 1-m thick layer of peat in the Everglades has a lower hydraulic conductivity than underlying sediments, and thus impedes exchange between the surface water and the surficial aquifer (Harvey and others, 2002). Although vertical water transport occurs through the Everglades peat layer, rates of vertical flow are difficult to quantify because the fluxes are relatively low. Quantifying those fluxes is important, however, because in the Everglades they often occur over a large area (Choi and Harvey, 2000). Common methods for

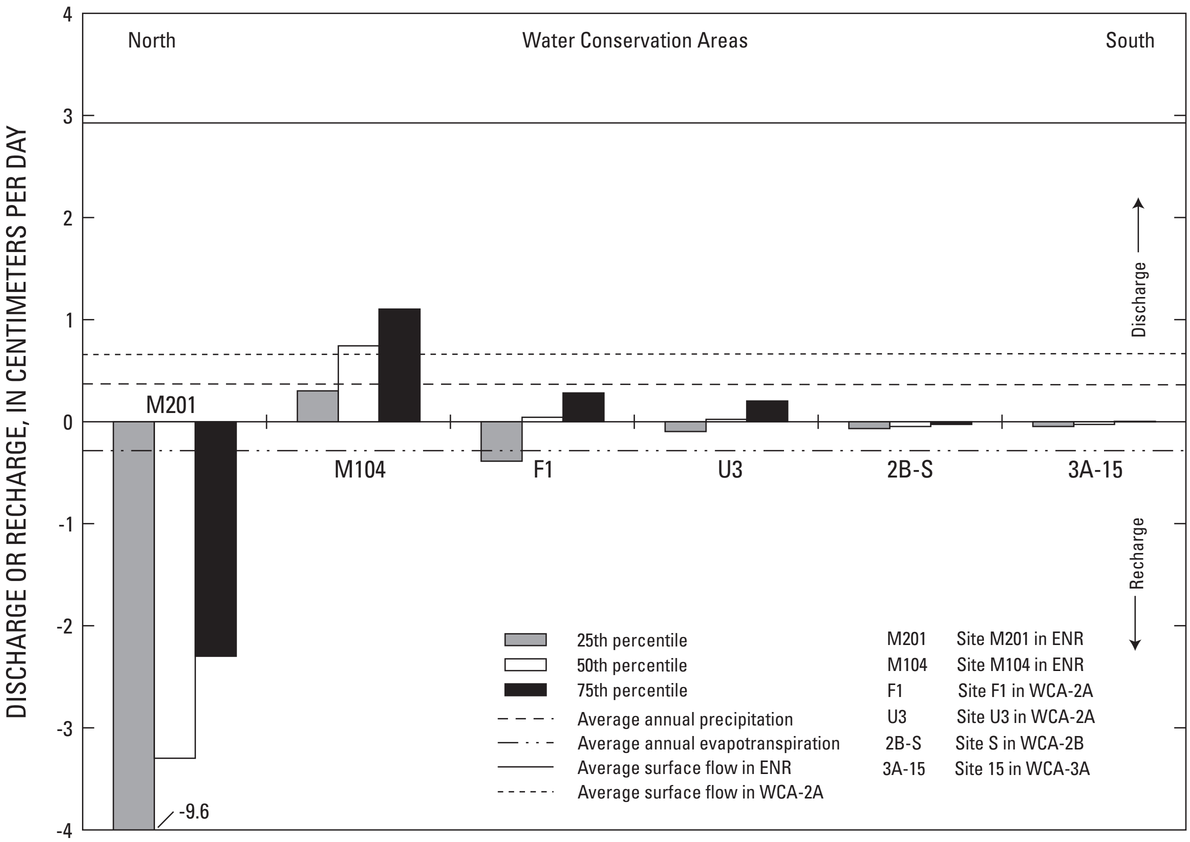


Figure 10. Estimates of discharge and recharge at selected sites, and time-averaged values of precipitation, evapotranspiration, and surface-water flows in Everglades Nutrient Removal (ENR) Project, and Water Conservation Areas 2A (WCA-2A), 2B (WCA-2B), and 3A (WCA-3A) in central Everglades, south Florida. Sites are located on figure 3.

measuring exchange across the peat layer have disadvantages: small hydraulic gradients are difficult to measure over short vertical distances; seepage meters tend to be imprecise at slow rates; radon profiles or emanation rates are complicated by methane bubble ebullition; and chloride profiles commonly exhibit a strong gradient only at the surface of the peat and are affected by other processes (such as bubble ebullition) in addition to recharge and discharge.

In this investigation, vertical fluxes through the peat layer were estimated by modeling the pore-water profiles of ^{223}Ra and ^{224}Ra. Field data were collected on natural distributions and production rates of radium in vertical profiles through Everglades peat, and these data were modeled using either one-dimensional advective or dispersive flow models.

Sampling Locations for Dissolved Radium

Water samples were collected from wells at site S10C N in WCA-1, approximately 300 m north of control structure S10C on the Hillsboro levee, and at sites S10C S and U3 in WCA-2A (fig. 11). S10C S is approximately 100 m south of the tailwater canal south of the Hillsboro levee. Because of water conservation practices, there is often a difference in ground-water level of approximately 0.3 to 1 m between sites S10C N and S10C S, and as a result, ground-water recharge is known to occur at S10C N and ground-water discharge occurs at S10C S (Harvey and others, 2002). Site U3 is in the interior of WCA-2A, 12 km from the levee, and the head difference at the levee has a much smaller effect on the ground-water movement at this site. Harvey and others (2002) showed that the long-term average vertical flux of ground water at site U3 is small (approximately 0.06 cm/d), though instantaneous rates may sometimes be as large as about 0.5 cm/d. All three sites are in undisturbed sediment and vegetation where the peat layer is approximately 1 m thick, and the bottom of the peat is well defined with either carbonate or siliceous sediments lying directly beneath it. Above the peat is an unconsolidated detrital layer, commonly called the “floc” layer, which is easily disturbed and resuspended into the overlying surface water. Samples were collected from sites S10C N and S10C S on April 5, 2001, and April 30, 2001. Samples were collected from site U3 on September 25, 2001.

Piezometers were installed at various depths in the sediments to collect water for measurements of dissolved radium. These piezometers consisted of either 0.95-cm stainless steel drivepoints with vertical slots near the bottom end that are

0.025-cm wide and 2-cm long, or 1.27-cm i.d. schedule 40 PVC pipes with 5 cm of slotted screen near the bottom. The piezometers were installed in a random array to sample at 10- to 20-cm vertical resolution while keeping the slotted tips at least 50 cm away from each other in all directions. Between 0.5 and 2 L of pore water were pumped at rates less than 100 ml/min and filtered through 0.45-μm (actual) pore-size filters, then passed through Mn-fiber to concentrate the radium isotopes (Moore, 1976). ^{223}Ra and ^{224}Ra were analyzed by delayed coincidence counting of the Mn-fiber (Moore and Arnold, 1996). Sub-samples of the filtered water were also analyzed for chloride by ion chromatography. In addition to the presentation of data in the remainder of this section, all raw data are provided in Appendix 18.

Calculation of Radium Distribution

In saturated sediments, a significant fraction of exchangeable radium is dissolved, but most is adsorbed to particles. This partitioning is commonly described as a simple, linear, sorption isotherm ($Ra_{Adsorbed} = K_D \times Ra_{Dissolved}$), which can be rearranged to solve for K_D, the Ra distribution coefficient,

$$K_D = \frac{[Ra_{Adsorbed}]}{[Ra_{Dissolved}]} \,, \qquad (7)$$

where $Ra_{Adsorbed}$ is the mass of radium per gram dry weight of peat, and $Ra_{Dissolved}$ is the mass of radium per mass of pore water.

K_D is often measured in the laboratory either by leaching the exchangeable radium from the sediment using high-ionic strength solutions, or by adding a radium spike or tracer to a sediment slurry and determining the amount taken up in the liquid and solid fractions (Rama and Moore, 1996; Krest and others, 1999). However, by treating a sample with dilute hydrogen peroxide, Rama and Moore (1996) demonstrated that oxidation of the sediment during transport and analysis may free up binding sites in the sediment and artificially increase the value of K_D. The Sun and Torgersen (1998) method whereby the dissolved and adsorbed phases are quickly separated and measured directly from the water or solid is an improvement, but some oxidation of the sample may still occur before separation.

Because of the low radium activities in the Everglades peat sediments and pore water, K_D could not be measured with good precision using Sun and Torgersen's (1998) method. Instead, K_D was determined for each site by dividing the production rate of radium in equilibrated sediments by the dissolved radium activity. The production rate of radium in the equilibrated sediments is equivalent to the total exchangeable radium, of which most will be sorbed to sediments. This calculation was performed only on data from upper portions of the peat cores where an equilibrium relation between the production rate and dissolved activity was observed in vertical profiles (constant pore water concentrations and constant production rates with depth). Because the dissolved fraction is collected in situ and the production measurement gives total exchangeable radium, oxidation is not a concern.

Sediment Analyses

Sediment cores 10.2 cm in diameter were taken at each site for measurements of radium production rates, porosity, and dry bulk density. Cores were sectioned in 5- or 10-cm intervals, and interval depths were corrected for compression as measured at the time of coring. Each interval was homogenized, and one fraction was taken to determine the average density of the sediment particles, the average porosity, and the dry bulk density (Lambe, 1951) (fig. 12a). Another fraction of sediment was aged for 60 days to ensure equilibrium between the radium isotopes and their respective parents, dried, disaggregated in a blender, and analyzed for the production rates of exchangeable ^{223}Ra and ^{224}Ra by delayed coincidence counting of the re-moistened sediment (Sun and Torgersen, 1998).

Models of Vertical Transport of Radium

Production rates for ^{223}Ra and ^{224}Ra are different in the peat layer than in the surface water or underlying sediments (fig. 12b), so profiles of the isotopes near the upper or lower interface can be modeled to determine the advective or dispersive flux across the interface. Water that crosses the interface will initially have a radium concentration greater or less than that supported by the local production rate, and as that water parcel continues to travel through the new layer, this dissolved concentration will eventually come into equilibrium with the new production rate. Similarly, at the surface of the peat, profiles can be used to determine the gain or loss due to ground-water recharge if the surface-water activities are different than the supported radium activities in the pore water.

The one-dimensional advection and dispersion models used in this investigation are an appropriate simplification for freshwater systems of the detailed one-dimensional, advective-diffusive transport model recently formulated by Sun and Torgersen (2001). Because of the estuarine system that was being studied, their model required considerations for changes in the adsorbed/dissolved radium partitioning coefficient (K_D) and a subjective assignment of separate zones of physical and biological mixing without explicit correlation to pore-water geochemistry or sediment morphology.

Model Derivation

^{223}Ra and ^{224}Ra are produced from the decay of their respective thorium parents. Thorium is extremely particle reactive ($K_D = 10^4$ to 10^5), so the primary source of these radium isotopes is in and on sediment surfaces. Because radium is much less particle reactive than thorium ($K_D \approx 10^2$-10^3 in freshwater), an appreciable fraction is dissolved in pore water. As a dissolved ion, radium is transported with pore fluids and

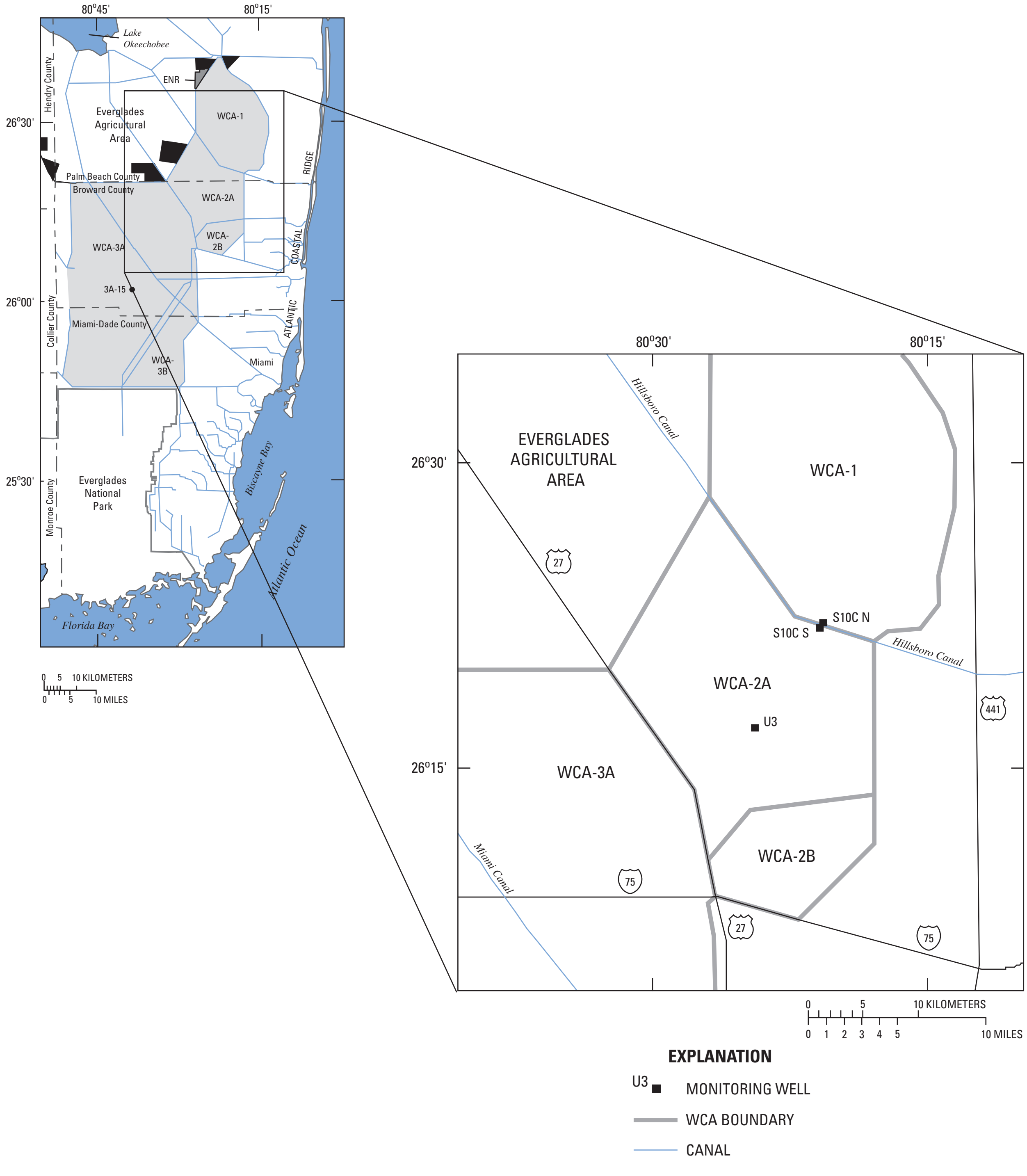


Figure 11. Locations of wells and piezometers sampled for dissolved radium in Water Conservation Areas 1 and 2A (WCA-1 and WCA-2A), central Everglades, south Florida.

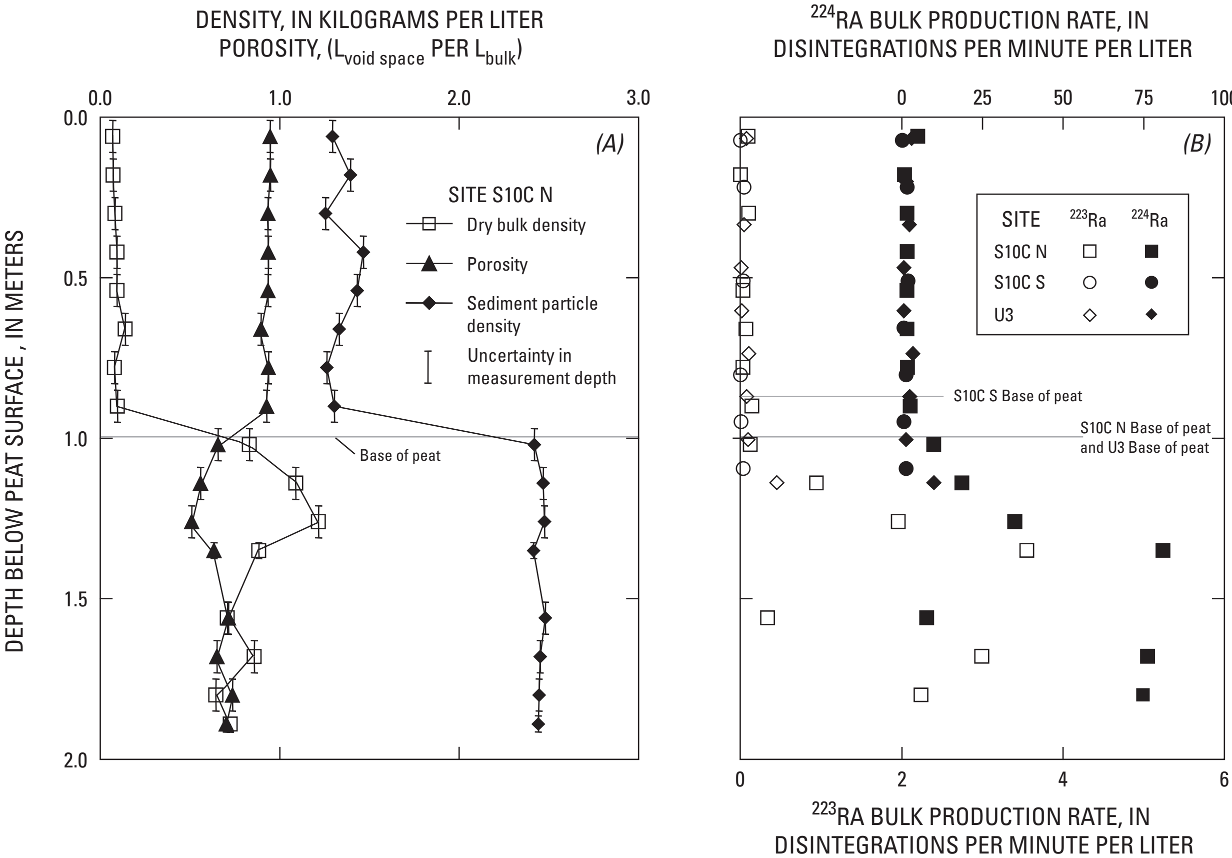


Figure 12. Characteristics of peat soil and underlying fresh water marl and sandy sediment, central Everglades, south Florida, including *(A)* physical characteristics of soil and underlying sediment at site S10C N and *(B)* production rates, *P*, of ^{224}Ra and ^{223}Ra at sites S10C N, S10C S, and U3. Samples were collected from sites S10C N and S10C S on April 5 and April 30, 2001, and from U3 on September 25, 2001.

its gain or loss near sediment/sediment or sediment/water interfaces can be modeled in saturated sediments as a balance of its production, decay, advection, dispersion, and exchange with particles (Berner, 1980):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} - v\frac{\partial C}{\partial Z} + \frac{\hat{P}\rho}{f K_D + (1-f)} - \lambda C + \frac{\partial C^*}{\partial t}\frac{\rho}{K_D} \tag{8}$$

where t is time;

Z is depth below the peat surface;

C is the number of dissolved radium atoms per volume of water;

C^* is the number of adsorbed radium atoms per mass of dry sediment;

D is the hydrodynamic dispersion coefficient in units of (length)^2 per time;

v is the pore-water advective velocity in units of length per time;

$\hat{P}$ is the production rate of exchangeable radium (dissolved plus adsorbed) from its respective parent isotope in atoms per time, per mass of bulk sediment;

ρ is the pore water density in mass per volume;

f is the mass of dry sediment per mass of bulk sediment;

K_D is the radium distribution coefficient (equation 7); and

λ is the respective decay constant (0.189 d^{-1} for ^{224}Ra, 0.0606 d^{-1} for ^{223}Ra).

When conditions are at steady-state, and in areas where advective fluxes greatly exceed dispersive fluxes, equation 8 can be simplified and solved for the concentration of radium at any depth in the peat ($C(Z)$):

$$C(Z) = P\lambda^{-1} + \left(C_I - P\lambda^{-1}\right)e^{-\Delta Z\cdot\lambda\cdot v^{-1}} \tag{9}$$

Here, C_I is the radium concentration at an interface defined as the depth of a transition between sedimentary layers or the depth of the sediment/surface water interface. ΔZ is calculated as the difference between the depth of the interface and the sample depth so that $\Delta Z = 0$ at the interface and is positive upward. The boundary conditions are $C(\Delta Z = 0)$ is equal to the measured C_I and $C(\Delta Z = \infty)$ is equal to P. P is equal to $\hat{P}$ /[f K_D+(1-f)], the fraction of the exchangeable radium production which will enter the pore water, and is analogous to the supported, dissolved radium activity at equilibrium. A semi-infinite boundary condition can be used in this system because the dissolved radium activities quickly equilibrate with changes in the production rate, generally within less than 0.5 m.

In some areas of the Everglades, vertical velocities are low and often reverse directions so that the average advective velocity approaches zero (Harvey and others, 2002). In these areas, it may be more appropriate to model dispersion as the dominant transport process. The steady-state solution to equation 8 for the case where dispersion dominates over advection is:

$$C(Z) = P\lambda^{-1} + \left(C_I - P\lambda^{-1}\right)e^{-|\Delta Z|\cdot\lambda^{0.5}\cdot D^{-0.5}} \quad (10)$$

The absolute value of the distance from the interface ($|\Delta Z|$) is needed in equation 10 to allow for the most general case where ΔZ could be a positive or negative distance from the interface in this coordinate system.

It would have been preferable to solve for advection and dispersion simultaneously, but at very low pore-water velocities it is unlikely that analytical uncertainties allow for separation of these variables. At low velocities the advective and dispersive terms are usually similar in magnitude; if both terms are included, they occur as a ratio in the solution and cannot be independently estimated. Indeed, model curves produced from equations 9 and 10 are nearly identical, and the choice of one depends primarily on knowledge of the hydraulics and geochemistry of the system.

The radium production rate is assumed to be constant through the sediment layer being studied, an assumption that should be valid in relatively homogeneous sediments, but should be tested for individual systems. In this freshwater system, it is assumed that K_D is constant through each layer of sediment as long as the ionic strength of the pore water does not change appreciably with depth. Because K_D is constant and the model is of steady-state conditions, retardation of radium is not a factor (Berner, 1980; Tricca and others, 2001).

Because radium is generally measured and discussed in terms of its activity (A) rather than its concentration, both sides of equations 9 and 10 are multiplied by λ ($A=C\lambda$). The vertical profile of dissolved radium is therefore described by:

$$A(Z) = P + \left(A_I - P\right)e^{-\Delta Z\cdot\lambda\cdot v^{-1}} \text{ (for advection),} \quad (11a)$$

or

$$A(Z) = P + \left(A_I - P\right)e^{-|\Delta Z|\cdot\lambda^{0.5}\cdot D^{-0.5}} \text{ (for dispersion),} \quad (11b)$$

where A_I is the dissolved radium activity at the interface and $A(Z)$ is the dissolved radium activity as a function of depth.

Test of Model Assumptions

Use of the one-dimensional advective and dispersive transport analytical models defined above requires meeting certain assumptions. The principal assumptions are that (1) the pore-water radium activity near the sediment/sediment or sediment/surface-water interface is out of balance with the activity that would be expected as a function of the radium production rate in the sediments and the partitioning of radium between the dissolved and adsorbed phase, and this disequilibrium is the result of either advective or dispersive transport across the interface; (2) each sedimentary layer is relatively homogeneous chemically and physically, and the interface between the layers is well-defined; (3) the radium production rates are constant within each layer, but significantly different between adjoining layers; and (4) the partitioning of radium between the dissolved and adsorbed phase is constant through each layer. If these assumptions are not met, more detailed geochemical terms are needed in the governing equation (Cochran, 1980; Sun and Torgersen, 2001).

The first of those assumptions is met because vertical hydraulic gradients and hydraulic conductivity of Everglades peat are sufficiently high to cause vertical advection through peat at rates that are relatively rapid with respect to the timescale of decay of the short-lived radium isotopes (Harvey and others, 2002). The second assumption is met because the Everglades peat layer is relatively homogeneous in bulk sediment properties (fig. 12a). For example, at site S10C N, the porosity of peat is very high (0.93 ± 0.02), the density of peat is relatively low (1.34 ± 0.08 g/cm^3), and the dry bulk density of peat is also very low (0.09 ± 0.02 g/cm^3). With regard to assumption 3 above, the base of the peat is well-defined and is characterized at all the sites by a distinct change from the high-porosity, low-density peat sediments to high-density, low-porosity silicate or carbonate sediments. Although the underlying silicates or carbonates are reasonably homogeneous in terms of their physical characteristics, the same is not necessarily true for their chemical characteristics; the production rates of ^{223}Ra and ^{224}Ra are low and constant through the peat layer but much more variable in the sediments below the peat (fig. 12b).

With regard to assumption 4, K_D values were determined from the relation between the exchangeable radium and dissolved radium (equation 7). The dissolved radium was approximated as the average of the dissolved radium activities between 10 and 50 cm deep ($\bar{A}$). Dissolved activities in this interval were all very similar, suggesting equilibrium had been reached between production, decay, and exchange. The total exchangeable radium was estimated as the production rate of the exchangeable radium ($\hat{P}$), again assuming that equilibrium conditions existed for this interval. The amount of adsorbed Ra was estimated as the difference between the total exchangeable ($\hat{P}$) and the dissolved radium ($\bar{A}$ /100). K_D values were then calculated according to a modification of equation 7:

$$K_D = \frac{[Ra_{Adsorbed}]}{[Ra_{Dissolved}]} = \frac{\left(\hat{P} - \bar{A}\rho/100\right)}{\bar{A}\rho/100} \quad (12)$$

Calculated K_D values ranged from 120 to 280 for the peat sediments (table 5).

In homogeneous sediments, changes in K_D would most likely result from changes in the ionic strength of the pore water. Because chloride can be measured with greater precision than K_D, chloride concentration was used as a proxy of ionic strength to test the constancy of K_D in the peat and aquifer sediments. Little or no correlation is observed between chloride concentrations and depth, or between pore-water radium activity and chloride concentrations (fig. 13). This suggests that K_D is constant in the peat layer. This relation cannot be extended below the base of the peat because of the confounding effects of changing sediment characteristics.

A test of the assumption of constant radium production was simplified by Sun and Torgersen's (1998) method whereby the emanation of ^{220}Rn from a column of moistened sediment is measured to determine the amount of exchangeable ^{224}Ra in the sample. Using this method, the amount of ^{224}Ra adsorbed to the sediment particles can be determined easily; this surface-bound radium is the fraction subjected to desorption, subsequent transport in the dissolved phase and readsorption. Using samples that were aged to ensure equilibrium between ^{224}Ra and its ^{228}Th parent, the production rate of surface-bound ^{224}Ra was determined. The production rate of the surface-bound ^{223}Ra in the peat samples also was determined by applying the same theory to the ^{227}Ac – ^{223}Ra – ^{219}Rn decay series. The ^{223}Ra and ^{224}Ra production rates are constant through the peat layer, but become more variable in the deeper sediments (fig. 12). The assumptions for modeling vertical transport of radium through the peat are therefore reasonable, but because of variability in production rates below the peat, vertical transport in the sand and limestone layers cannot be described accurately by the simplified transport models.

If the radium distribution coefficient (K_D) changed with depth, a similar dissolved radium gradient in the pore water might be observed. Therefore, it is essential to determine K_D through the sediment layer. Sun and Torgersen (1998, 2001) measured K_D directly from the sediment samples and the pore water extracted from the sediment interval. However, because of the low radium concentrations in the Everglades peat and pore-water samples, estimates of K_D could be determined experimentally only from certain samples collected far enough from the interface to ensure equilibrium between the dissolved radium and its production rate. The agreement between the average dissolved radium activity in samples collected away from the interface ($\bar{A}$) and the model-derived estimate of the production rate of the dissolved radium (P) indicates that equilibrium has been reached between production, decay, and exchange in this interval (table 5).

Because of the large potential for error in estimating K_D in freshwater sediments, small trends of variation in K_D as a function of depth might not be noticed in the data even though they could have large effects on the dissolved radium activities. Because the strongest control on the radium distribution coefficient in homogeneous portions of the sediment is likely to be the ionic strength of the solution (Copenhaver and others, 1993; Webster and others, 1995), and because chloride concentration is the overwhelming contributor to the anion side of the charge balance, the constancy of the chloride concentration with depth was used as a first-order approximation of the constancy of K_D (fig. 13).

Furthermore, radium activity shows no correlation to the chloride concentration at any site, except possibly in the most surficial samples at site S10C S (fig. 13b). This slight correla-

Table 5. Calculated radium distribution coefficients (K_D) in Everglades peat for the radium transport model.

[$\hat{P}$, production rate of exchangeable radium as determined by the model; dpm/kg, disintegrations per minute per kilogram; $\bar{A}$ dissolved radium activity (average of dissolved radium activities between 10 and 50 centimeters in the peat); dpm/100L, disintegrations per minute per 100 liters; P, production rate of dissolved radium (see table 6); n.d., not determined]

	Site					
	S10C S		S10C N		U3	
	^{224}Ra	^{223}Ra	^{224}Ra	^{223}Ra	^{224}Ra	^{223}Ra
$\hat{P}$ (dpm/kg)	21.2	0.49	25.5	0.66	34.9	0.91
$\bar{A}$ (dpm/100L)	8.42	.34	10.2	.29	20.2	.55
P (dpm/100L)	7.60	.40	n.d.	n.d.	17.0	.60
K_D (using $\bar{A}$)	250	144	250	230	170	160
K_D (using P)	280	120	n.d.	n.d.	210	150

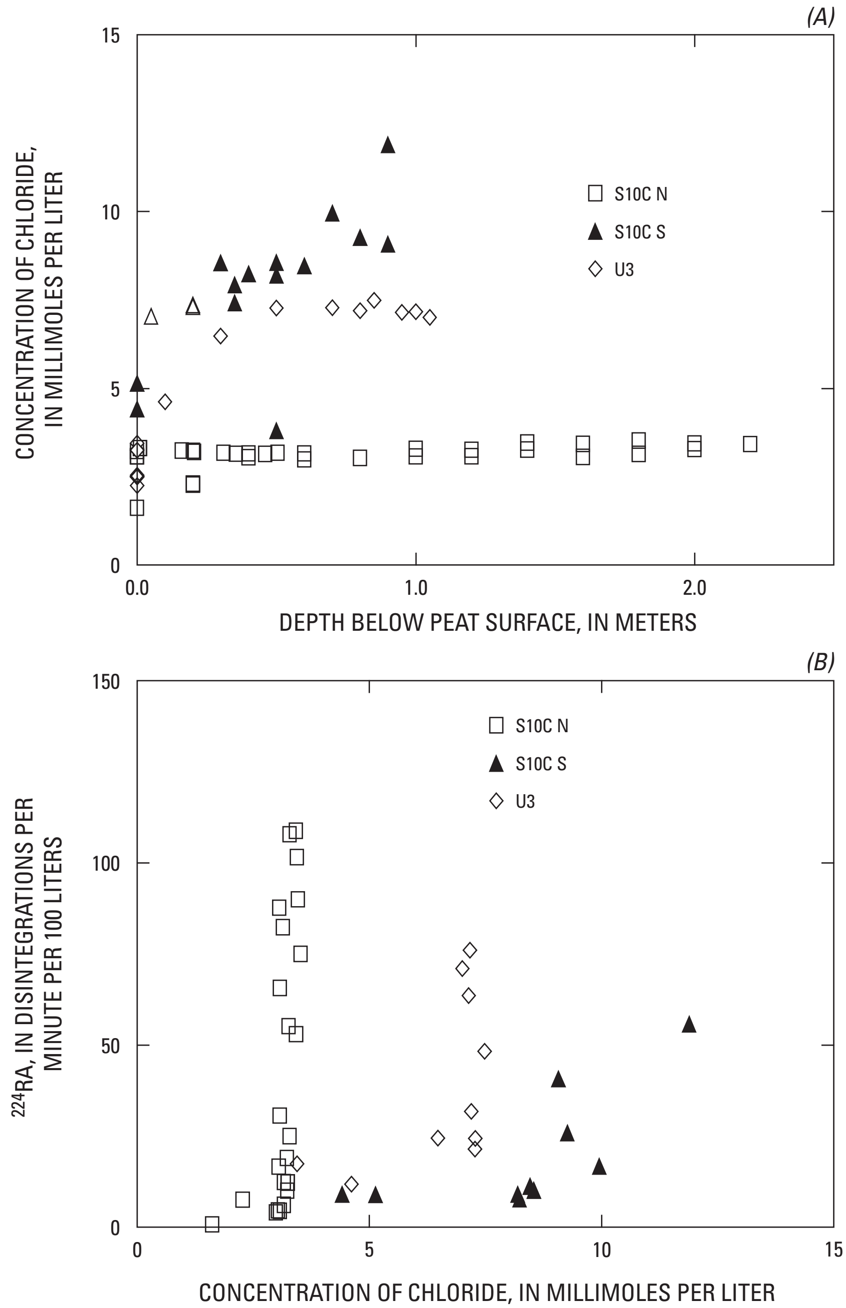


Figure 13. Concentrations of dissolved chloride in relation to depth below the peat surface *(A)*, and pore-water ^{224}Ra activities in relation to chloride concentrations *(B)*, central Everglades, south Florida. The trend for ^{223}Ra is similar and is not shown here. Samples were collected from sites S10C N and S10C S on April 5 and April 30, 2001, and from U3 on September 25, 2001.

tion is not of concern in this investigation because pore-water radium concentrations in the upper part of the peat are all very similar and have little or no bearing on the radium distribution in the bottom of the core where the concentration gradient was modeled.

Resulting Estimates of Recharge and Discharge

Pore-water ^{224}Ra and ^{223}Ra activities in the peat layer at site S10C S are highest near the base of the peat as a result of upward transport from below; activities decrease exponentially to a constant value in the upper portion of the peat as the excess radium decays, and the activity of the dissolved plus adsorbed fraction approaches equilibrium with the production rate (fig. 14a,b). Modeled data for upwards advection of radium and pore fluids are based on equation 11a. For all data sets, the "best fit" parameters *v* or *D*, A_f, and *P* were determined using a curve-fitting routine that maximized the log of the likelihood function using a Nelder-Mead simplex algorithm and assuming a Poisson distribution. Based on the ^{224}Ra and ^{223}Ra model fits, the advective velocity at site S10C S is 2.4 ± 0.6 cm/d or 0.50 ± 0.25 cm/d, respectively. This slight discrepancy may reflect the lack of steady-state conditions, and/or the fact that the modeled velocities for each tracer are essentially average velocities over the mean life (λ-1) of the isotope (approximately 5.3 d for ^{224}Ra, and 16 d for ^{223}Ra). Additionally, the discrepancy may represent analytical errors.

Radium profiles at S10C S are consistent with ground-water discharge with a modeled advective velocity (averaged for the results of the two radium isotopes) of 1.5 ± 0.4 cm/d. The model result for the advective velocity is not very sensitive to the boundary conditions; the analytical uncertainty of the radium activity and production-rate boundary conditions adequately cover the spread of radium activities in the pore-water profiles (fig. 14). An advantage of this model is that the activity gradient being modeled occurs deep within the peat, away from the surface of the peat where mechanical disturbances to the system may easily distort the signal.

Data from site S10C N are modeled using equation 11a and show that activities are nearly constant through the peat, but are slightly higher at the very surface of the peat (fig. 14c, d). The activity gradient near the surface and the lack of a gradient at depth, despite an increased production rate in the sand beneath the peat, indicate that ground water is recharging at this site. Sampling intervals were not adequate to precisely determine the activity gradient at the top of the peat, but model fits are useful to constrain the possible maximum rate of advective transport. The ^{224}Ra profile indicates that the magnitude of the recharge is less than 0.9 cm/d. The ^{223}Ra profile constrains the magnitude of recharge to less than 0.43 cm/d. Because the radium production rate is not constant in the sediments below the peat, the rate of recharge at site S10C N could not be further constrained by modeling the radium profiles below the peat.

The dispersive transport model equation 11b was fitted to pore-water ^{224}Ra and ^{223}Ra activities at site U3 (fig. 14e, f), resulting in coefficient of dispersion values of 60 ± 18 cm^2/d and 23 ± 5 cm^2/d from ^{224}Ra and ^{223}Ra profiles, respectively. Model results for all sites are summarized in Table 6.

Comparison of Radium Transport Model Results with Other Results

There is good agreement between the pore-water advective velocity determined from the dissolved radium profiles at S10C S in April 2001 and the vertical flux of water from the Darcy-flux calculations (fig. 15). The pore-water advective velocity determined from radium profiles at site S10C S falls between the 20th and 60th percentiles of all Darcy-flux estimates for the five-year period of record at this site (fig. 15b).

There also was good agreement between the pore-water vertical velocities determined from the dissolved radium profiles at S10C N and S10C S (discharge velocity of 2.5 cm/s, 100 m south of the levee at S10C S, and a recharge velocity of less than 0.5 cm/s, 330 m north of the levee at S10C N) and the vertical flux of water as a function of distance from the levee as determined by a one-dimensional, analytical model (fig. 16).

The radium profile at site U3 in the interior of WCA-2A is very similar to the profile at the ground-water discharge site, S10C S (fig. 14 and table 6). Fitting the advective transport model to the U3 data results in an average advective velocity of 2.3 ± 0.3 cm/d, which is a slightly higher value than that calculated for S10C S (1.5 ± 0.4 cm/d), though not statistically different. The issue of whether the primary transport mechanism is advective or dispersive cannot be resolved by measuring the flux to the surface water: for advective transport, the radium flux (*J*) is roughly calculated as the average radium pore-water activity in the upper part of the core multiplied by the velocity (Berner, 1980):

$$J = A \cdot v \tag{13}$$

and, in the case of dispersion, the maximum flux is a function of the dispersion coefficient and the decay constant (Krest and others, 1999):

$$J = \Delta A \cdot \sqrt{D\lambda} \tag{14}$$

where ΔA can be approximated in this case as the difference between the pore-water and surface-water radium activities. On the basis of the values for *v* and *D* calculated from the radium pore-water profiles, radium fluxes to the overlying surface water at site U3 should be equal whether the primary transport is modeled as a function of advection or dispersion (table 6).

In summary, modeling of radium transport in pore water provided precise estimates of recharge and discharge through Everglades peat. In addition to providing estimates of recharge and discharge, modeling of radium transport in pore water also estimates the flux of radium to surface water, which can

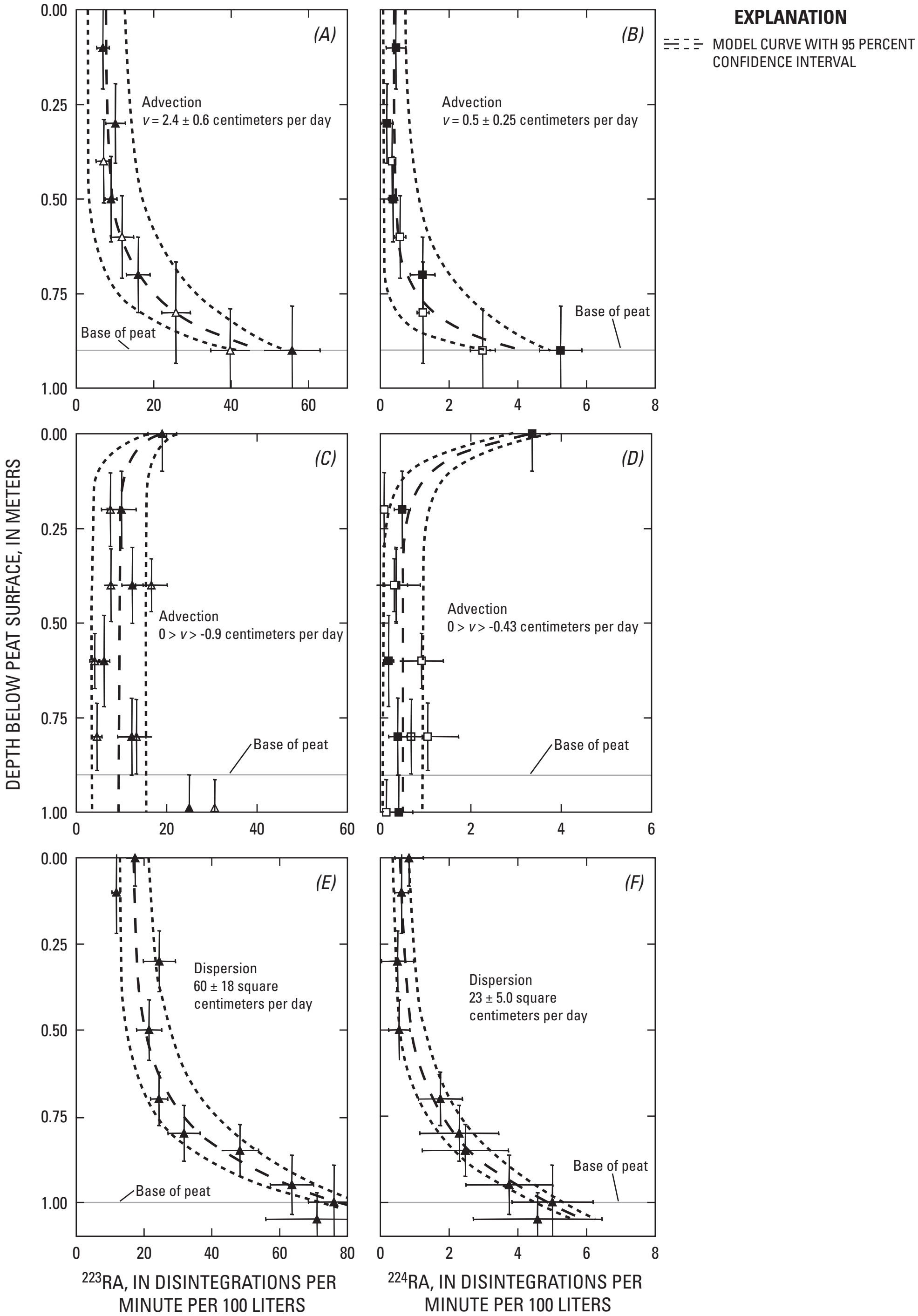


Figure 14. Pore-water radium activities in relation to depth below peat surface at sites S10C S *(A, B)*, S10C N *(C, D)*, and U3 *(E, F)*, central Everglades, south Florida. Model curves in *(A)*, *(B)*, *(E)*, and *(F)* indicate the best fit to the data along with 95-percent confidence intervals based on the uncertainty of the three parameters: *v* (vertical velocity) or *D* (dispersion), A_I (dissolved radium activity at sediment interface), and *P* (production rate of dissolved radium). Central model curves in *(C)* and *(D)* indicate the maximum estimate for v using the best estimate for A_I and *P*. Outer model curves use the same value for *v* as the central curves, spread is based on the analytical uncertainty of A_I and *P*. Samples were collected from sites S10C N and S10C S on April 5 and April 30, 2001, and from U3 on September 25, 2001.

Table 6. Pore-water radium activities in Everglades peat and radium fluxes to the surface water calculated by the radium transport model.

[dpm/m^2/d, disintegrations per minute per square meter per day; *v*, pore-water velocity; cm/d, centimeters per day; C_I, radium concentration at upstream peat interface; dpm/100L, disintegrations per minute per 100 liters; *P*, production rate of dissolved radium; *D*, longitudinal dispersion coefficient for vertical flow in pore water; cm^2/d, square centimeters per day; –, not applicable; n.d., not determined]

Site	Model parameter	Radium activity[a]			Flux (dpm/m^2/d)	
		^{223}Ra	^{224}Ra	Average	^{223}Ra	^{224}Ra
S10C S	*v* (cm/d)	0.5 ± 0.25	2.4 ± 0.6	1.5 ± 0.4	0.06	1.1
	C_I (dpm/100L)	4.1 ± 0.4	48 ± 3	–	–	–
	P (dpm/100L))	0.4 ± 0.3	7.6 ± 2.3	–	–	–
S10C N	*v* (cm/d)	-0.43[b]	-0.9[b]	-0.43[b]	n.d.	n.d.
	C_I (dpm/100L)	n.d.	n.d.	–	–	–
	P (dpm/100L)	n.d.	n.d.	–	–	–
U3	*v* (cm/d)	1.2 ± 0.2	3.4 ± 0.5	2.3 ± 0.3	.14	3.9
	C_I (dpm/100L)	4.9 ± 0.2	77 ± 3	–	–	–
	P (dpm/100L)	0.6 ± 0.1	17 ± 2	–	–	–
U3	D (cm^2/d)	23 ± 5.0	60 ± 18	42 ± 9.3	.07	4.1
	C_I (dpm/100L)	4.9 ± 0.2	77 ± 4	–	–	–
	P (dpm/100L)	0.6 ± 0.1	17 ± 2	–	–	–

[a] Unit determined by model parameter unit.

[b] True value is less than *v* in absolute magnitude.

be used in mass-balance models for surface-water radium. Furthermore, results of the solution of these one-dimensional vertical models will be useful for estimating the transport rates of nutrients and other solutes into or out of the pore water and for quantifying solute storage and release rates and biogeochemical cycling. One of the key advantages of this technique is that dispersion and upward advection are measured at depth in the sediment column, away from mechanical disturbances to the surficial sediment. In an environment with consistent radium production rates in deeper sediment layers, this advantage would hold true for recharge measurements as well. These techniques can be adapted for any wetland systems that have well-defined layers (sedimentary or sediment/surface water transition) creating distinct discontinuities in the radium production rate. In environments where there are uncertainties in the constancy of lithology or ionic strength within layers, more data and a more detailed model representation would be required.

Estimates from Modeling Tritium Transport and Decay in Surface Water and Ground Water

In a large wetland ecosystem such as the Everglades, there is considerable interest in both short and long timescales of surface-water and ground-water interactions. Short timescale interactions in the Everglades include vertical exchange between wetland surface water and peat pore water (Krest and Harvey, 2003; Harvey and others, 2005), although longer timescale interactions between wetland surface water and the underlying sand and limestone aquifer also are of interest (e.g. Bolster and others, 2001; Price and others, 2003; Wilcox and others, 2004). Previous investigations of interactions between surface water and shallow ground water in the Everglades were usually conducted near levees (Swayze, 1988; Meyers and others, 1993; Genereux and Slater, 1999; Bolster and others, 2001; Sonenshein, 2001; Nemeth and Solo-Gabriele, 2003). In general, interactions between surface water and ground water are much less well understood in the interior areas of the Everglades. For example, the effect that levees have in causing local increases in recharge and discharge

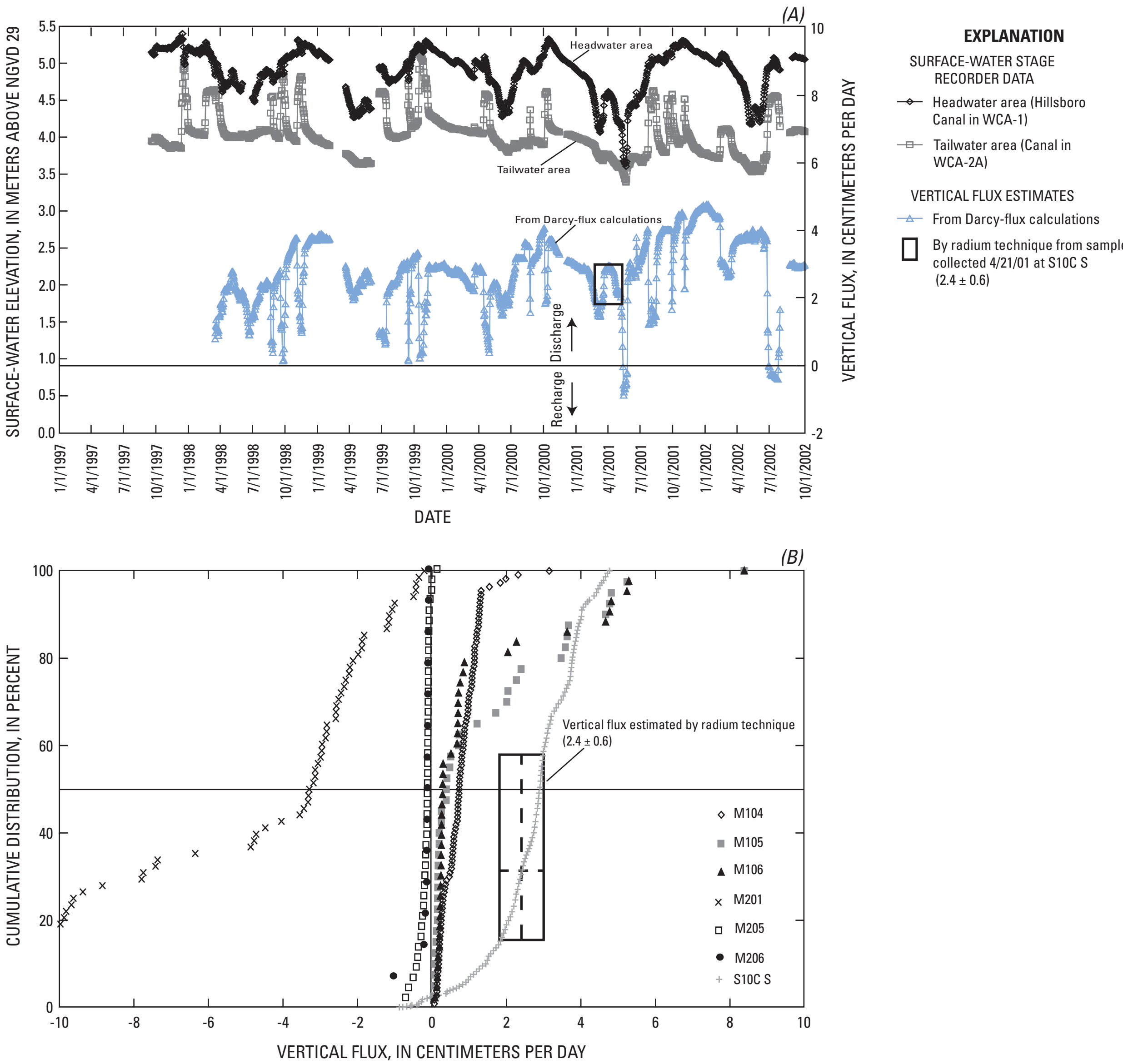


Figure 15. Vertical fluxes of water based on Darcy-flux calculations and estimated by radium technique (using ^{223}Ra) at site S10C S, surface-water elevations for headwater and tailwater canals at site S10C, January 1997 through October 2002 *(A)*, and cumulative distributions of vertical fluxes at other near-levee sites calculated by Darcy-flux technique *(B)*. *(B)* modified from figure 7, this report. Boxes represent uncertainty in vertical flux.

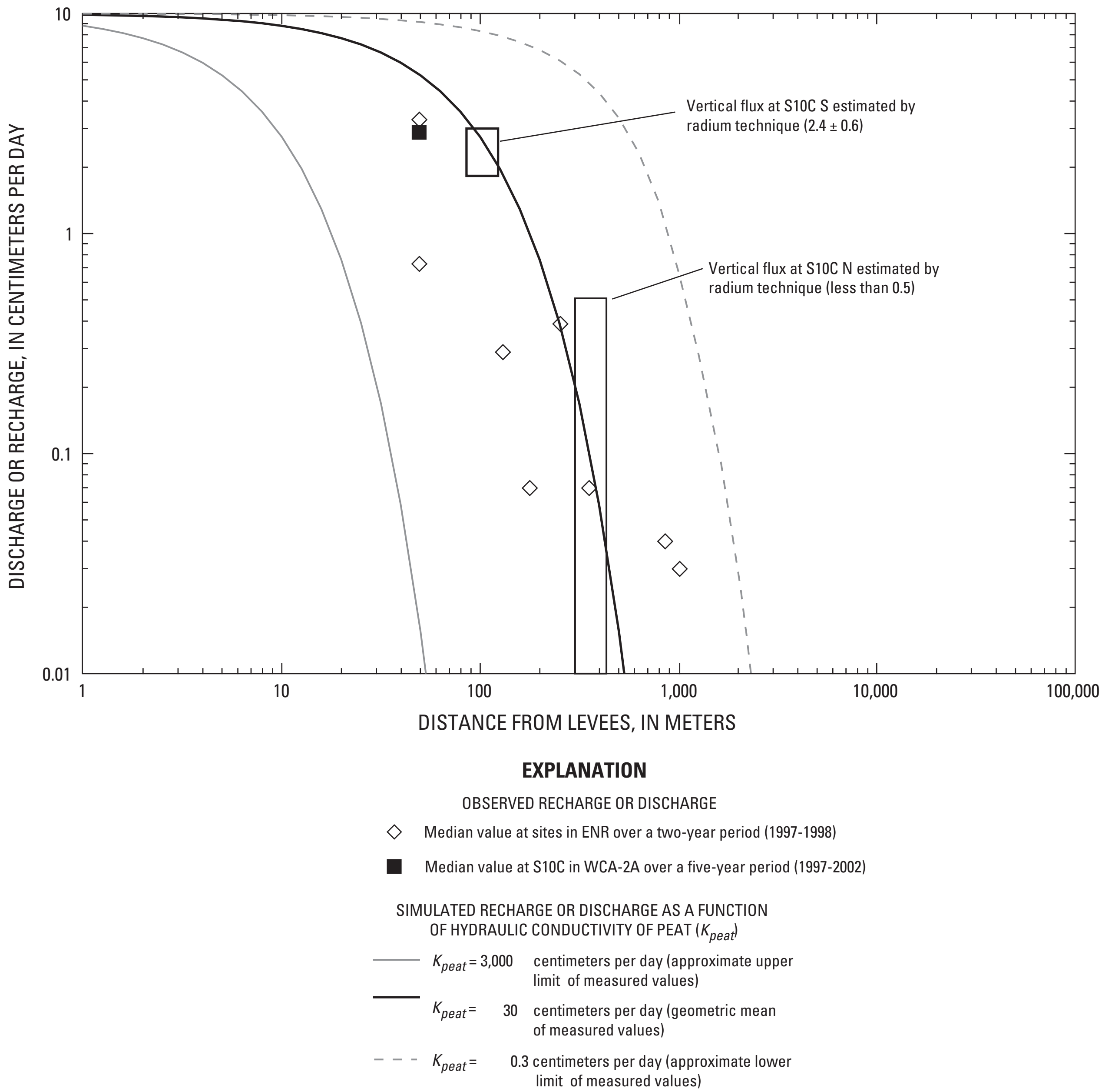


Figure 16. Magnitude of observed and simulated discharge or recharge fluxes at sites in the Everglades Nutrient Removal Project (ENR) and at S10C in Water Conservation Area 2A (WCA-2A), in relation to distance from the levees, and vertical fluxes estimated by radium technique (using ^{223}Ra) at S10C S and at S10C N. Height and width of boxes represents uncertainty in vertical flux determined by radium technique and distance from levee, respectively. Modified from figure 8, this report.

within adjacent wetlands is generally confined to within a kilometer (Harvey and others, 2004). Municipal pumping wells appear to be important at greater distances (Wilcox and others, 2004), but in general there is comparatively little information about recharge and discharge in the vast areas of the Everglades interior.

Recent measurements of hydrogen and helium isotopes in ground water beneath the interior areas of the Everglades have provided new insights about interactions between surface water and ground water in these remote areas. For example, ground waters in the top 30 meters of the surficial aquifer in the southern Everglades have isotopically determined residence times that range from years to decades in the shallow aquifer, but ground water in the deeper parts of the aquifer is much older (beyond the detection range for these isotopes) (Price and others, 2003). Recharge and discharge fluxes across the surface of the interior wetlands have recently been estimated by modeling vertical transport of naturally occurring, short-lived, radium isotopes in peat pore water (Krest and Harvey, 2003). Another method to determine recharge and discharge fluxes across the peat surface is to measure the gradient in hydraulic head vertically through the peat and combine those data with bail-test estimates of the hydraulic conductivity of peat as a means to compute recharge and discharge fluxes (Harvey and others, 2004). That approach indicated relatively high values of recharge and discharge (on the order of cm per day) that could not be explained by the effects of levees on ground-water flow. Other factors that could control recharge and discharge in the remote interior areas of the wetlands include seasonal and interannual variation in precipitation, as well as the effects of surface-water gravity waves created by pumping and spillway operations. For example, water releases through levee spillways cause the propagation of gravity waves toward interior areas of the wetland, which appear to drive alternating periods of discharge and recharge as they pass by locations in the interior wetlands (Harvey and others, 2004). Use of ground-water geochemical tracers could further improve understanding of recharge and discharge in the Everglades. Improved models of surface-water and ground-water exchange are also needed as the basis for improved water-quality models.

For the present investigation, concentrations of naturally occurring tritium were measured in ground water of Water Conservation Area 2A and used as the basis for quantifying long-term average recharge and discharge in the remote areas of the WCA-2A basin interior. The modeling of water and tracer flow was intentionally kept simple so that chemical submodels could be easily added in the future to address water-quality issues in the Everglades. A second objective was therefore to take a step towards evaluating whether the simple model of coupled surface-water and ground water flow used here could be used in the future as a valid framework for modeling solute transport and reaction processes in the Everglades.

Ground-Water Sampling and Chemical Analysis

Tritium was measured in ground water from wells at seven sites in WCA-2A (fig. 17). Six of the sites (F1, F4, E1, E4, U3, and S7E) are in the interior of the wetland where research wells had been emplaced in the underlying limestone and sand aquifer. Each site has two to six wells with depths ranging from 2 to 37 m below the ground surface. Site S10C has wells at three depths and is on the Hillsboro levee at the northern boundary of WCA-2A. Each site also had a research platform and surface-water stage recorder, many of which were set up more than a decade ago by the SFWMD for the purpose of establishing a "nutrient-threshold" for water in the central Everglades.

Details about the construction of wells and their emplacement are presented in an earlier section of this report and in Harvey and others (2000) and Harvey and others (2002). Before obtaining ground-water samples, all wells were purged at rates ranging from 0.5 to 3 gal/min until three well volumes had been pumped, or longer if necessary for measurements of water-quality parameters (temperature, pH, specific conductivity, oxidation-reduction potential, and dissolved oxygen) to stabilize in a flow cell attached to the discharge line. After purging, ground-water sampling began by pumping at a rate of approximately 0.25 gal/min with a peristaltic pump through pre-cleaned 6-m sections of flexible tubing.

Ground-water samples were analyzed for a number of constituents. All of the chemical data collected from WCA-2A wells after 1998 are included in Appendixes 19-21 of this report. Only collection and analysis of tritium and $^3H/^3He$ samples are discussed in this report. Unfiltered ground-water samples for tritium analysis were collected in 500- or 1,000-ml glass bottles with polyseal caps in September 1997, January 2000, April 2000, September 2000, and September 2001. Samples were sent to the Tritium Laboratory at Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, Fla., where tritium was measured by internal gas proportional counting of H_2-gas followed by electrolytic enrichment and liquid scintillation counting. Accuracy of these low-level tritium measurements is approximately 0.1 tritium unit (TU) (0.3 pCi per liter of H_2O). The average standard deviation of replicate measurements reported by RSMAS for this investigation's samples was approximately 0.3 TU. The sum of accuracy and average uncertainty (0.4 TU) was used as the best estimate of an MDL, which separates field measurements of tritium into two classes: samples with greater than 0.4 TU have a high probability of containing some relatively young (less than 50 years since recharge) ground water, but samples with less than 0.4 TU have a high probability of containing a dominant component of much older, "tritium-dead" ground water. Further details of tritium analysis and interpretation are available from the RSMAS Tritium Laboratory (University of Miami, 2003).

Several ground-water samples were collected for $^3H/^3He$ age-dating in September 1997. These samples were analyzed at the Lamont-Doherty Earth Observatory, New York. Details

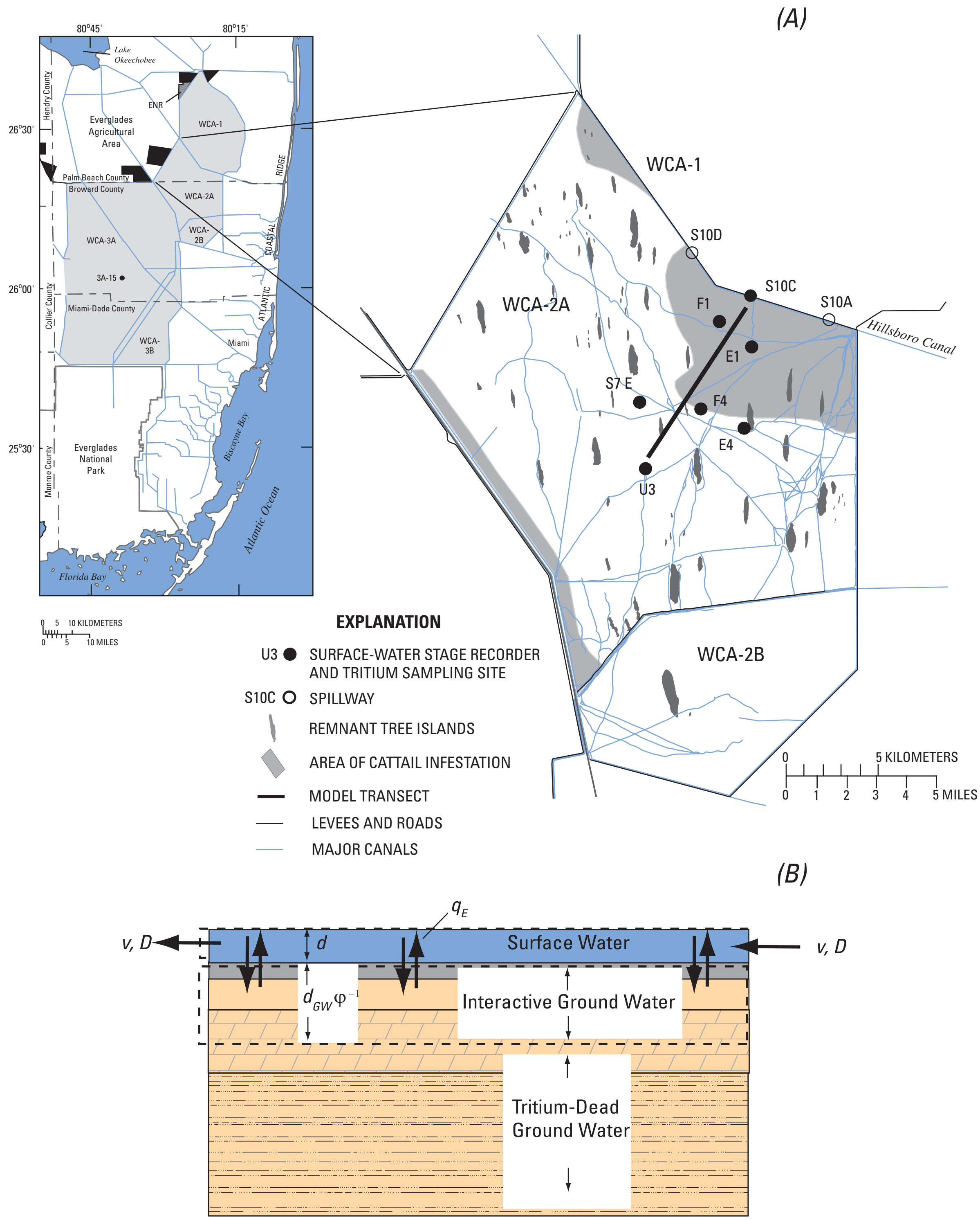


Figure 17. Maps and schematic diagrams associated with model for tritium transport in Water Conservation Area 2A (WCA-2A), central Everglades, south Florida, showing *(A)* locations of monitoring wells sampled for tritium in relation to model transect, and *(B)* conceptual flow system showing model variables v, surface-water velocity; D, longitudinal dispersion in surface water; d, surface-water depth; d_{GW}, water storage depth in ground water; φ, peat and/or aquifer porosity; and q_E, water exchange flux.

of sample collection, handling, and analysis are available from the USGS Reston Chlorofluorocarbon Laboratory (U.S. Geological Survey, accessed April 14, 2004). Although the results of $^3H/^3He$ analysis provide more specific information about the residence time of the water sample in the aquifer, the collection of samples and measurement of $^3H/^3He$ are more problematic than the sample collection for and measurement of tritium. These problems include natural degassing processes in the aquifer and bubble capture in the sample, as well as assumptions and corrections associated with the input of terrigenic ^3He to the sample (Schlosser and others, 1998).

Coupled Model of Surface Water and Ground Water Flow

The purpose of the tritium measurements and transport modeling was to estimate average (decadal timescale) recharge and discharge fluxes of water in the interior wetlands of WCA-2A. Tritium was generally only detectable in a shallow layer of fresh ground water near the top of the surficial aquifer. The layer of ground water that is actively exchanged with surface water on a decadel timescale is referred to as "interactive" ground water. It lies above a thicker layer of relict sea water in the lower part of the aquifer that dates from an earlier geologic period of higher sea level stand (Harvey and others, 2002). The model considers the depth of water storage and average residence time of ground water in that interactive layer, as well as several other parameters (tritium concentration in rainfall, and average water depth, velocity, and longitudinal dispersion in surface water). Average recharge and discharge fluxes over the 50-yr simulation period are calculated from modeling results.

The USGS numerical code OTIS (One-dimensional Transport with Inflow and Storage) (Runkel, 1998) was used for the tritium transport simulations. Although developed for streams, the OTIS code is general enough to be applied anywhere that surface-water transport characteristics are significantly affected by mass transfer into and out of storage reservoirs. For example, OTIS was recently used to simulate transport through waste water treatment wetlands in Florida (Martinez and Wise, 2003) and solute transport through wetlands of Everglades National Park (Harvey and others, 2005). For the present case the model simulates transport and decay of tritium in surface water in WCA-2A and exchange of tritium with ground water that occurs as a result of recharge and discharge. Characteristics of long-term averaged average surface water flow velocity and depth, along with measurements of the vertical distribution of tritium in an aquifer with known porosity, along with the well known decay rate of tritium, are the principal constraints that allow recharge and discharge to be determined.

Tritium transport was modeled along a 12-km transect of unit width that extends from the northern boundary of WCA-2A and WCA-1 (near site S10C) into the center of WCA-2A. The transect is roughly oriented parallel with the principal surface-water flow path which is toward the southwest in WCA-2A (Harvey and others, 2002). Figure 17B illustrates the major components of the model schematically. The governing equations for the present investigation are presented below. Note that the variables of a typical application of the OTIS model in a stream (Runkel, 1998) are recast following a derivation that uses "exchange flux" in the formulation of the mass transfer terms between surface water and the storage zones (Harvey et al., 1996). The equations for stream and storage zone are as follows,

$$\frac{\partial C}{\partial t} = -\frac{Q}{w \cdot d}\frac{\partial C}{\partial x} + \frac{1}{w \cdot d}\frac{\partial}{\partial x}\left(w \cdot d \cdot D \frac{\partial C}{\partial x}\right) + \frac{q_E}{w \cdot d}\left(C_{GW} - C\right) - \lambda \cdot C \quad , \qquad (15)$$

$$\frac{\partial C_{GW}}{\partial t} = \frac{q_E}{w \cdot d_{GW}}\left(C - C_{GW}\right) - \lambda \cdot C_{GW} \, , \qquad (16)$$

where Q is the average volumetric flow rate of surface water through the wetland [L^3/t]; t is time [t]; x is distance [L]; C is the concentration of tritium [TU] in surface water; C_{GW} is the concentration of tritium [TU] in 'interactive' ground water layer defined as the layer of shallow ground water that undergoes exchange with surface water due to alternating periods of recharge and discharge; D [L^2 t^{-1}] is the longitudinal dispersion coefficient in surface water; w [L] is the width of the modeled cross-section in surface water and ground water; d [L] is the average depth of the surface water; d_{GW} [L] is the average depth of water storage in the layer of interactive ground water; λ[1/t] is the first-order coefficient for radioactive decay of tritium in surface water and ground water (1.8 x 10^{-9} s^{-1} or 5.6 % per year); and q_E [L^2 t^{-1}] is the coefficient describing bi-directional exchange that occurs between surface water and ground water by vertical fluxes (recharge and discharge) across the ground surface. The units of exchange flux can be interpreted physically as a volume of water exchanged per unit time, per unit length along the model domain in the direction of surface water flow.

Application of the model involves adjusting the parameters of the model to fit measured tritium data. Among the ground-water parameters, calibration is simplified because depth of ground water storage, d_{GW}, is independently specified from the tritium observations. Note that ground-water residence time is uniquely related to depth of water storage (multiplied by transect width) and divided by a water exchange flux,

$$q_E = \frac{d_{GW}\, w}{t_{GW}}. \qquad (17)$$

As a result, the residence time is the only ground-water parameter that need be adjusted to fit observed tritium data.

Average recharge and discharge fluxes (in units of $L^3 L^{-2} t^{-1}$ or simply $L t^{-1}$) are both estimated by dividing the exchange flux by the transect cross sectional width, *w*, as shown,

$$\text{recharge or discharge} = \frac{q_E}{w}. \quad (18)$$

Note that for the present model of flow through central WCA-2A that the flow system is wide enough that transport can be assumed to be invariant with small to moderate changes in width. A "transect" model of unit width ($w = 1$) is therefore appropriate, which results in estimates of recharge and discharge that are both equivalent to the water exchange flux, q_E.

Model Initial and Boundary Conditions

The simulation started in 1953, just before significant bomb testing began and when tritium in precipitation was relatively low. The initial and boundary conditions that were needed include specification of an upstream boundary condition for tritium in surface water, and specification of the initial concentration of tritium throughout surface water and shallow interactive ground-water at the start of the simulation. In the mid 1950's, tritium levels increased substantially in precipitation worldwide due to the advent of nuclear bomb testing. Tritium peaked in precipitation in 1963 and has decreased slowly ever since. The upstream boundary condition for our simulation (tritium concentration in surface water at the upstream location where water inflow occurs to the wetland transect) was prescribed on the basis of estimates of tritium in precipitation at Miami, FL. The initial conditions for the simulation were determined by initializing all surface-water and ground-water concentrations with the tritium concentration in precipitation in 1953, and then following the procedure of Runkel (1998) by running the model until steady concentrations were achieved at all locations.

Tritium data were available for Miami from 1964 to 1991 and from 1996 to 2001 (IAEA/WMO, 2001). Because ground water with a decadal-scale residence time would not be expected to reflect the monthly variations in tritium concentrations that affect precipitation, the tritium data for precipitation were averaged annually (weighted by monthly precipitation) to smooth the data record. For years without tritium measurements in Miami, the values were calculated based on a linear regression approach using the longer record of measurements from Ottawa, Canada (IAEA, 1981). Tritium values used for the years 1963 to 1991 and 1996 to 2001 were the annual averaged of the monthly measured values in Miami (Fig. 18). Annual mean values shown in figure 18 for the years prior to 1963, and the years 1992 to 1994 were determined from a regression of Miami tritium on tritium data from Ottawa (log [Miami tritium] = 0.9826[Ottawa tritium] – 0.8920, $r^2 = 0.96$). Tritium was not measured in either city in 1995, so the 1995 tritium value for Miami was estimated by linear interpolation between estimates for 1994 and 1996 (value for 1995 shown in figure 18 as an x).

Model Sensitivity Analysis

Before applying the model to simulate the field data, a "base" simulation was needed with rough, order-of-magnitude estimates of parameters, for the purpose of exploring model behavior and sensitivity. Results of sensitivity analyses would be important for testing assumptions of the model and guiding the final simulations to quantify recharge and discharge. An average surface-water velocity (0.5 cm s^{-1}) and depth of surface water (0.3 m) were selected to represent long-term average values for the base simulation (Harvey and others, 2002; Rybicki and others, 2002). A preliminary estimate of the depth of water storage in the interactive layer of the aquifer was based on observed depths of the layer of freshwater that overlies the much older relict seawater in the aquifer (Harvey and others, 2002). An initial estimate of exchange flux was calculated (using Equation 17) to be consistent with a modeled ground-water residence time on the order of decades. Table 7 contains the initial parameter estimates used in the base simulation for sensitivity analyses.

Sensitivity of the model results to individual parameters was tested by adjusting parameters of the base simulation one at a time by a factor of 2 and re-running the model. Figure 19 shows an example of how tritium concentrations in ground water are affected by varying the exchange flux across the ground surface. Overall results of the sensitivity analysis are summarized in Table 8. The Root Mean Squared Error (RMSE) of tritium concentrations in the interactive ground-water zone was calculated for each new simulation with relation to the base simulation. The RMSE is a measure of the absolute difference in the base simulation and new simulation results caused by the parameter change. The results show that the modeled tritium concentrations in shallow interactive ground water were primarily sensitive to two parameters, d_{GW} and q_E (Table 8). The sensitivity to surface-water velocity and longitudinal dispersion in surface water are minor in comparison. Since d_{GW} is constrained by the observations of tritium and since this parameter only appears in the model in ratio with q_E , only the model ground-water residence time ($t_{GW} = (d_{GW}\, w) / q_E$), needed be adjusted to achieve a final model fit to tritium data because all other parameters were either relatively insensitive (surface-water velocity v and longitudinal dispersion *D*), or fixed ($w = 1$).

Justification for Model Simplifications

One of the most important model simplifications is that temporally and spatially averaged recharge must equal discharge. This simplification is reasonable if 1) temporal averaging is long enough that changes in water storage in the wetland are negligible, and 2) if all water that is recharged across the wetland ground surface is eventually discharged across the same surface. With regard to assumption 1), temporal averaging of the water balance in WCA-2A over decades is almost certainly long enough that changes in water storage in the wetland can be ignored. With regard to 2), there is thought to be a

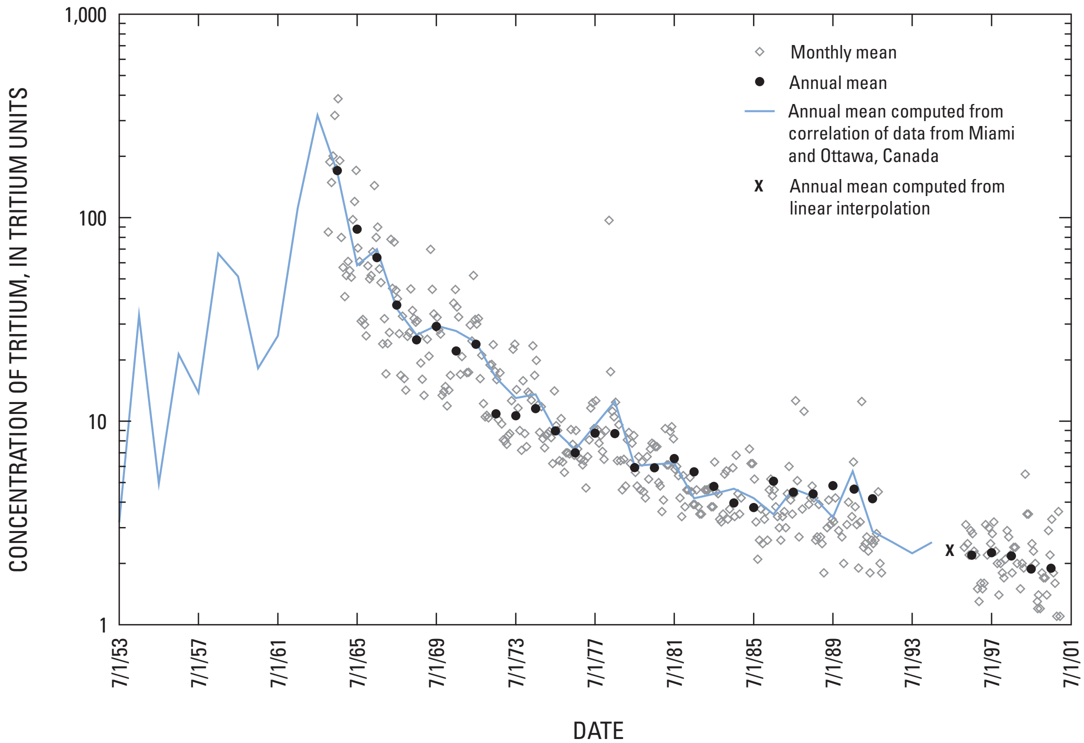


Figure 18. Mean annual tritium concentrations in precipitation estimated for Miami, Florida. Data from International Atomic Energy Agency/World Meterological Organization, 2001, and International Atomic Energy Agency, 1981.

Table 7. Parameter estimates used in the base simulation run of a tritium transport model in Water Conservation Area 2A, central Everglades, south Florida.

[cm/s, centimeters per second; m, meters; m^2/s, square meters per second; cm/d, centimeters per day; s, second

Parameter	Value
Surface-water velocity, v	0.5 cm/s
Depth of surface water, d	.30 m
Longitudinal dispersion in surface water, D	.01 m^2/s
Depth of shallow interactive ground water, d_{GW}	1.9 m
Water exchange flux across ground surface, q_E	.2 cm/d
Tritium decay rate, λ	1.8 x 10^{-9}/s

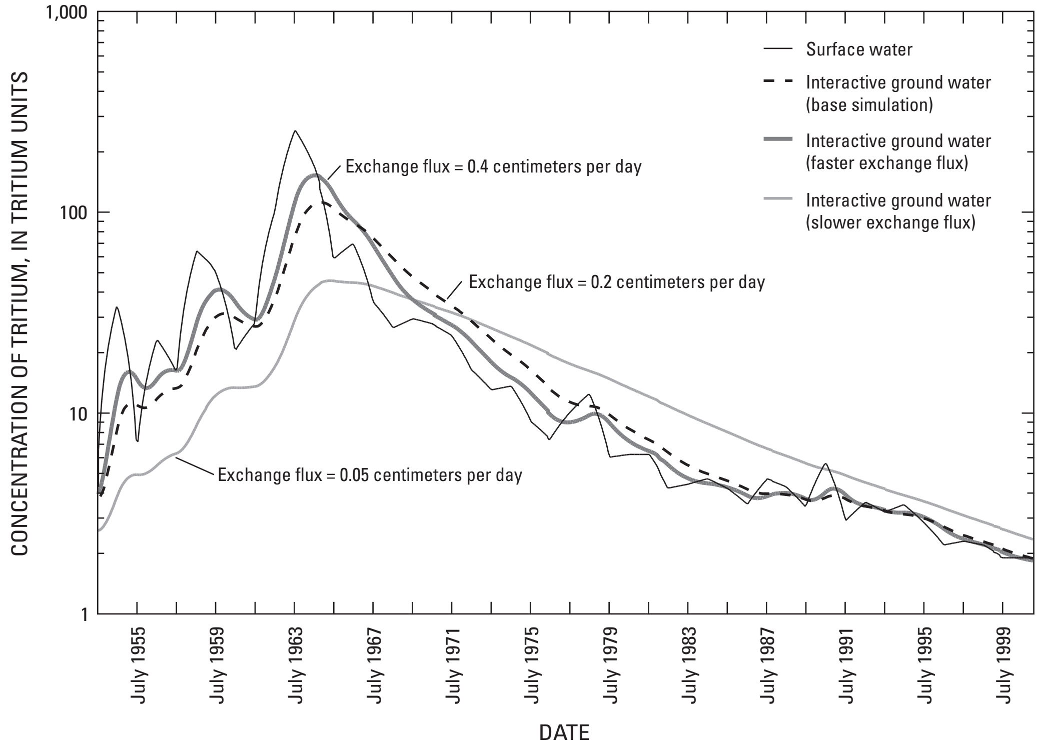


Figure 19. Sensitivity of the tritium transport model for WCA-2A, central Everglades, south Florida, to changes in the exchange flux, q_E, between surface water and the layer of shallow interactive ground water.

small "net recharge" flux over the long term in WCA-2A due to very slow transport to ground water areas outside WCA-2A, but that flux is thought to be mainly important near the eastern boundary of WCA-2A and, when averaged over WCA-2A as a whole, the net flux is thought to represent only a small difference between the much larger recharge and discharge fluxes across the wetland ground surface (Harvey and others, 2002).

Our use of a model that does not allow for horizontal flow in ground water also needs to be justified. Also needing justification is the decision to average parameters spatially along the transect even though the model allows for horizontal spatial variation in ground-water storage, residence time, and water exchange flux parameters. For example, the choice was to either account for horizontal spatial variation in parameters by implementing 'subreaches' within the model, each with different parameters. Or, if spatial variation is minimal or is random, reach-averaged values of the parameters could be determined for a single reach. The second choice was selected as being most reasonable for this model of surface-water and ground-water interactions in WCA-2A. Several considerations were important, including a consideration of the timescales of the various processes and the form of the spatial variability. Those considerations are summarized as follows; 1) horizontal ground-water velocities in WCA-2A (~0.02 cm d^{-1}) from Harvey and others (2002) indicate that the residence time of horizontally flowing ground water in WCA-2A is on the order of hundreds of thousands of years, which is extremely slow relative to the timescale of tritium decay (12.43 years), the residence time of surface water along the transect (approximately 30 days), and the timescale of significant changes in the tritium concentration of precipitation (years); and 2) horizontal variation in the water exchange flux (based on variability of observed tritium profiles in ground water) do not appear to vary systematically along the transect.

We addressed the question of what is the appropriate level of simplification of our model by evaluating the sensitivity analysis results (Table 8) and evaluating variability of tritium measurements. It appears safe to ignore the effects of horizontal ground-water flow based on the relative timescales of surface-water and ground-water flow, tritium variation in precipitation, and horizontal movement of ground water. Also due to the relative timescales of flow and tritium decay, no longitudinal gradient is expected to develop in surface-water tritium. These comparisons explain the insensitivity of the model to the average velocity and longitudinal dispersion coefficient in surface water (Table 8). The question of whether to represent longitudinal variability in ground-water parameters in sub-reaches, or simply average that variability in a single reach, rested on the evaluation of measured tritium profiles in ground water; these data are presented in the next section. It is sufficient to say here that that evaluation supported use of a one-reach model with (horizontally) spatially-averaged parameters. It is important to note that the model's complexity could easily be expanded as needed for modeling other data sets.

Is further simplification of the model possible? Since the model is generally insensitive to average characteristics of surface water flow and transport, and because spatial variation in the measured tritium profiles can be appropriately averaged, the problem of estimating recharge and discharge in the central Everglades potentially reduces even further to the simple calculation presented in equation 17. Use of equation 17 instead of the full model depends on having independent estimates of average ground-water residence time and depth of water storage in the interactive layer of the aquifer. This simple procedure to calculate recharge and discharge fluxes will be especially useful for data such as that presented by Price and others (2003), where numerous independent estimates of ground-water residence time and depth of the interactive layer were determined by measurement of $^3H/^3He$ ratios in ground water in Everglades National Park. It should be emphasized that use of such a simple calculation as equation 17 to compute recharge and discharge in the Everglades is justified only because we demonstrated that tritium transport and decay in the interior areas of the Everglades are insensitive to rates of horizontal transport of ground water, as well as the insensitive to surface-water velocities and rates of longitudinal dispersion. Application in areas of the Everglades closer to its boundaries, or application with different tracers could invalidate use of equation 17.

Comparison of Measured and Modeled Tritium Concentrations

Tritium measurements from 25 wells at seven sites in WCA-2A are shown plotted as a function of depth in the aquifer in figure 20A. The data were temporally averaged because no clear temporal trends existed for samples collected over the four-year sampling period. Based on the results of the sensitivity analysis, and on the examination of residence times of surface water and ground water flowing horizontally in WCA-2A relative to the half life of tritium, horizontal transport of tritium both in surface water and ground water were expected to have minimal effects on vertical distribution of tritium in the aquifer. Therefore, tritium data from different locations in the wetland were combined by averaging spatially tritium values from similar vertical intervals of well-screen depth. Averaged data are shown in figure 20B. Tritium data for individual wells along with the spatially averaged tritium concentrations and standard deviations for four well-screen depth ranges (0–4.5 m, 4.5–9m, 15–18 m, and 34–37 m) are shown in figure 20B. As explained earlier, tritium measurements beneath the S10C levee were not included in the spatial averages.

The first important observation about spatially averaged tritium data is that reliable detections of tritium (>0.4 TU) were almost entirely restricted to wells less than 8 m deep (Fig. 20B). Average ground-water tritium concentrations were 1.8 T.U. in the shallowest depth range (0–4.5 m), 0.63 T.U. in the next deepest depth range (4.5–9 m), and below the M.D.L. in the two depth ranges in deeper ground water (15–18 m and 34–37 m) (Fig. 20B). Relatively high rates of ground-water flow beneath levees is a well studied phenomena (Swayze, 1988; Meyers and others, 1993; Genereux and Slater, 1999; Bolster and others, 2001; Sonenshein, 2001; Nemeth and Solo-Gabriele, 2003) that was also characterized locally in WCA-2A (Krest and Harvey, 2003; Harvey and others, 2004). Since the present goal was to quantify recharge and discharge in the interior areas of WCA-2A, tritium data beneath the levee were not used in modeling analysis. In an upcoming section we justify the assumption that horizontal flow of tritium in ground water from levee boundaries was not important to our analysis.

Table 8. Sensitivity of tritium transport model results (simulated tritium concentrations in ground water) due to factor-of-2 changes in input parameters.

Parameter	Root Mean Squared Error (change from base simulation)	
	Due to increase in parameter	Due to decrease in parameter
Depth of shallow interactive ground water, d_{GW}	236	235
Water exchange rate across ground surface, q_E	231	233
Surface-water velocity, v	3	6
Longitudinal dispersion of surface water, D	2.8×10^{-4}	1.4×10^{-4}

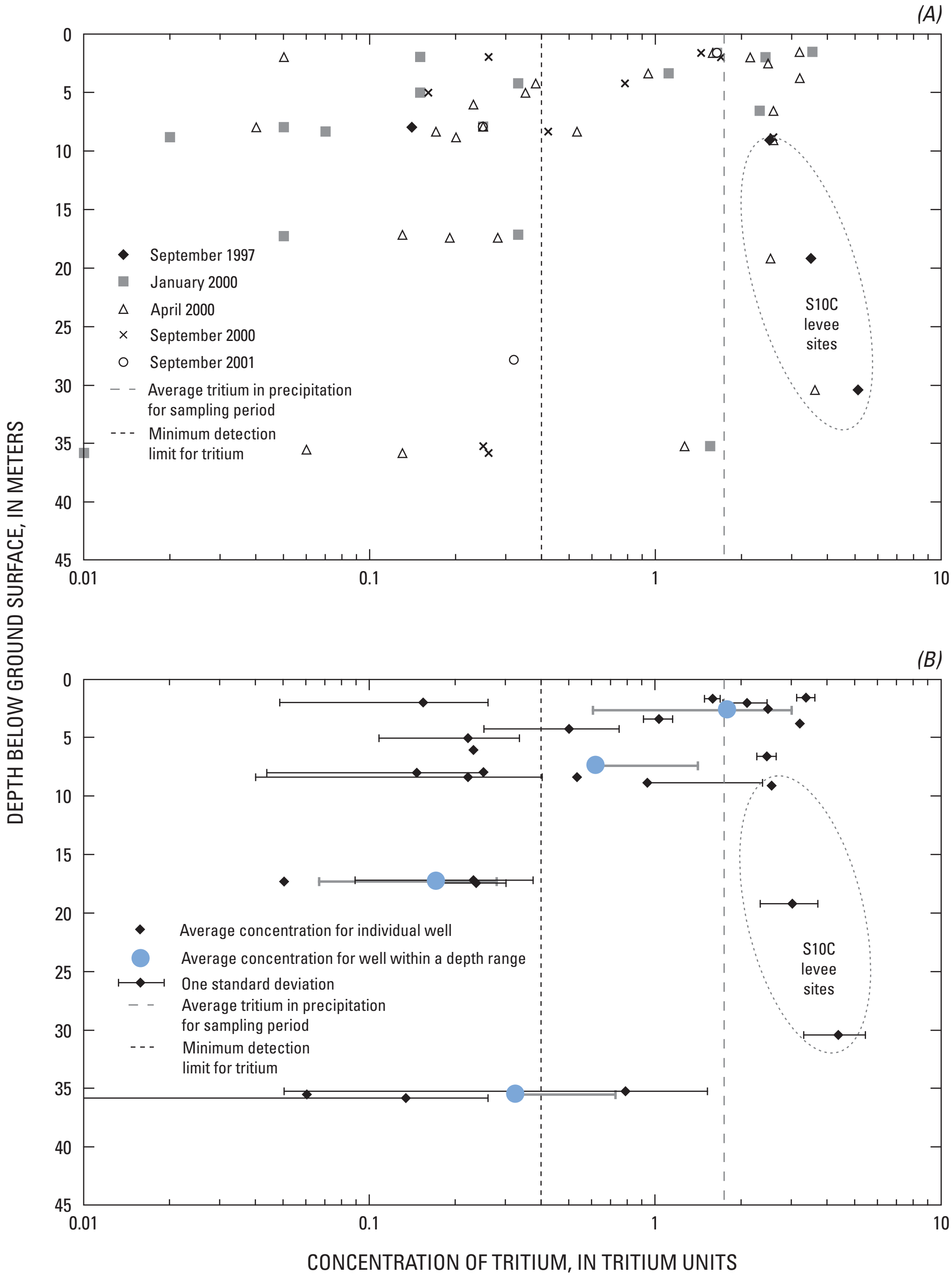


Figure 20. Tritium concentrations in relation to depth of wells for samples collected between September 1997 and September 2001 from 25 monitoring wells in Water Conservation Area 2A (WCA-2A), central Everglades, south Florida *(A)*, and average concentrations for each individual well and for wells in the same depth range (0-4.5 meters; 4.5-9 meters, 15-18 meters; and 34-37 meters), *(B)*.

Estimating Tritium Concentration and Ground-Water Storage

In order to determine the average tritium concentration throughout the top 8 m of interactive ground water, the depth-distribution of tritium and porosity must be taken into account. Tritium concentrations clearly decrease with increasing depth in the aquifer, but the exact form of the decline in tritium concentration is difficult to specify. The best method of depth averaging was presumed to be computing a depth and porosity-weighted average of tritium concentrations based on average tritium concentration at the midpoints of the two depth classes of wells. The shallow depth class ranged between 0 and 4.5 m with a midpoint of 2.25 m, and the deeper class ranged between 4.5 and 8 m with a midpoint of 6.75 m, respectively. The average concentration for each well class was assigned to all depths within the corresponding depth range. Furthermore, depths in the top 1 m (peat) of the aquifer were assigned a porosity of 0.98 to represent peat, while the layer between 1 and 8m (sandy limestone) were assigned a porosity of 0.3 (Harvey and others, 2002). The total storage depth of water that resulted from those calculations was 3.1 m in the top 8 m of the aquifer. Approximately one third of the water storage (0.98 m) was accounted for by water storage in peat. The resulting estimates of average tritium concentration in the 8-m layer of interactive ground water was 1.5 T.U. It should be noted that this estimate of average tritium concentration is uncorrected for mixing that may have occurred with deeper, tritium-dead ground water. Vertical mixing between those waters would cause both residence time (t_{GW}) and the depth (d_{GW}) of the relatively young component of ground water to be overestimated. The reasons for overestimation are that upward transport of tritium-dead water dilutes the average tritium concentration of young ground water with tritium free water, leading to overestimation of residence time for the component of young ground water. At the same time, downward transport of young ground water with tritium increases the apparent depth of interactive ground water. The approach we chose was to proceed with the modeling and accept the possible overestimation of t_{GW} and d_{GW}. Even if vertical mixing was later shown to be important, we relied on the fact that mixing would probably have little effect on estimates of recharge and discharge. That is because 1) the total mass of tritium in ground water remains unaffected by vertical mixing, 2) both residence time and depth are simultaneously overestimated if vertical mixing with tritium dead water occurs, and 3), since water storage depth and residence time in the interactive ground water layer appear in ratio in the calculation of exchange flux (equation 17), it is probable that vertical mixing would have little or no overall effect on our estimate of exchange flux. A later evaluation of the effect of vertical mixing was made possible by comparison of model estimated residence times with residence times estimated using measurements of $^3H/^3He$ ratios in several wells. Significant vertical mixing with tritium-dead water would be evident in shorter residence times estimated from $^3H/^3He$ ratios compared with model-estimated residence times obtained by fitting to tritium data. The results of the residence time comparison and the resulting interpretation of the importance of vertical mixing are discussed later in this paper.

Determination of Average Recharge and Discharge Fluxes

Tritium transport was simulated using fixed values of surface-water velocity, surface- water depth, and longitudinal dispersion in surface water (values given in Table 8). Figure 21 shows a range of simulation results using the following values of ground-water residence time, t_{GW} = 1, 3, 10, 30, 100, 300, and 1000 years. Figure 22 compares the results of those simulations with measurements of tritium in ground water categorized by well depth class. Although, there is wide variation in residence times associated with ground waters of a specific depth class, there is a tendency for shallow ground waters (< 4.5 m) to be associated with younger ages (< 100 years), and deeper ground waters (> 15-m) are consistently associated with modeled residence times greater than 100 years. The "best fit" simulation to the average ground water tritium concentration was determined to have a ground-water residence time of 90 years. The best fit simulation is not shown, but the close fit of the simulation with 100 year residence time is apparent in figure 23. Dividing the water storage depth in the layer of aquifer with interactive ground water that was determined earlier (3.1 m) by 90 years results in an exchange flux of 0.01 cm d^{-1}. As explained earlier, the values of spatially averaged recharge and discharge fluxes associated with the exchange flux are also 0.01 cm d^{-1}.

We suspected that the residence time of 90 years for shallow interactive ground water might be overestimated due to vertical mixing with deeper, tritium-dead ground water. Independent data were needed to gain further perspective and substantiate a final interpretation. Alternative estimates of ground-water age come from the few analyses of tritium-helium-3 ratios ($^3H/^3He$) that were possible for the sampled wells. There is a practical reason why $^3H/^3He$ may be a better tracer of residence time when available. It provides a better estimate of only the young component of ground water, without being affected by dilution with much older ground water. This is a consequence of using the parent/daughter isotopic ratio as the tracer, because the ratio $^3H/^3He$ is not diluted by upward mixing of tritium-dead ground water. Consequently the residence time is not overestimated. However, the samples are more difficult to collect without corruption and more expensive to analyze. As a consequence, our $^3H/^3He$ measurements were limited to 4 samples.

The average residence time of shallow ground water indicated by three of the $^3H/^3He$ analyses was 25 years (Table 9). The fourth analysis was from levee site S10C collected from the shallowest well (C) at a depth of 9 m. That water had a much younger age (approximately 2 years), which reflects the much higher driving forces for recharge on the up gradient

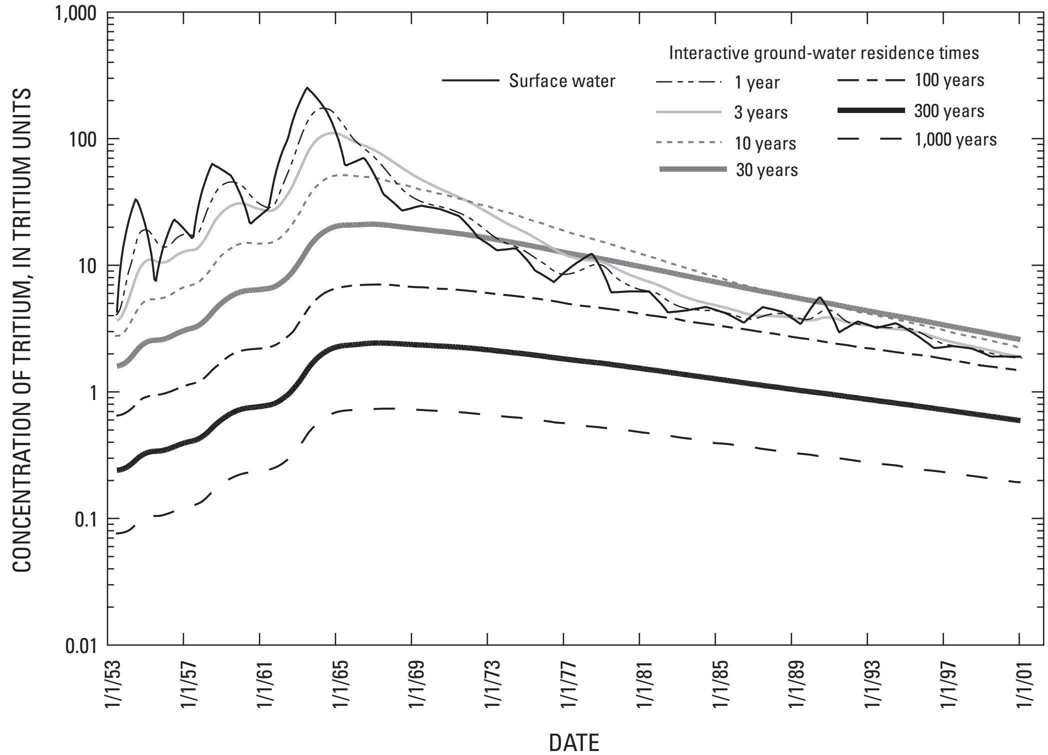


Figure 21. Simulated ground-water residence times in relation to measured tritium concentrations in ground water and concentrations of tritium in surface water (from precipitation data) for the interior wetlands of Water Conservation Area 2A (WCA-2A), central Everglades, south Florida.

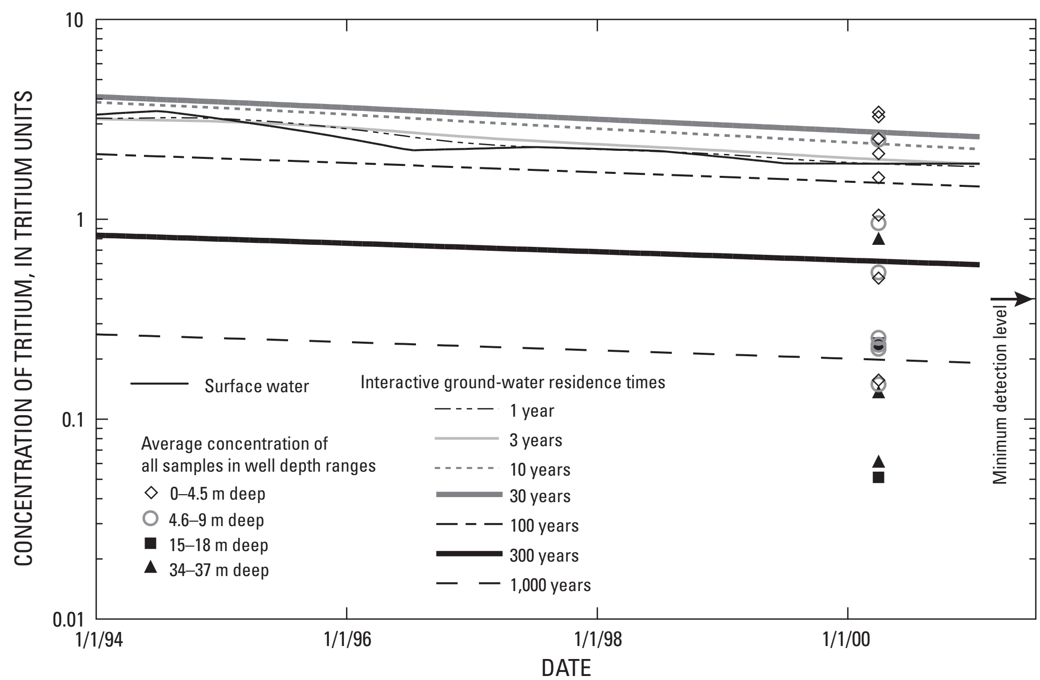


Figure 22. Simulated ground-water residence times in relation to measured tritium concentrations in wells in the interior wetlands of Water Conservation Area 2A, central Everglades, south Florida. Results from well sampling in September 1997, January 2000, April 2000, September 2000, and September 2001 were averaged and plotted for a single (midpoint) date in April 2000.

side of the levee near the S10C site that drives rapid ground-water flow beneath the levee (Harvey and others, 2002). This sample was collected too close to a levee to be representative of interior wetlands and was omitted from the calculation of average residence time in ground water of interior wetlands.

It is important to emphasize once more that the estimates of recharge and discharge from tritium modeling are considered reliable even though modeling of tritium overestimated ground-water residence time. That is because both ground-water residence time and water storage depth are simultaneously overestimated if vertical mixing occurs (that is, the total mass of tritium in ground water is unaffected by vertical mixing). Thus, the resulting overestimates of water storage depth and residence time in the interactive ground water will tend to compensate one another in the calculation of exchange flux (equation 17), with minimal effect on resulting estimates of recharge and discharge.

Tritium Model Compared with Other Estimates

Short-term estimates of recharge and discharge from interior areas of the Everglades were recently published (e.g. Krest and Harvey, 2003; Harvey and others, 2004; Harvey and others, 2005), and those fluxes show variability over timescales ranging across from weekly, monthly, seasonal, and interannual timescales. Longer-term (decadal) average estimates of recharge and discharge in interior areas of the wetland would be useful. The present paper addresses that need through application and testing of a coupled model of tritium transport and decay in surface and ground water of WCA-2A in the central Everglades. The form of the model not only permits estimates of recharge and discharge, but, through model sensitivity analyses and comparison with independent estimates of ground water residence time and horizontal flow rates of ground water and surface water, allows some basic assumptions about spatial variability across the wetland, dominance of vertical compared with horizontal flow in the wetland, etc, to be tested.

Tritium was detectable to a depth of approximately 8 m in the 60-m deep surficial aquifer beneath the central Everglades in WCA-2A. This contrasts with the results of Price and others (2003) who found detectable tritium to a depth of 30 m in Everglades National Park. Because of our testing and justifications, we can use the simplified approach of estimating recharge and discharge fluxes for the investigation by Price et al. using equation 17 and compare it with our results from the central Everglades. Since the residence time of shallow ground water (based on $^3H/^3He$ ratios) was similar in the two studies (approximately 25 years), the greater depth of recharge of young waters in the southern Everglades suggests that recharge and discharge fluxes are probably larger than in the central Everglades, by perhaps a factor of 3 or more. Much of the southern Everglades overlie the highly indurated limestones of the Biscayne aquifer, which is known for its very high hydraulic conductivity (Fish and Stewart, 1991). The north-central Everglades, on the other hand, overlie a sandier unit of the surficial aquifer which has a lower hydraulic conductivity (Harvey and others, 2002). Peat thickness, which affects vertical water movement by retarding flow, is generally less in the southern Everglades compared with the north-central Everglades. Greater hydraulic conductivity in the surficial aquifer and thinner peat support the expectation that recharge and discharge fluxes could be a factor of 3 higher in southern Everglades. However, this preliminary comparison of recharge and discharge fluxes remains a hypothesis at this stage until more estimates of recharge and discharge fluxes in the southern Everglades become available.

An exchange flux of 0.01 cm/d^{-1} is an order of magnitude smaller than independent estimates based on modeling naturally occurring, short-lived isotopes of radium (Krest and Harvey, 2003) and Darcy-flux calculations made for the years 1997–2002 (Harvey and others, 2004). There are several possible explanations for this difference. One is uncertainty in

Table 9. Ground-water residence times as estimated from analysis of tritium-helium ratios in samples collected during September, 1997 from three wells in central Everglades, south Florida. Well locations are shown in figure 17 and figure 4.

Well	Well depth, in meters	Residence time, in years +/- 1 standard deviation
U3-GW4	1.6	21 +/- 1
U3-GW3	8.0	25 +/- 15
F1-GW4	2.0	35 +/- 1
S10C C	9.1	2 +/- 2

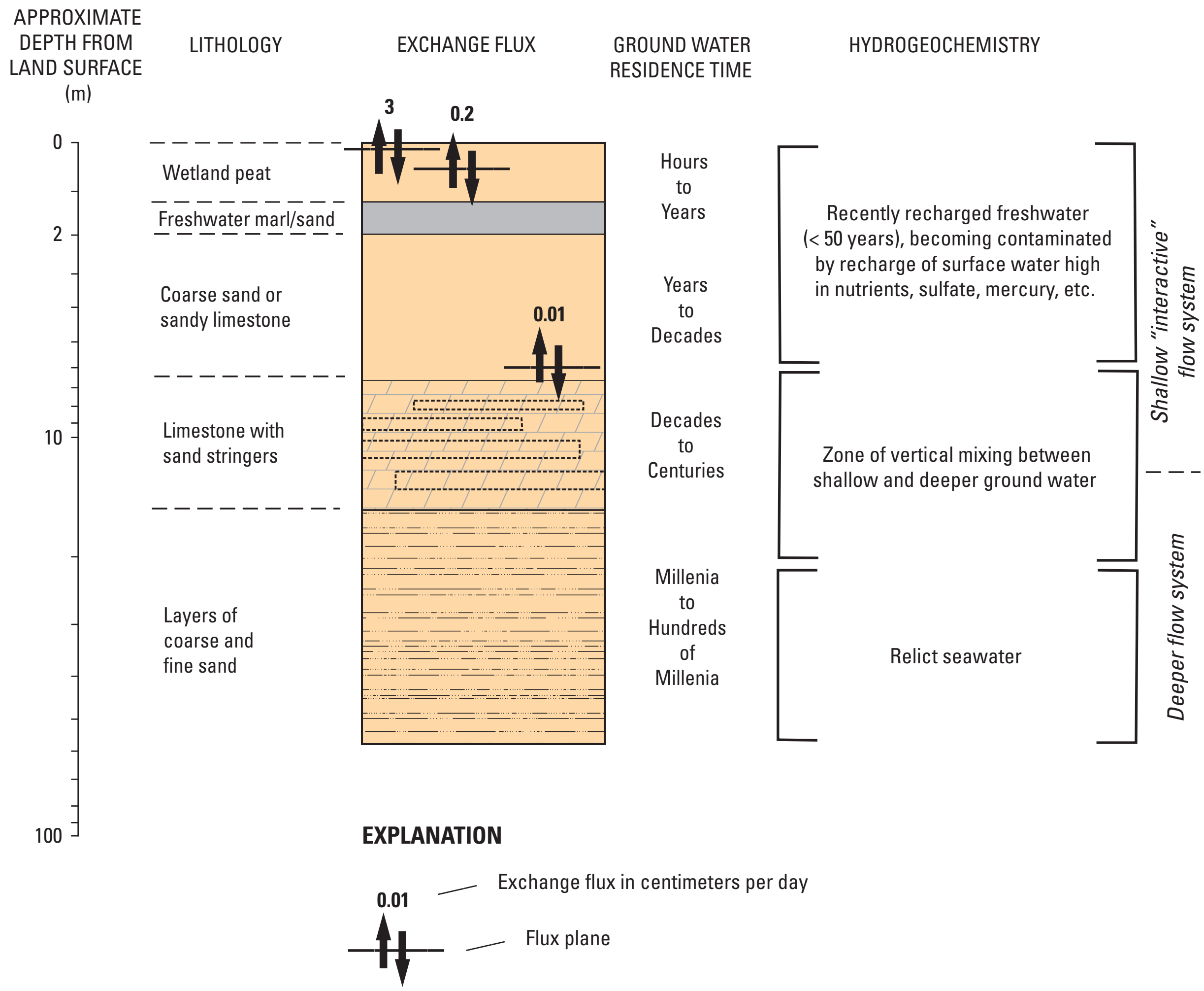


Figure 23. Summary of lithology, water exchange fluxes, residence time of ground water, and hydrogeochemistry in the interior wetlands of Water Conservation Area 2A, central Everglades, south Florida. The depths of the three flux planes where exchange flux was estimated are 0.03, 0.66, and 5.25 m. Sources of information and greater detail about vertical fluxes and residence time estimates are included in Table 10. More detailed information about lithology and hydrogeochemistry is available in Harvey and others (2002).

assuming that actual tritium concentrations in surface water are equal to the measured tritium in precipitation. If discharge of deep ground water to the canal bottom at the upstream end of the WCA-2A flow system is substantial, then tritium in Everglades surface water may have been overestimated. The potential effect of this error was investigated by reducing the size of the bomb spike in our simulation (by about 50%), which would decrease the ground-water age estimate, from about 90 to 50 years. The effect on the exchange flux estimate is to increase recharge and discharge flux estimates by about a factor of 2, which is not nearly sufficient to explain an order of magnitude difference between the tritium-based estimate and the other independent estimates.

The order of magnitude differences between estimates of recharge and discharge made using long (ground water tritium modeling) and short (radium modeling in peat pore water and Darcy flux calculations) timescale methods is probably not the result of bias or error in any method. Instead of great inaccuracies in one approach or the other, we believe that the order of magnitude disagreement between tritium modeling and Darcy flux calculations is more likely the result of comparing techniques that are sensitive to different timescales of interactions between surface water and ground water. The relatively short timescale calculations based on measurements in peat are good at characterizing high fluxes that occur periodically but are short-lived and switch direction frequently (Harvey and others, 2004). Those short-lived fluxes are mainly effective in causing exchange between wetland surface water and peat pore water. Tritium modeling in shallow ground water is insensitive to large and short-lived fluxes that frequently switch direction, because those events only have a minimal effect on tritium in ground water. Instead, tritium modeling is sensitive to the annual and longer term fluctuations associated with factors such as climatic variability, because those longer timescales are effective in exchanging surface water with ground water at depths up to 8 m in the surficial aquifer. Thus, we believe that it is possible for two independent estimates of recharge and discharge to differ substantially because of different averaging timescales. The correct estimate to use for any particular investigation will depend on the particular problem of interest and its associated timescale. For example, recharge and discharge operating on short timescales could be highly relevant to understanding transport, storage, and re-release of phosphorus from peat pore water. In contrast, longer timescale interactions between surface water and the sand and limestone aquifer could be important in understanding the extent to which relict sea water and its associated dissolved salts are being mobilized deep in the aquifer and discharged to surface water.

Comparison of Results from Different Methods of Estimating Recharge and Discharge

Each of the new techniques for quantifying recharge and discharge in the Everglades that has been discussed in this report has advantages and disadvantages. The first new technique was Darcy-flux calculations. Darcy-flux calculations demonstrated the changing direction of recharge and discharge over timescales ranging from days to weeks, to seasons, and beyond. Another result was that time-averaged values of recharge and discharge in the interior wetlands were much larger than could be explained by a simple hydrogeologic model for WCA-2A (that only could account for recharge and discharge associated with ground-water flow beneath the levees located at the boundaries of WCA-2A). The main disadvantage of the Darcy-flux approach was the significant uncertainty associated with estimating vertical hydraulic gradients and vertical hydraulic conductivities in peat. An additional disadvantage was the high cost of installation of wells and installation and maintenance of surface-water level recorders at multiple sites. Although the installation of research wells may not be justified strictly for hydraulic measurements, it should be noted that the same wells serve the dual purpose of providing ground-water samples for a broad suite of water-quality parameters, including constituents that are potentially useful as environmental solute tracers (e.g. radium and tritium). Because of the uncertainties in the measurements, the resulting estimates of recharge and discharge were considered to be relatively uncertain until independent confirmation was available.

A second level of evaluating methods is a comparison between results of different methods. Seepage meters performed well in some parts of the Everglades (Sonenshein, 2001; Choi and Harvey, 2000), but as explained in Harvey and others (2000), the relative inaccessibility of research sites in WCA-2A, in addition to differences in the hydraulic properties of the peat compared with other parts of the Everglades (Harvey and others, 2004), meant that seepage meters were not an option for the present investigation in WCA-2A. The next available method was modeling vertical transport of short-lived radium isotopes in peat (Krest and Harvey, 2003). Radium modeling in peat averages recharge and discharge fluxes over timescales similar to the decay constants of the isotopes (days to weeks). A disadvantage of this technique was the large amount of aqueous and solid-phase analyses for radium isotopes that were necessary to achieve one-time estimates of recharge or discharge at just a few sites. There is ongoing work, however, to simplify these analyses. Nevertheless, a direct comparison of the resulting water fluxes with Darcy-flux calculations was possible using the radium technique, and was discussed in detail in a previous section of this report. A final comparison involved results based on modeling of tritium transport and decay in the limestone/sand aquifer beneath the Everglades (detailed in a previous section of the present report). This approach provided estimates of recharge and discharge that are averaged over decades due to the longer timescale of tritium decay. At a minimum the technique requires several wells, with short screens emplaced at different levels of the aquifer to characterize the vertical distribution of tritium. Another disadvantage of tritium modeling is that uncertainties of modeled ages of ground water increase as the amount of time increases since the bomb pulse of the late 1950s and 1960s. However, the ability to quantify and interpret $^3H/^3He$ has improved the reliability of the overall method.

The basis of comparison between methods is the magnitude of the vertical exchange flux (q_E, defined earlier in this report), a parameter closely related to recharge and discharge in a system where both recharge and discharge occur as a flux across the same interface (wetland ground surface). In a wetland system such as the Everglades, the vertical exchange flux is generally a good estimate of both recharge and discharge because these quantities are linked both spatially or temporally. In other words, the exchange flux represents water that recharges the subsurface and then later discharges back to surface water. When recharge and discharge are averaged over relatively long spatial and temporal timescales in a very flat setting such as the Everglades, the difference between recharge and discharge (the "net" vertical flux) is usually a small quantity involving only that part of recharge or discharge which results from hydraulic communication with areas outside the WCA-2A basin. In WCA-2A there is evidence for a small net vertical recharge of water (Harvey and others, 2002), and that flux is considerably smaller than "total" recharge and discharge fluxes in WCA-2A. The estimate of net recharge that is included in table 2 is assumed to account for the small portion of the total recharge in WCA-2A that flows beneath levees out of the WCA-2A domain. Because net recharge is so small, the vertical exchange fluxes in table 10 can be interpreted as temporally and spatially averaged estimates of both recharge and discharge in WCA-2A (table 10).

Temporally and spatially averaged vertical exchange fluxes for the central part of WCA-2A were 0.2 cm per day for the Darcy-flux approach, 0.9 cm per day for the radium modeling approach in peat pore water, and 0.01 cm per day for the tritium modeling approach in ground water. A related study introduced a salt tracer (KBr) by injecting a tracer solution into surface water with arrival of the tracer measured at shallow depths in peat ranging between 1.5 and 15 cm deep (Harvey and others, 2005). That investigation determined an exchange flux of 3 cm per day. All of those estimates can be contrasted with results of the SFWMM, for which the time-averaged estimates of vertical exchange ranged between 0.03 and 0.1 cm per day depending on the particular simulation (table 10). Considered together, the estimates of exchange flux reported above range over two orders of magnitude. The remainder of this section discusses possible reasons for such a broad range of estimates.

Central to a comparison of results from different measurements of exchange flux is recognizing that each technique of vertical exchange has a unique timescale of averaging, depending on frequency and location (that is, depth) of measurements, and whether the measurements are made in peat pore water or in underlying ground water. Figure 23 summarizes the results discussed above. The respective averaging depths of the tritium modeling, Darcy-flux calculations, radium modeling, and Br tracer experiments are 5.25, 1, 0.66, and 0.03 m, respectively. These depths are illustrated as the flux planes shown in figure 23. Part of the difference in estimates of exchange flux is also attributable to factors such as the decay rate of the tracers used (days to tens of days for the short-lived radium isotopes and 12.4 years for tritium). As a

Table 10. Independent estimates of surface-subsurface water exchange fluxes in Everglades, south Florida.

[cm/d; centimeters per day; SFWMM, South Florida Water Management Model; –, not applicable]

Estimation technique	Measurement sites	Average magnitude of exchange flux (cm/d)	Depth of subsurface measurements used in estimation (m)	Minimum averaging timescale	Reference
Bromide tracer	Florida International University Shark Slough Flume "A" Everglades National Park	3	0.015 - 0.15	Hours	Harvey and others, 2005
Radium tracer	WCA-2A site U3	0.9	0.2 - 1	Weeks to months	Krest and Harvey, 2003
Darcy-flux	WCA-2A sites F1, F4, U3, E1, E4	0.2	2	Months during period 1997-2000	Harvey and others, 2004
SFWMM	WCA-2A, whole basin water balance "verification run"	0.1	–	Years (1991-1995)	SFWMD, 1999
SFWMM	WCA-2A, whole basin water balance "calibration run"	0.03	–	Decades(1979-1990)	SFWMD, 1999
Tritium tracer	WCA-2A sites F1, F4, U3, E1, E4, S7E	0.01	2 - 9	Decades(1953-2001)	this report

result, each technique is sensitive to a different temporal scale of variation in water exchange. For example, the technique based on modeling ^{224}Ra in peat pore water produced one of the highest estimates of exchange flux. That estimate appears to have been primarily sensitive to rapid reversals in vertical flow that drive short-term (daily to weekly) reversals in the direction of vertical exchange. Those short-term reversals are only effective in causing water exchanges between surface water and peat pore water. On the other hand, because of the longer half-life of tritium and because the sampling was done in the sand and limestone aquifer and not in peat pore water, results from modeling tritium transport are sensitive only to seasonal and longer-term components of exchange, which ignores the relatively high-velocity but short term components of exchange that are only effective in exchanging surface water with peat pore water. As a result, the estimate of vertical exchange produced by tritium modeling was two orders of magnitude lower than the estimate from ^{224}Ra modeling method in peat pore water.

Both the Darcy-flux calculations and SFWMM results are based on hydraulic computations using daily averaged measurements of water level, which makes the methods potentially sensitive to weekly to monthly timescale fluctuations associated with relatively frequent reversals in the direction of vertical flow between recharge and discharge (Harvey and others, 2004). Both the Darcy-flux and SFWMM measurement approaches depend on hydraulic head, which should respond very quickly to changing surface-water levels and energy potentials in ground water that drive flow into or out of the sediment. The relevant criteria involve calculations of the rate of pressure propagation through peat, and these calculations suggest that the equilibration time for hydraulic head in ground water following a change in surface-water head is on the order of minutes (Harvey and others, 2004). Spatial and temporal averaging of the SFWMM reduces the sensitivity of that modeling approach, because SFWMM results are typically presented as monthly or annual averages of daily estimates. When run on a decadal timescale (1979–1990) the SFWMM produced a smaller time-averaged exchange flux (0.03 cm per day) compared to when the model was run over a shorter (5-year, 1991–1995) time period (0.1 cm per day) (table 10). In addition, SFWMM calculations are made on a 2- x 2-mi grid, which smoothes hydraulic head values by averaging peaks and troughs in hydraulic heads associated with the movement through the wetlands of water pulses released by water-control structures. SFWMM results are therefore less sensitive to weekly to monthly timescale interactions between surface water and peat pore water and more sensitive to longer-timescale patterns of interaction with ground water of the sand and limestone aquifer. This dependence of the estimated exchange flux on spatial and temporal averaging scales is not new. Instead, it is consistent with results from an investigation in Wisconsin using the USGS ground-water flow model MODFLOW (Stoertz and Bradbury, 1989). Stoertz and Bradbury (1989) found that greater spatial and temporal averaging of hydraulic heads decreased the estimates of recharge and discharge. The order-of-magnitude differences in the exchange fluxes determined by using independent methods in WCA-2A do not imply that any particular estimate is “wrong.” Instead, each estimate provides information about the magnitude of recharge and discharge that is relevant to a particular timescale of fluctuating directions of recharge and discharge, and depth of water exchange in the subsurface. For example, the weekly to monthly timescale fluctuations in recharge and discharge that are detected by bromide tracer, radium modeling, and Darcy-flux calculations are mainly informative about exchange of surface water with peat pore water. Instead, the effectively longer-term averaging accomplished by modeling tritium in ground water, or by spatially and temporally avering hydraulic cacluations in the SFWMM, produces techniques that are only sensitive to exchange between surface water and deeper ground water in the aquifer underlying the peat and wetland.

Therefore, there is no single measure of recharge and discharge that can be applied for all research purposes in the central Everglades. However, some estimates are more appropriate than others to meet a particular objective. Methods that are sensitive to the short-term fluctuations that mainly cause exchange between surface water and pore water in the peat are most appropriate for models focused on water quality and ecology. For example, the higher values of recharge and discharge (table 10) are more appropriate for use with the Everglades Landscape Model (ELM) (Fitz and others, in press; also see South Florida Water Management District, 2002) or with Dynamic Model for phosphorus in STAs (DMSTA) (Kadlec and Walker, 1999). In those water quality simulation the effects of vertical water exchange between surface water and peat pore water (and associated solute transport and biogeochemical reactions) are highly relevant to water quality. In contrast, water-balance investigations that are averaged over large spatial scales or longer timescales (for example, simulations with SFWMM) probably can make better use of longer-term estimates (which are lower numbers) determined by ground-water measurements and modeling of tritium as an independent check on recharge and discharge fluxes used in the models. In those investigations, the net exchange flux is more relevant than the larger exchange fluxes that mainly affect water quality. An exception may be in regional simulations built upon the parameters of the SFWMM that also consider water quality. One example is modeling the fate of freshwater in the Everglades which is slowly increasing in its contents of total dissolved solids. Part of the problem is with the presence and operation of canals, which pierce the relatively low conductivity peat substrate to gain a direct hydraulic connection with the underlying aquifer which contains high concentrations of relict sea salt in its lower two thirds. Abrupt water level changes in the wetland basins of the Everglades and in canals that are the result of water management operations can increase the vertical hydraulic gradients that cause upward mixing of those salts. In most regional simulations of hydrology in the Everglades, the influence of vertical mixing on upward movement of salt into shallow ground water and surface water has not been considered.

Suggestions for Future Investigations

Due to water-management practices and agricultural runoff, surface waters in the central Everglades tend to be contaminated with excessive levels of nutrients, salts, and mercury (Harvey and others, 2002). In the past several decades the application of best-management practices on farmlands adjacent to the Everglades has helped improve the quality of water flowing into the Everglades. The retention of recharged surface water and its solutes for decades in shallow ground water could have legacy effects for the future, because contaminants that were recently recharged potentially could be returned very slowly to surface waters over a period of decades. Of particular importance could be the recharge of phosphorus over the past few decades, which potentially could be returned to surface water in the next few decades with discharging ground water even if the quality of agricultural runoff continues to improve. The likely timescale at which contaminants now stored in peat pore water and the limestone and sand aquifer are returned to surface water could be years to decades and longer. Our findings provide a reasonable hydrologic basis and the hydrologic part of a modeling framework to investigate the phenomenon of "contamination legacy effects" further. One possible result of improved modeling of contaminants would be quantification of how long the initial improvements in quality of water inflows to the Everglades will take to have the desired effect throughout the Everglades system. A second use of such models would be predicting the effects of higher "restored" flows in causing downstream propagation of contaminants from parts of the Everglades where they are currently stored to points downstream that currently have good water quality. It should be stressed that these ideas are preliminary, and that they need to be thoroughly tested by combining the hydrologic model presented here with biogeochemical data, along with further improvements in components of the coupled surface-subsurface-biogeochemical model. Only through such improvements can predictions for future water quality be made more reliably.

The present study concluded that any single method of estimating recharge and discharge will be biased, because of its limited "window of detection" for the broad timescales of interactions between surface water and ground water that occur in the interior wetlands of the Everglades. How can inherently biased measures of recharge and discharge be made useful to practical problems related to Everglades restoration? With the proper cautions on interpretation, all methods of estimating recharge and discharge contribute useful information to an overall assessment of recharge and discharge in the Everglades. From the comparison of methods in this report, for example, comes an estimate of the depth distribution of recharge and discharge fluxes showing that the majority of the recharged water is retained in shallow flow paths within peat in contrast with a much smaller amount of water that interacts with the sand and limestone aquifer. Selecting a single method for future studies requires prejudgement by an investigator of the likely spatial and temporal timescales that are considered essential to a particular investigation's goals and objectives. For example, if the focus of a given Everglades investigation is on surface-water quality, then the investigators will be interested in timescales not too far removed from the surface-water residence time in basins of the central Everglades (months). In that case, the components of surface-water and ground-water interactions that are most relevant are the short-term exchanges associated with flow of surface water into and back out of pore water in the peat. These rapid exchanges between surface water and peat pore water could have profound effects on biogeochemical reactions, and are therefore relevant to ecological simulations. Investigators interested in those processes will therefore mainly be interested in methods to estimate recharge and discharge that are based on measurements in peat (bromide tracer, radium-flux modeling, Darcy-flux calculations) rather than results from tritium modeling or longer-term averaging of SFWMM results. In contrast, longer-term estimates determined by modeling tritium and highly spatially averaged surface-water and ground-water hydraulic head measurements (SFWMM) are probably less applicable to surface-water-quality modeling, and more applicable to ground-water-quality modeling, or longer-term investigations of ground-water transport involving horizontal as well as vertical transport conditions. A good example of a long-term research investigation is determining the fate of recharged water in locations such as WCA-3B, where recharge in the Everglades is thought to be an important source of water to municipal well fields to the east of the Everglades. Some investigations may involve several timescales and thus will require multiple measurement types and updated modeling strategies.

Summary and Conclusions

Knowledge of interactions between surface water and ground water is central to an understanding of water budgets, water quality, and ecology in the Everglades, a wetland of national and international significance for which there is presently very little previous information of that kind. Vertical fluxes entering the subsurface (by recharge) or returning to surface water (by discharge) are the principal pathways by which surface water is exchanged with ground water in the underlying peat and sand/limestone aquifer. Managers and restoration planners have few reliable estimates of recharge and discharge in Everglades wetlands, especially in the parts of the wetlands far from the levees. Possibly the most poorly understood aspect of the problem is how the actions of water managers affect interactions between surface water and groundwater in ways that the affect Everglades ecology. One barrier to progress is the logistical constraints on measurements;

another is inexperience on what are the best measurements to make to support various needs across several disciplines. This report is a product of a cooperative investigation conducted by the USGS and the South Florida Water Management District (SFWMD) aimed at developing and testing techniques that would provide reliable estimates of recharge and discharge in interior areas of WCA-2A and several other sites in the central Everglades. Goals included testing and comparing several new methods to estimate recharge and discharge, in addition to characterizing spatial and temporal variability of recharge and discharge, and determining the relative importance of several possible controlling factors. The new methods of estimating recharge and discharge included (1) Darcy-flux calculations based on measured vertical gradients in hydraulic head and hydraulic conductivity of peat; (2) modeling vertical transport and decay of the naturally occurring isotopes ^{224}Ra and ^{223}Ra (with half-lives of 4 and 11 days, respectively) through peat; and (3) modeling of transport and decay of naturally occurring and “bomb-pulse” tritium (half-life of 12.4 years) in surface water and ground water.

The Darcy-flux measurement approach was used to estimate ground-water recharge and discharge at 15 sites in the Everglades Nutrient Removal (ENR) Project area and in Water Conservation Area 2A (WCA-2A). This approach required estimates of hydraulic conductivity of peat that were made at 11 of the 15 sites. A simple hydrogeologic simulation was used to assess how levees at the margins of Water Conservation Area 2A have influenced recharge and discharge. Simulations and measurements showed that the highest rates of recharge and discharge (approximately 2 cm per day) occurred within 600 m of levees, as a result of ground-water flow beneath levees. The simulations suggested that recharge and discharge should be orders of magnitude smaller in the interior areas of WCA-2A (> 600 m from levees). However, measurements showed that recharge and discharge were substantially higher than simulations predicted, comparable to fluxes near levees. A 5-year time series (1997-2002) of Darcy-flux estimates indicated that recharge and discharge in the interior wetlands of WCA-2A reversed in direction on weekly, monthly, and annual timescales. Ground-water discharge tended to occur during average to moderately dry conditions when local surface-water levels were decreasing. Recharge tended to occur during moderately wet periods or during very dry periods just as water levels began to increase following precipitation or in response to a “pulse” of surface water released from water-control structures. Discharge also tended to occur at sites in the wetland interior for approximately a week preceding the arrival of the surface-water pulse. It was concluded that ground-water recharge and discharge appear to vary cyclically in the interior wetlands of the central Everglades, and are driven by the differential responses of surface water and ground water to annual, seasonal, and weekly trends in precipitation and operation of water-control structures.

Measurement of environmental solute tracers that retain information about the time that has elapsed since recharge occurred offer another possible solution to estimating recharge and discharge in the Everglades. Activities of short-lived radium isotopes (^{223}Ra and ^{224}Ra) were measured in pore water of peat at several research sites in WCA-2A. These radium concentration profiles differed from the amount that could be explained without water flow by local production, decay, and exchange with solid phases. The measured disequilibrium is caused by vertical transport of radium with water flowing vertically in the peat along flow paths connecting ground water in the underlying aquifer with surface water. The rate of vertical water flow through wetland sediment was determined from the radium disequilibrium using a combined model of transport, production, decay, and exchange with solid phases. This technique was tested in WCA-2A by quantifying vertical advective velocities at three sites. Vertical water fluxes were determined to be between 0 and 0.5 cm per day for a recharge site, and 1.5 ± 0.4 cm per day for a discharge site located on the upgradient and downgradient sides of the Hillsboro levee, respectively. A site in the interior of WCA-2a experienced both recharge and discharge at an “exchange” rate of approximately 0.9 cm per day. The radium technique should be applicable to any wetland system with different production rates of these isotopes in distinct sedimentary layers or surface water, and is most straightforward in systems where constant ionic strength in pore-water can be assumed, thereby simplifying the modeling of radium exchange.

Average long-term (decadal timescale) recharge and discharge fluxes across the ground surface were estimated in WCA-2A by simulating transport of tritium (^{3}H) and radioactive decay in surface water and ground water. Model parameters included the storage depth of shallow ground water near the top of the aquifer that exchanges with surface water (referred to as “interactive” ground water), average residence time of that ground water, and the associated recharge and discharge fluxes. The residence time of interactive ground water in the simulation was adjusted to achieve the best fit with measured concentrations of tritium concentrations and the measured depth distribution of tritium in the aquifer. Several direct estimates of ground-water residence time determined from tritium/helium-3 isotopic ratios (^{3}H/^{3}He) provided an important check on the results. Recharge and discharge fluxes were computed directly from best estimates of average residence time and depth of shallow, interactive ground water. The results of a model using only tritium data suggested that interactive ground water had an average residence time of 90 years and a storage depth of 3.1 m. Both the residence time and storage depth estimates are expected to be overestimated by the approach that only used tritium data because of the effects of vertical mixing with deeper, older, “tritium-dead” ground water. Analysis of ^{3}H/^{3}He, which is not sensitive to mixing with deep, tritium-dead ground water, indicated an approximate residence time of 25 years for shallow ground water. Results from both the tritium model and ^{3}H/^{3}He analysis were that the long-term average estimates of recharge and discharge in WCA-2A are on the order of 0.01 cm/d.

A comparison between results of the new methods described above revealed order-of-magnitude differences, with fluxes ranging between 0.01 and 3 cm per day. These differences must to some extent reflect real spatial and temporal variability of recharge and discharge in the wetlands. However, an even more important determinant of the order-of-magnitude variability of these estimates is of the inherent limitations of each method. Only a small component is detected by each method of the full distribution of recharge and discharge fluxes that are operative at all spatial and temporal in nature. For example, the comparison of methods demonstrated that recharge and discharge estimates decrease with increasing depth in the subsurface. This is not an artifact of measurements but instead reflects the true nature of surface-water and ground-water interactions in the Everglades. For example, it is only a matter of hours to days from the time that surface water is recharged into shallow flow paths through peat soil before it reemerges as discharge. Meanwhile, the much smaller component of the recharged water that flows more deeply into the sand and limestone aquifer (meters of tens of meters) could be retained for decades, centuries, or even millennia before it is returned to the surface as ground-water discharge. The result is a distribution of flow depths and associated residence times of recharged water in ground water prior to discharge back to surface water.

Another important influence on results is the interaction between true signals of temporal variability of recharge and discharge (especially reversals between these fluxes) and the averaging timescale selected by the investigator. Furthermore, there are inherent aspects of each measurement technique (such as the half-life of an environmental tracer) that influence the sensitivity of each method to a particular timescale of surface-subsurface exchange. For example, modeling transport of the short-lived isotopes of radium in the 1-meter-thick layer of wetland peat provided one of the largest estimates of recharge and discharge (0.9 cm per day), because the approach used relatively short-lived isotopes of radium (4 and 11 day half lives) that are sensitive to the relatively high-frequency (weekly to monthly) reversals in the flux direction caused by precipitation events and surface-water releases from water-control structures. In contrast, recharge and discharge estimates based on modeling transport of the much longer-lived (12 year half-life) isotope tritium were not sensitive to the high-frequency reversals in flux direction in peat, due to tritium's longer half-life and also to fact that tritium was measured in the sand and limestone aquifer where the effects of high-frequency fluctuations in peat pore water are damped out. Consequently, tritium modeling was sensitive only to the relatively small component (0.01 cm per day) of the total exchange fluxes that involve decadal timescale interactions between surface water and ground water.

The South Florida Water Management Model (SFWMM) has been an important tool and has been used extensively by the South Florida Water management District (SFWMD) to design many of the hydrological aspects of the Everglades restoration. Therefore, comparing results of the new methods presented in this report with SFWMM results was important. Because the SFWMM is spatially discretized on a 2-mi by 2-mi square grid, and because recharge and discharge are often estimated from modeling results by averaging on annual or longer timescales, the SFWMM also is subject to scale dependence in its results. Like tritium modeling, longer runs of the SFWMM generally provide results that reflect longer timescale and deeper subsurface interactions between surface water and ground water. For example, a decadal timescale run of the SFWMM (1979 – 1990 "calibration" simulation) produced an estimate of recharge and discharge (0.03 cm per day) that was consistent with tritium modeling (0.01 cm per day). Decreasing the length of a model run for the SFWMM appears to increase its sensitivity to shorter term interactions between surface water and ground water. For example, a shorter (5-year) run of the SFWMM (1991-1995 "verification" simulation) produced an estimate of recharge and discharge that was consistent with Darcy-flux calculations in this investigation (0.1 compared with 0.2 cm per day for the Darcy-flux calculations, respectively).

In summary, measurements of recharge and discharge in the central Everglades are both spatially and temporally scale dependent. As a consequence of the scale dependence, there is no simple measure of recharge and discharge that is generally applicable for all uses. Different methods to estimate recharge and discharge are inherently limited by the technique that is selected as well as by the spatial and temporal averaging of the measurements imposed by the investigator. Consequently, no single method quantifies the full spectrum of shallow and deep recharge and discharge fluxes that are simultaneously active in the Everglades. Each method, however, potentially provides useful information about a particular spatial and temporal subset of the total recharge and discharge fluxes that are occurring. For example, the daily to monthly timescale fluctuations in recharge and discharge that are detected by Darcy-flux calculations and radium modeling are mainly informative about exchange of surface water with peat pore water, whereas the longer-term averaging by tritium modeling and the SFWMM are mainly sensitive to deeper exchange with ground water in the underlying aquifer.

Acknowledgments

We gratefully acknowledge the contributions of many SFWMD and USGS personnel in emplacing wells and seepage meters and servicing those instruments in the remote interior areas of the central Everglades, including Eugene Shinn (USGS), Christopher Reich (USGS), Donald Hickey (USGS), Robert Mooney (USGS), Cynthia Gefvert (SFWMD), Jonah Jackson (USGS), James Vincent (SFWMD), Peter Dauenhauer (SFWMD), Bruce Webb (SFWMD), Simon Sunderland (SFWMD), Edward Rectenwald (SFWMD), Walter Bedit (SFWMD), and Mark Hummel (SFWMD). William Orem (USGS) and David Krabbenhoft (USGS) of the USGS Integrated Geochemical Studies in the Everglades project, Reston, Virginia and the USGS Mercury Studies Team, Middleton, Wisconsin, respectively, are acknowledged for their continuing collaboration in field work. We thank the following individuals for their detailed comments on an early draft of the manuscript: Christopher McVoy (SFWMD), Ken Tarboton (SFWMD), Harry Jenter (USGS), Cynthia Gefvert (SFWMD), Fred Sklar (SFWMD), and Wasantha Lal (SFWMD). Heidi Bazell (SFWMD) provided extensive help with the SFWMD database. The investigation was supported by the USGS Greater Everglades Priority Ecosystem Science Initiative and the USGS National Research Program. Finally, we acknowledge the help and leadership of managers at USGS and SFWMD, including Aaron Higer (USGS), Jayantha Obeysekera (SFWMD), Ronald Best (USGS), and John Lukasiewicz (SFWMD).

References Cited

Barlow, P.M., and Moench, A.F., 1998, Analytical solutions and computer programs for hydraulic interaction of stream-aquifer systems: U.S. Geological Survey Open-File Report 98-415A, 85 p.

Bates, A. L., Orem, W.H., Harvey, J.W., and Spiker, E.C., 2002, Tracing sources of sulfur in the Florida Everglades: Journal of Environmental Quality, v. 31, p. 287-299.

Berner, R. A., 1980, Early diagenesis–a theoretical approach, Princeton Series in Geochemistry: Princeton, NJ, Princeton University Press, 241 p.

Bolster, C., Genereux, D., and Saiers, J., 2001, Determination of specific yield for a limestone aquifer from a canal drawdown test: Ground Water, v. 39, p. 768-777.

Brand, E.W., and Premchitt, J., 1980, Shape factors of cylindrical piezometers: Geotechnique, v. 30, p. 369-384.

Chin, D.A., 1990, A method to estimate canal leakage to the Biscayne aquifer, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4135, 32 p.

Choi, J., and Harvey, J.W., 2000, Quantifying time-varying groundwater discharge and recharge in wetlands–A comparison of methods in the Florida Everglades: Wetlands, v. 20, no. 3, p. 500-511.

Cochran, J. K., 1980, Radium, thorium, uranium and 210Pb in deep sea sediment and sediment pore waters in the north equatorial Pacific: American Journal of Science, v. 280, p. 849-889.

Copenhaver, S. A., Krishnaswami, S., Turekian, K. K., Epler, N., and Cochran, J. K., 1993, Retardation of U-238 and Th-232 decay chain radionuclides in Long-Island and Connecticut aquifers: Geochimica et Cosmochimica Acta, v. 57, p. 597-603.

Fennema, R.J., Neidrauer, C.J., Johnson, R.A., MacVicar, T.K., and Perkins, W.A., 1994, Computer model to simulate natural Everglades hydrology, in Davis, S.M., and Ogden, J.C., eds., Everglades - The Ecosystem and its Restoration: Boca Raton, St Lucie Press, p. 249-290.

Fish, J.E., 1988, Hydrogeology, aquifer characteristics, and ground-water flow of the Surficial aquifer system, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 87-4034, 92 p.

Fish, J.E., and Stewart, M., 1991, Hydrogeology of the Surficial aquifer system, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4108, 50 p., 11 sheets.

Fitz, H.C., Sklar, F.H., Waring, T., Voinov, A.A., Costanza, R., and Maxwell, T., 2004, Development and application of the Everglades Landscape Model, pages 143-173 in Costanza, R., and Voinov, A.A., eds, Landscape Simulation Modeling: a spatially explicit, dynamic approach. Springer, 330 pages.

Genereux, D., and Guardiario, J., 1998, A canal drawdown experiment for determination of aquifer parameters: Journal of Hydrogeologic Engineering, v. 3, no. 4, p. 294-302.

Genereux, D., and Slater, E., 1999, Water exchange between canals and surrounding aquifer and wetlands in the Southern Everglades, U.S.A.: Journal of Hydrology, v. 219, p. 153-168.

Gleason, P.J., and Stone P., 1994, Age, origin, and landscape evolution of the Everglades peatland, in Davis, S.M., and Ogden, J.C., eds., Everglades - The Ecosystem and its Restoration: Boca Raton, St Lucie Press, p. 149-198.

Harvey, J.W., 1996, Vertical exchange of ground water and surface water in the Florida Everglades: U.S. Geological Survey Factsheet FS-169-96, 2 p.

Harvey, J.W., Krupa, S.L., Gefvert, C., Choi, J., Mooney, R.H., and Giddings, J.B., 2000, Interaction between ground water and surface water in the northern Everglades and relation to water budget and mercury cycling - Study methods and appendixes: U.S. Geological Survey Open-File Report 00-168, 395 p.

Harvey, J.W., Krupa, S.L., Gefvert, C., Mooney, R.H., Choi, J., King, S.A., and Giddings, J.B., 2002, Interaction between surface water and ground water and effects on mercury transport in the north-central Everglades: U.S. Geological Survey Water-Resources Investigations Report 02-4050, 82 p.

Harvey, J.W., Krupa, S.L., and Krest, J.M.,2004, Groundwater recharge and discharge in the central Everglades: Ground Water, v. 42, no. 7, p. 1090-1102.

Harvey, J.W., Saiers, J.E., and Newlin, J.T., 2005, Solute transport and storage mechanisms in wetlands of the Everglades, south Florida: Water Resources Research, v. 41, W05009, doi:10.1029/2004WR003507.

Harvey, J.W., Wagner, B.J., and Bencala, K.E., 1996, Evaluating the reliability of the stream tracer approach to to characterize stream-subsurface water exchange: Water Resources Research, vol. 32, no. 8, p. 2441 – 2451.

Howie, B., 1987, Chemical characteristics of water in the Surficial aquifer system, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4330.

International Atomic Energy Agency/World Meteorological Organization (IAEA/WMO), 2001, Global Network of Isotopes in Precipitation. The GNIP Database Accessible at: http://isohis.iaea.org.

International Atomic Energy Agency (IAEA), 1981, Statistical treatment of environmental isotope data in precipitation: Technical Reports Series No. 206, 256 p.

Jensen, J.R., Rutchey, K., Koch, M.S., and Narumalani, S., 1995, Inland wetland change detection in the Everglades Water Conservation Area 2A using a time series of normalized remotely sensed data: Photogrammetric Engineering and Remote Sensing, v. 61, no. 2, p. 199-209.

Kadlec, R. and Walker, W.W., 1999. Management models to evaluate phosphorus impactson wetlands, in Reddy, K.R., O'Conner, G.A., and Schelske, C.L.,eds., Phosphorus biogeochemistry of subtropical ecosystems: CRC Press, Inc. Boca Raton, Florida, p 621-642.

Klein, H., and Sherwood, C.B., 1961, Hydrologic conditions in the vicinity of Levee 30, northern Dade County, Florida: Florida Bureau of Geology Report of Investigations No. 24, 24 p.

Krabbenhoft, D.P., Hurley, J.P., Olson, M.L., and Cleckner, L.B., 1998, Diel variability of mercury phase and species distributions in the Florida Everglades: Biogeochemistry, v. 40, p. 311-325.

Krest, J. M., Moore, W. S., and Rama, 1999, ^{226}Ra and ^{228}Ra in the mixing zones of the Mississippi and Atchafalaya Rivers–Indicators of groundwater input: Marine Chemistry, v. 64, p. 129-152.

Krest, J.M., and Harvey, J.W., 2003, Using natural distributions of short-lived isotopes to quantify groundwater discharge and recharge: Limnology and Oceanography, v. 48, no. 1, p. 290-298.

Lambe, T. W., 1951, Soil testing for engineers, series in soil engineering: New York, John Wiley & Sons, 165 p.

Lee, D.R., 1977, A device for measuring seepage flux in lakes and estuaries: Limnology and Oceanography, v. 22, p. 140-147.

Light, S.S., and Dineen, J.W., 1994, Water control in the Everglades - A historical perspective, in Davis, S.M., and Ogden, J.C., eds., Everglades - The Ecosystem and its Restoration: Boca Raton, St Lucie Press, p. 47-84.

Luthin, J.N., and Kirkham, D., 1949, A piezometer method for measuring permeability of soil in-situ below a water table: Soil Science, v. 68, p. 349-358.

Martinez, C.J., and Wise, W.R., 2003, Analysis of constructed treatment wetland hydraulic s with the transient storage model OTIS: Ecological Engineering, vol. 20, p. 211-222.

McCormick, P.V., Shuford, R.B.E., III, Backus, J.G., and Kennedy, W.C., 1998, Spatial and seasonal patterns of periphyton biomass and productivity in the northern Everglades, Florida, U.S.A.: Hydrobiologia, v. 362, p 185-208.

McVoy, Christopher W., South Florida Water Management District, written commun., 2003

Meyers, J.G., Swart, P.K., and Meyers, J.L., 1993, Geochemical evidence for groundwater behavior in an unconfined aquifer, south Florida: Journal of Hydrology, v. 148, p. 249-272.

Miller, W.L., 1978, Effect of bottom sediments on infiltration from the Miami and tributary canals to the Biscayne aquifer, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 78-36.

Miller, W., 1987, Lithology and base of the Surficial aquifer system, Palm Beach County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4067, 1 pl.

Miller, W.L., 1988, Description and evaluation of the effects of urban and agricultural development on the Surficial aquifer system, Palm Beach County, Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4056, 58 p.

Moore, W. S., 1976, Sampling 228Ra in the deep ocean: Deep-Sea Research, v. 23, p. 647-651.

Moore, W. S., and Arnold, R., 1996, Measurement of Ra-223 and Ra-224 in coastal waters using a delayed coincidence counter: Journal of Geophysical Research-Oceans, v. 101, p. 1321-1329.

National Research Council, 2003, Does water flow influence Everglades landscape patterns, The National Academies Press, http://books.nap.edu/catalog/10758.html, 41 p.

Nemeth, M.S., and Solo-Gabriele, H.M., 2001, Evaluation of the use of reach transmissivity to quantifyexchange between groundwater and surface water: Journal of Hydrology, v. 274, p. 145-159.

Perkins, R.D., 1977, Depositional framework of Pleistocene rocks in south Florida, in Enos, P., and Perkins, R.D., eds., Quaternary sedimentation in south Florida: Geological Society of America Memoir 147, p. 131-196.

Price, R.M., Top, Z., Happell, J.D., and Swart, P.K., 2003, Use of tritium and helium to define groundwater flow conditions in Everglades National Park: Water Resources Research, v. 39, no. 9, 1267:DOI:10.1029/2002WR001929.

Rama, and Moore, W. S., 1996, Using the radium quartet for evaluating groundwater input and water exchange in salt marshes: Geochimica et Cosmochimica Acta, v. 60, p. 4645-4652.

Reese, R.S., and Cunningham, K.J., 2000, Hydrogeology of the Gray limestone aquifer in southern Florida: U.S. Geological Survey Water Resources Investigations Report 99-4213, 244 p.

Rohrer, K.P., 1999, Hydrogeological characterization and estimation of ground water seepage in the Everglades nutrient removal project: South Florida Water Management District WRE-372, 147 p.

Romanowicz, E., and Richardson, C.J., 2000, Modelling hydroperiods and flooding depths in the northern Everglades, Water Conservation Area 2A, in INTECOL: Millennium Wetland Event and Annual Meeting of the Society of Wetland Scientists, August 6-12, 2000, Program with Abstracts, p. 324.

Runkel, R.L., 1998, One-dimensional transport with inflow and storage (OTIS) – A solute transport model for streams and rivers: U.S. Geological Survey Water-Resources Investigations Report 98-4018, 73 p.

Rutchey, K., and Vilchek, L., 1999, Air photointerpretation and satellite imagery analysis techniques for mapping cattail coverage in a northern Everglades impoundment: Photogrammetric Engineering and Remote Sensing, v. 65, no. 2, p. 185-191.

Rybicki, N.B., Reel, J.T., Gammon, P.T. and Garrett, M.K., 2002, Vegetative resistance to flow in south Florida Everglades – summary of vegetation sampling in Water Conservation Area 2A, September 1999: U.S. Geological Survey Open-File Report 02-38, 42 p.

Schlosser, P., Shapiro, S.D., Stute, M., Aeschbach-Herig, W., Plummer, L.N., and Busenberg, E., 1998, Tritium/3He measurements in young groundwater - Chronologies for environmental records, in Conference on Isotope Techniques in the Study of Environmental Change, Proceedings: Vienna, Int. Atomic Energy Agency, p. 165-189.

Science Coordination Team (South Florida Ecosystem Restoration Working Group), 2003, The Role of Flow in the Everglades Ridge and Slough Landscape, 62 p., accessed April 14, 2004 at http://sofia.usgs.gov/publications/papers/sct_flows/

Shinn, E.A., Reese, R.S., and Reich, C.D., 1984, Fate and pathways of injection-well effluent in the Florida Keys: U.S. Geological Survey Open-File Report 94-276, 116 p.

Sonenshein, R.S., 2001, Methods to quantify seepage beneath Levee 30, Miami-Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 01-4074, 36 p.

South Florida Water Management District (SFWMD), 1999, A primer to the South Florida Water Management Model (version 3.5), Hydrologic Systems Modeling Division, Planning Department, South Florida Water Management District, accessed April 9, 2004 at http://www.sfwmd.gov/org/pld/hsm/models/sfwmm/v3.5/wmmpdf.htm

South Florida Water Management District (SFWMD), 2002, The Everglades Landscape Model, accessed April 14, 2004, at http://sfwmd.gov/org/wrp/elm/.

South Florida Water Management District (SFWMD), 2003, Central and Southern Florida Project Comprehensive Review Study, accessed April 9, 2004 at http://www.sfwmd.gov/org/pld/restudy/hpm/index.html

Stoertz, M.W., and Bradbury, K.R., 1989, Mapping recharge areas using a groundwater flow model – a case study: Ground Water v. 27, no. 2, p. 220-229.

Sun, Y., and Torgersen, T., 1998, Rapid and precise measurement method for adsorbed 224Ra on sediments: Marine Chemistry, v. 61, p. 163-171.

Sun, Y., and Torgersen, T., 2001, Adsorption-desorption reactions and bioturbation transport of 224Ra in marine sediments: a one-dimensional model with applications: Marine Chemistry, v. 74, p. 227-243.

Swayze, L.J., 1988, Ground-water flow beneath Levee 35A from Conservation Area 2B, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 87-4280, 22p.

Tarboton, Ken, South Florida Water Management District, written commun., 2003

Tarboton, K.C., Neidrauer, C.J., Santee, E.R. and Needle, J.C., 1999, Regional Hydrologic Modeling for Planning the Management of South Florida's Water Resources through 2050: ASAE Paper No. 992062, in 1999 Annual International Meeting, ASAE/CSAE, Toronto, Canada, 19-21 July.

Tavenas, F., Diene, M., and Leroueil, S., 1990, Analysis of the in situ constant-head permeability test in clays: Canadian Geotechnical Journal, v. 27, p. 305-314.

Thibodeaux, L.J., 1996, Environmental chemodynamics-movement of chemicals in air, water, and soil: New York, John Wiley and Sons, 593 p.

Tricca, A., Wasserburg, G. J., Porcelli, D., and Baskaran, M., 2001, The transport of U- and Th-series nuclides in a sandy unconfined aquifer: Geochimica et Cosmochimica Acta, v. 65, p. 1187-1210.

University of Miami, 2003, Tritium Laboratory, Rosenstiel School of Marine and Atmospheric Science (RSMAS), accessed April 14, 2004, at http://www.rsmas.miami.edu/groups/tritium/.

Urban, N.M., Davis, S.M., and Aumen, N.G., 1993, Fluctuations in saw grass and cattail densities in Everglades Water Conservation Area 2A under varying nutrient, hydrologic and fire regimes: Aquatic Botany, v. 46, p. 203-233.

U.S. Army Corps of Engineers, 1952, Part I, Agricultural and conservation areas - Supplement 5 - Test levee investigations: Partial definite report, North-central and South Florida Project for Flood Control and Other Purposes, 28 p., 14 pl.

U.S. Geological Survey, Tritum/Helium-3 Dating, Reston Chlorofluorocarbon Laboratory, accessed April 14, 2004, at http://water.usgs.gov/lab/3h3he/index.html

Webster, I. T., Hancock, G. J., and Murray, A. S., 1995, Modeling the effect of salinity on radium desorption from sediments: Geochimica et Cosmochimica Acta, v. 59, p. 2469-2476.

Wilcox, W.M., Solo-Gabriele, H.M., and Sternberg, L.O., 2004, Use of stable isotopes to quantify flows between the Everglades and urban areas in Miami-Dade County Florida: Journal of Hydrology, vol. 293, p.1-19.

Appendix 1–22

Appendix 1. Site locations, well and drivepoint information, and peat depths in and near Water Conservation Area 2A, central Everglades, south Florida.

NAD, North American Datum; NAD83, North American Datum of 1983; sw, surface-water sample collected using peristaltic pump with pump tubing often placed inside screened drivepoint to prevent sampling of macro algae; –, not applicable; gw, ground-water sample collected from established well; also see Harvey and others, 2000, for well-construction information; in, inch; sch, schedule; PVC, polyvinyl chloride (drivepoint with 5 centimeters of 0.01-in screen); ss, stainless steel; w/thin ext, with thin-walled PVC riser extension above screen; pw-peat, pore-water sample collected from drivepoint emplaced in peat layer; sw-mc, surface-water sample collected from Aquatic Cycling of Mercury in the Everglades mesocosm operated by U.S. Geological Survey Mercury Studies Team (http://sofia.usgs.gov/projects/evergl_merc/); pw-dl, pore-water sample collected from drivepoint emplaced in detrital layer; pw-tran, pore-water sample collected from fresh water marl/sand sediments that are transitional to underlying sand-limestone aquifer)]

Site ID	Site and sample type	Latitude	Longitude	NAD for lat/long	Northing (meters, NAD83)	Easting (meters, NAD83)	Well depth: ground surface to well screen top, in feet	Drivepoint depth: surface to screen center, in centimeters	Drivepoint type and outside diameter	Total depth (peat and detrital layer)/depth of detrital layer, in centimeters
1/2 Westgate to camp 6	sw	26 18 12.8	80 19 18.7	27	2909518.65	567714.69	–	–	–	–
1/2 Westgate to south trail intersect	sw	26 19 07	80 18 44.9	27	2911190.99	568643.08	–	–	–	–
1st trail split	sw	26 21 08.6	80 18 21.5	27	2914935.34	569271.77	–	–	–	–
2nd trail split	sw	26 21 06.7	80 18 39	27	2914874.29	568787.02	–	–	–	–
A1	sw	26 21 11.81	80 20 58.42	83	2914971.91	564899.32	–	–	–	–
A3	sw	26 21 18.78	80 21 15.05	83	2915184.03	564437.32	–	–	–	–
A4	sw	26 17 39.56	80 23 15.9	83	2908423.49	561119.77	–	–	–	–
A5	sw	26 18 57.2	80 22 28.6	27	2910858.00	562442.31	–	–	–	–
A6	sw	26 18 30.97	80 21 10.56	83	2910022.02	564587.63	–	–	–	–
A7	sw	26 18 31.03	80 21 42.58	83	2910019.45	563699.79	–	–	–	–
A8	sw	26 18 32.54	80 21 43.18	83	2910065.83	563682.92	–	–	–	–
Back in main trail	sw	26 20 49.8	80 19 28	27	2914347.20	567431.56	–	–	–	–
Boat ramp	sw	26 21 02.99	80 17 53.20	27	2914767.00	570057.12	–	–	–	–
Camp 6	sw	26 17 54.3	80 20 01.1	27	2908943.41	566541.90	–	–	–	–
E1	sw	26 21 04.431	80 21 15.104	27	2914782.11	564460.51	–	–	–	100
E1-3	gw	26 21 04.431	80 21 15.104	27	2914782.11	564460.51	19.7	–	–	100
E1-4	gw	26 21 04.431	80 21 15.104	27	2914782.11	564460.51	8.2	–	–	100
E1-102	pw-peat	26 21 04.431	80 21 15.104	27	2914782.11	564460.51	–	102	1.25 in sch 40 PVC	100
E4	sw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	–	–	–	100
E4-3	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	16.4	–	–	100
E4-4	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	6.4	–	–	100
E4-5	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	117.3	–	–	100
E4-6	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	56.6	–	–	100
E4-7	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	28.9	–	–	100
E4-8	gw	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	13.8	–	–	100
E4-80	pw-peat	26 18 31.114	80 21 26.072	27	2910064.01	564179.96	–	80	1.25 in sch 40 PVC	100
Emain junction	sw	26 20 13.9	80 21 18.5	27	2913227.12	564374.14	–	–	–	–
E-S10 Trail williow	sw	26 21 46.55 [a]	80 21 13.55 [a]	27	2916078.07	564497.10	–	–	–	–
F1	sw	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	–	–	160/24
F1-24	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	24	1/2 in sch 40 PVC	160/24
F1-34	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	34	1/2 in sch 40 PVC	160/24
F1-50	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	50	3/8-in ss	160/24
F1-54	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	54	1/2 in sch 40 PVC	160/24
F1-84	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	84	1/2 in sch 40 PVC	160/24
F1-100	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	100	3/8-in ss	160/24
F1-114	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	114	1/2 in sch 40 PVC	160/24
F1-125	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	125	3/8-in ss	160/24
F1-144	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	144	1/2 in sch 40 PVC	160/24
F1-154	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	154	1/2 in sch 40 PVC, w/thin ext	160/24
F1-164	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	164	1/2 in sch 40 PVC, w/thin ext	160/24
F1-169	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	169	1/2 in sch 40 PVC, w/thin ext	160/24
F1-174	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	174	1/2 in sch 40 PVC, w/thin ext	160/24

Appendix 1. Site locations, well and drivepoint information, and peat depths in and near Water Conservation Area 2A, central Everglades, south Florida.—Continued

NAD, North American Datum; NAD83, North American Datum of 1983; sw, surface-water sample collected using peristaltic pump with pump tubing often placed inside screened drivepoint to prevent sampling of macro algae; –, not applicable; gw, ground-water sample collected from established well; also see Harvey and others, 2000, for well-construction information; in, inch; sch, schedule; PVC, polyvinyl chloride (drivepoint with 5 centimeters of 0.01-in screen); ss, stainless steel; w/thin ext, with thin-walled PVC riser extension above screen; pw-peat, pore-water sample collected from drivepoint emplaced in peat layer; sw-mc, surface-water sample collected from Aquatic Cycling of Mercury in the Everglades mesocosm operated by U.S. Geological Survey Mercury Studies Team (http://sofia.usgs.gov/projects/evergl_merc/); pw-dl, pore-water sample collected from drivepoint emplaced in detrital layer; pw-tran, pore-water sample collected from fresh water marl/sand sediments that are transitional to underlying sand-limestone aquifer)]

F1-179	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	179	1/2 in sch 40 PVC, w/thin ext	160/24
F1-184	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	184	1/2 in sch 40 PVC, w/thin ext	160/24
F1-3	gw	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	25.9	–	–	160/24
F1-4	gw	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	6.5	–	–	160/24
F1-MC1	sw-mc	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	–	–	160/24
F1-MC2	sw-mc	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	–	–	160/24
F1-MC5	sw-mc	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	–	–	160/24
F1-181	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	181	3/4 in sch 40 PVC	160/24
F1-41	pw-peat	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	41	3/4 in sch 40 PVC	160/24
F1-223	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	223	1.25 in sch 40 PVC	160/24
F1-176	pw-tran	26 21 38.075	80 22 10.652	27	2915809.52	562915.79	–	176	3/8-in ss	160/24
F4	sw	26 18 59.788	80 23 07.31	27	2910932.47	561368.65	–	–	–	120
F4-3	gw	26 18 59.788	80 23 07.31	27	2910932.47	561368.65	21.5	–	–	120
F4-4	gw	26 18 59.788	80 23 07.31	27	2910932.47	561368.65	5.0	–	–	120
F4-66	pw-peat	26 18 59.788	80 23 07.31	27	2910932.47	561368.65	–	66	3/4 in sch 40 PVC	120
F4-130	pw-peat	26 18 59.788	80 23 07.31	27	2910932.47	561368.65	–	130	3/8-in ss	120
L Split main trail	sw	26 20 50	80 19 23.1	27	2914354.07	567567.35	–	–	–	–
L Split willow	sw	26 20 41.4	80 19 49.3	27	2914085.71	566842.49	–	–	–	–
Main trail offshoot	sw	26 20 53.3	80 19 26.4	27	2914455.11	567475.35	–	–	–	–
Near F1	sw	26 21 31.7	80 22 08.7	27	2915613.66	562970.85	–	–	–	–
Plane	sw	26 17 01.8	80 22 38.1	27	2907306.63	562196.00	–	–	–	–
South trail intersect	sw	26 19 52.9	80 18 24.9	27	2912606.01	569190.02	–	–	–	–
S10C-A	gw	26 22 15.35	80 21 04.055	27	2916965.38	564755.80	99.6	–	–	–
S10C-B	gw	26 22 15.35	80 21 04.055	27	2916965.38	564755.80	62.8	–	–	–
S10C-C	gw	26 22 15.35	80 21 04.055	27	2916965.38	564755.80	29.7	–	–	–
S10C-HW	sw	26 22 15.35	80 21 04.055	27	2916965.38	564755.80	–	–	–	–
S10C-N	sw	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	–	–	130/55
S10C-N-9	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	9	1/8-in ss	130/55
S10C-N-11	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	11	1/8-in ss	130/55
S10C-N-13	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	13	1/8-in ss	130/55
S10C-N-17	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	17	1/8-in ss	130/55
S10C-N-21	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	21	1/8-in ss	130/55
S10C-N-25	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	25	1/8-in ss	130/55
S10C-N-30	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	30	1/8-in ss	130/55
S10C-N-31	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	31	1/8-in ss	130/55
S10C-N-32	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	32	1/8-in ss	130/55
S10C-N-34	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	34	1/8-in ss	130/55
S10C-N-35	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	35	1/8-in ss	130/55
S10C-N-38	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	38	1/8-in ss	130/55
S10C-N-41	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	41	1/8-in ss	130/55
S10C-N-42	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	42	1/8-in ss	130/55
S10C-N-45	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	45	1/8-in ss	130/55
S10C-N-46	pw-dl	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	46	1/8-in ss	130/55
S10C-N-55	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	55	1/2 in sch 40 PVC	130/55
S10C-N-56	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	56	1/8-in ss	130/55
S10C-N-60	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	60	1/8-in ss	130/55
S10C-N-71	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	71	1/8-in ss	130/55
S10C-N-75	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	75	1/2 in sch 40 PVC	130/55

Appendix 1. Site locations, well and drivepoint information, and peat depths in and near Water Conservation Area 2A, central Everglades, south Florida.—Continued

NAD, North American Datum; NAD83, North American Datum of 1983; sw, surface-water sample collected using peristaltic pump with pump tubing often placed inside screened drivepoint to prevent sampling of macro algae; –, not applicable; gw, ground-water sample collected from established well; also see Harvey and others, 2000, for well-construction information; in, inch; sch, schedule; PVC, polyvinyl chloride (drivepoint with 5 centimeters of 0.01-in screen); ss, stainless steel; w/thin ext, with thin-walled PVC riser extension above screen; pw-peat, pore-water sample collected from drivepoint emplaced in peat layer; sw-mc, surface-water sample collected from Aquatic Cycling of Mercury in the Everglades mesocosm operated by U.S. Geological Survey Mercury Studies Team (http://sofia.usgs.gov/projects/evergl_merc/); pw-dl, pore-water sample collected from drivepoint emplaced in detrital layer; pw-tran, pore-water sample collected from fresh water marl/sand sediments that are transitional to underlying sand-limestone aquifer)]

S10C-N-86	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	86	1/8-in ss	130/55
S10C-N-90	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	90	1/8-in ss	130/55
S10C-N-95	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	95	1/2 in sch 40 PVC	130/55
S10C-N-101	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	101	1/8-in ss	130/55
S10C-N-105	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	105	1/8-in ss	130/55
S10C-N-115	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	115	1/2 in sch 40 PVC	130/55
S10C-N-135	pw-peat	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	135	1/2 in sch 40 PVC	130/55
S10C-N-155	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	155	1/2 in sch 40 PVC	130/55
S10C-N-175	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	175	1/2 in sch 40 PVC	130/55
S10C-N-195	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	195	1/2 in sch 40 PVC	130/55
S10C-N-215	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	215	1/2 in sch 40 PVC	130/55
S10C-N-235	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	235	1/2 in sch 40 PVC	130/55
S10C-N-255	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	255	1/2 in sch 40 PVC	130/55
S10C-N-275	pw-tran	26 22 26.46	80 21 02.04	83	2917268.01	564787.43	–	275	1-1/4 in sch 40 PVC	130/55
S10C-S	sw	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	–	–	140/50
S10C-S-4	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	4	1/8-in ss	140/50
S10C-S-6	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	6	1/8-in ss	140/50
S10C-S-8	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	8	1/8-in ss	140/50
S10C-S-29	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	29	1/8-in ss	140/50
S10C-S-30	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	30	1/8-in ss	140/50
S10C-S-33	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	33	1/8-in ss	140/50
S10C-S-37	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	37	1/8-in ss	140/50
S10C-S-45	pw-dl	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	45	1/8-in ss	140/50
S10C-S-55	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	55	1/8-in ss	140/50
S10C-S-70	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	70	1/8-in ss	140/50
S10C-S-80	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	80	3/8-in ss	140/50
S10C-S-85	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	85	1/8-in ss	140/50
S10C-S-90	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	90	3/8-in ss	140/50
S10C-S-100	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	100	3/8-in ss	140/50
S10C-S-110	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	110	3/8-in ss	140/50
S10C-S-120	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	120	3/8-in ss	140/50
S10C-S-130	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	130	3/8-in ss	140/50
S10C-S-140	pw-peat	26 22 13.80	80 21 08.88	83	2916877.57	564599.84	–	140	3/8-in ss	140/50
S10C-TW	sw	26 22 15.35	80 21 04.055	27	2916965.38	564755.80	–	–	–	–
S7E	sw	26 19 25.923	80 24 51.195	27	2911723.11	558484.69	–	–	–	–
S7E-1	gw	26 19 25.923	80 24 51.195	27	2911723.11	558484.69	116.3	–	–	–
S7E-2	gw	26 19 25.923	80 24 51.195	27	2911723.11	558484.69	57.0	–	–	–
S7E-3	gw	26 19 25.923	80 24 51.195	27	2911723.11	558484.69	27.3	–	–	–
S7E-4	gw	26 19 25.923	80 24 51.195	27	2911723.11	558484.69	12.3	–	–	–
U1-174	gw	26 14 26.021	80 21 21.284	27	2902524.79	564350.23	–	175	–	150
U3	sw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	–	–	150/7
U3-50	pw-peat	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	50	3/8-in ss	150/7
U3-100	pw-peat	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	100	3/8-in ss	150/7
U3-112	pw-peat	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	112	3/8-in ss	150/7
U3-3	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	26.1	–	–	150/7
U3-4	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	5.3	–	–	150/7
U3-5	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	115.4	–	–	150/7
U3-6	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	56.2	–	–	150/7
U3-7	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	27.3	–	–	150/7

Appendix 1. Site locations, well and drivepoint information, and peat depths in and near Water Conservation Area 2A, central Everglades, south Florida.—Continued

NAD, North American Datum; NAD83, North American Datum of 1983; sw, surface-water sample collected using peristaltic pump with pump tubing often placed inside screened drivepoint to prevent sampling of macro algae; –, not applicable; gw, ground-water sample collected from established well; also see Harvey and others, 2000, for well-construction information; in, inch; sch, schedule; PVC, polyvinyl chloride (drivepoint with 5 centimeters of 0.01-in screen); ss, stainless steel; w/thin ext, with thin-walled PVC riser extension above screen; pw-peat, pore-water sample collected from drivepoint emplaced in peat layer; sw-mc, surface-water sample collected from Aquatic Cycling of Mercury in the Everglades mesocosm operated by U.S. Geological Survey Mercury Studies Team (http://sofia.usgs.gov/projects/evergl_merc/); pw-dl, pore-water sample collected from drivepoint emplaced in detrital layer; pw-tran, pore-water sample collected from fresh water marl/sand sediments that are transitional to underlying sand-limestone aquifer)]

U3-8	gw	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	11.0	–	–	150/7
U3-MC1	sw-mc	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	–	–	150/7
U3-MC2	sw-mc	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	–	–	150/7
U3-MC3	sw-mc	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	–	–	150/7
U3-MC4	sw-mc	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	–	–	150/7
U3-139	pw-tran	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	139	1.25 in sch 40 PVC	150/7
U3-57	pw-peat	26 17 13.664	80 24 41.991	27	2907655.53	558758.38	–	57	1.25 in sch 40 PVC	150/7
U3-S-7	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	7	1/2 in sch 40 PVC	150/7
U3-S-17	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	17	1/2 in sch 40 PVC	150/7
U3-S-37	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	37	1/2 in sch 40 PVC	150/7
U3-S-57	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	57	1/2 in sch 40 PVC	150/7
U3-S-77	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	77	1/2 in sch 40 PVC	150/7
U3-S-87	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	87	1/2 in sch 40 PVC	150/7
U3-S-92	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	92	1/2 in sch 40 PVC, w/thin ext	150/7
U3-S-102	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	102	1/2 in sch 40 PVC	150/7
U3-S-107	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	107	1/2 in sch 40 PVC	150/7
U3-S-112	pw-peat	26 17 13.68	80 24 42.54	83	2907616.16	558720.81	–	112	1/2 in sch 40 PVC	150/7
Unknown 1	sw	26 17 35.63	80 23 30.15	27	2908340.49	560747.56	–	–	–	–
Westgate	sw	26 18 28.3	80 18 54	27	2909999.10	568397.08	–	–	–	–
Willow head-main trail	sw	26 20 35.2	80 20 10.4	27	2913891.96	566258.59	–	–	–	–

[a] Location approximate

Appendix 2. Hydraulic conductivities of peat and underlying transitional sediments (fresh water marl/sand) from ground-water sampling sites in central Everglades, south Florida

[*K*, hydraulic conductivity; cm, centimeters; cm/d, centimeters per day]

	Site ID	Drivepoint diameter (cm)	Drivepoint screen length (cm)	Drivepoint depth: sediment surface to screen center (cm)	Method[a]	*K*(cm/d)
			Peat			
WCA-2A interior	F1-34	1.5	12.7	10	2	68
	F1-54	1.5	12.7	30	2	170
	F1-84	1.5	12.7	60	2	28
	F1-114	1.5	12.7	90	2	14
	F1-144	1.5	12.7	120	2	120
	F1-154	1.5	12.7	130	2	37
	U3-S-17	1.5	12.7	10	2	93
	U3-S-37	1.5	12.7	30	2	100
	U3-S-57	1.5	12.7	50	2	71
	U3-S-77	1.5	12.7	70	2	150
	U3-S-87	1.5	12.7	80	2	150
	U3-S-92	1.5	12.7	85	2	13
	U3-S-102	1.5	12.7	95	2	73
	U3-S-107	1.5	12.7	100	2	34
	U3-S-112	1.5	12.7	105	2	37
	E4-80	3.2	11.4	80	1	1,400
	F4-66	1.9	14.5	66	1	7.1
	F4-130	1	1	130	1	24
near WCA-2A levee	S10C-N-75[b]	1.5	12.7	20	2	30
	S10C-N-95[b]	1.5	12.7	40	2	22
	S10C-N-115[b]	1.5	12.7	60	2	42
	S10C-N-135[b]	1.5	12.7	80	2	17
ENR	M104-108	1	1	108	1	69
	M104-91	1	1	91	1	31
	M104-61	3.2	12.5	61	1	0.4
	M104-133	3.8	6.5	133	1	0.4
	M106-87	1	1	87	1	25
	M105-80	1	1	80	1	110
	M207-78	1.9	14.5	78	1	11
	M203-53	3.8	19.8	53	1	0.3
	M203-77	1.9	14.5	77	1	0.17
	M201-S-66	3.8	13.5	66	1	29
	M201-NW-50	2.5	14.5	50	1	6
	M201-NE-62	3.2	12.5	62	1	15
			Transitional sediments			
WCA-2A interior	F1-164	1.5	12.7	140	2	39
	F1-169	1.5	12.7	145	2	21
	F1-174	1.5	12.7	150	2	50
	F1-179	1.5	12.7	155	2	18
	F1-184	1.5	12.7	160	2	15
	F1-181	1.9	14.5	181	1	420
	F1-223	3.2	12.4	223	1	180
	U3-139	3.2	11.3	139	1	240

Appendix 2. Hydraulic conductivities of peat and underlying transitional sediments (fresh water marl/sand) from ground-water sampling sites in central Everglades, south Florida

[*K*, hydraulic conductivity; cm, centimeters; cm/d, centimeters per day]

	Site ID	Drivepoint diameter (cm)	Drivepoint screen length (cm)	Drivepoint depth: sediment surface to screen center (cm)	Method[a]	*K*(cm/d)
near WCA-2A levee	S10C-N-155[b]	1.5	12.7	100	2	17
	S10C-N-175[b]	1.5	12.7	120	2	7.5
	S10C-N-195[b]	1.5	12.7	140	2	2.4
	S10C-N-215[b]	1.5	12.7	160	2	1.2
	S10C-N-235[b]	1.5	12.7	180	2	3.3
	S10C-N-255[b]	1.5	12.7	200	2	20
	S10C-N-275	3.2	12.7	220	2	8.4
ENR	M103-118	1.9	14.5	117	1	4
	M206-79	1.9	14.5	79	1	38
	M201-NW-103	3.8	4.8	103	1	46
	M204-130	1.9	14.5	130	1	38
	M102-120	1.9	14.5	120	1	6.9

[a] 1 indicates that K was determined by bail-test method (Luthin and Kirkham, 1949) and 2 indicates use of a constant head, pump-out method (Tavenas and others, 1990; Brand and Premchitt, 1980).

[b] Hydraulic conductivity for these sites is a geometric mean of repeat tests conducted between 5/1/01 and 9/23/01.

Appendix 3 Surface- and ground-water levels at sites in Water Conservation Area 2A, central Everglades, south Florida.

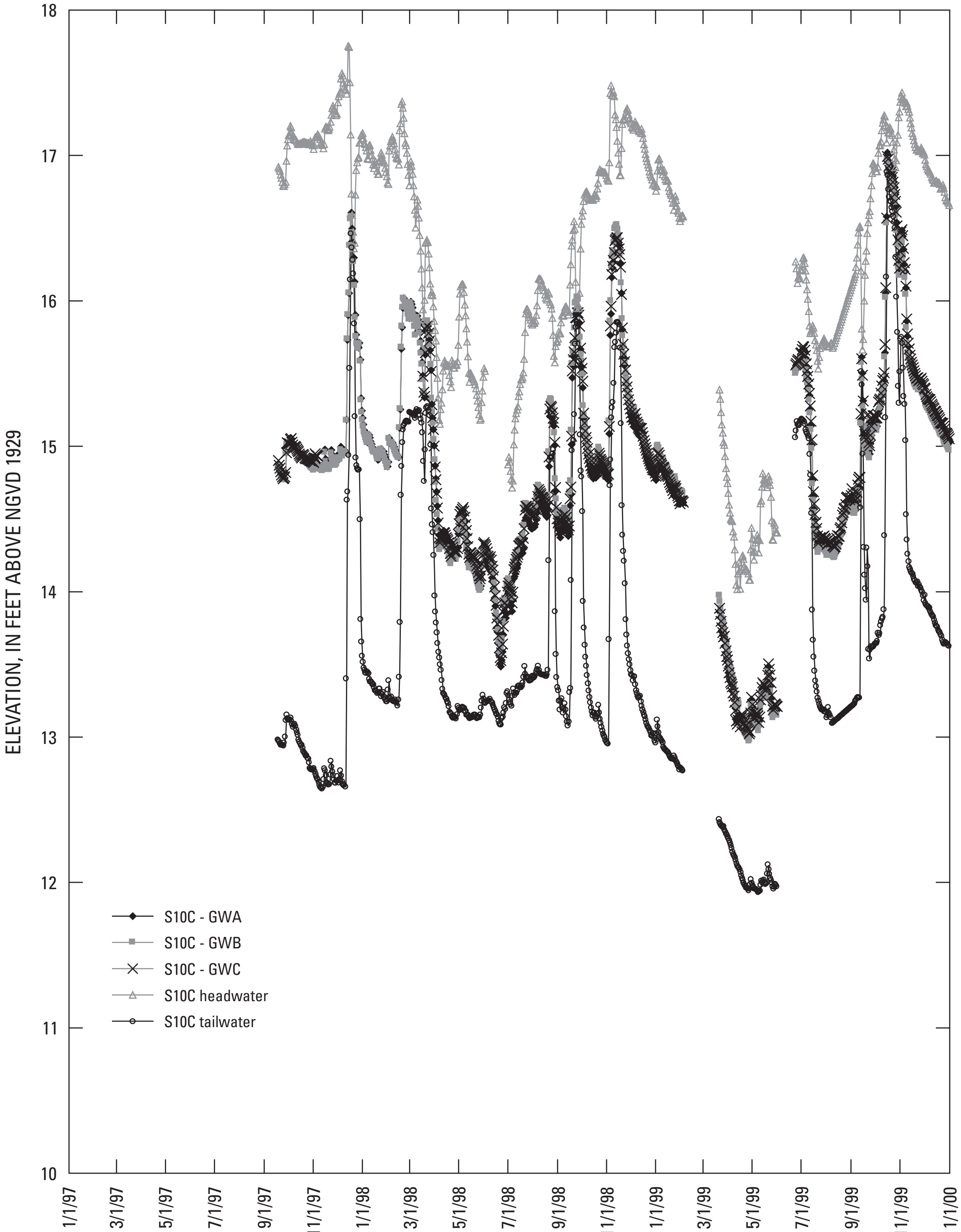
[NGVD 29; National Geodetic Vertical Datum of 1929; sw, surface water; –, not applicable; gw, ground water]

Site ID	Site type	Water-level observation date and time	Surface-water level,in feet above NGVD 29	Ground-water data		
				Tapedown, in feet	Reference elevation, in feet above NGVD 29	Hydraulic head, in feet above NGVD 29
E4	sw	1/13/2000 12:43	13.25	–	–	–
E4	sw	1/14/2000 9:11	13.24	–	–	–
E4-3	gw	1/13/2000 12:43	–	4.02	17.29	13.27
E4-4	gw	1/13/2000 12:43	–	4.00	17.28	13.28
E4-5	gw	1/14/2000 9:11	–	2.97	17.74	14.77
E4-6	gw	1/14/2000 9:11	–	2.88	17.74	14.86
E4-7	gw	1/14/2000 9:11	–	2.47	17.58	15.11
E4-8	gw	1/14/2000 9:11	–	2.42	17.56	15.14
F1	sw	1/13/2000 15:28	13.27	–	–	–
F1-3	gw	1/13/2000 15:28	–	4.64	17.96	13.32
F1-4	gw	1/13/2000 15:28	–	4.66	18.02	13.36
F4	sw	1/14/2000 14:07	13.21	–	–	–
F4-3	gw	1/14/2000 14:07	–	4.15	17.38	13.23
F4-4	gw	1/14/2000 14:07	–	4.35	17.57	13.22
S7E-1	gw	1/12/2000 10:00	–	2.03	16.43	14.40
S7E-2	gw	1/12/2000 10:00	–	2.94	16.45	13.51
S7E-3	gw	1/12/2000 10:00	–	3.62	16.43	12.81
S7E-4	gw	1/12/2000 10:00	–	3.65	16.46	12.81
U3	sw	1/13/2000 12:13	13.22	–	–	–
U3-3	gw	1/13/2000 8:50	–	3.83	17.23	13.40
U3-4	gw	1/13/2000 8:50	–	3.92	17.19	13.27
U3-5	gw	1/13/2000 8:50	–	1.59	18.38	16.79
U3-6	gw	1/13/2000 8:50	–	1.89	18.38	16.49
U3-7	gw	1/12/2000 15:00	–	2.62	18.28	15.66
U3-8	gw	1/12/2000 15:00	–	2.58	18.25	15.67
E1	sw	4/28/2000 11:00	13.84	–	–	–
E1-3	gw	4/28/2000 11:55	–	4.19	18.03	13.85
E1-4	gw	4/28/2000 11:30	–	4.20	18.04	13.83
E4	sw	4/25/2000 8:00	13.12	–	–	–
E4-3	gw	4/25/2000 11:35	–	4.17	17.29	13.12
E4-4	gw	4/25/2000 9:30	–	4.15	17.28	13.13
E4-5	gw	4/25/2000 12:50	–	3.13	17.74	14.61
E4-6	gw	4/25/2000 9:10	–	3.00	17.74	14.74
E4-7	gw	4/25/2000 12:15	–	2.59	17.58	14.99
E4-8	gw	4/25/2000 10:30	–	2.55	17.56	15.01
F1	sw	4/28/2000 9:20	13.73	–	–	–
F1-3	gw	4/28/2000 10:15	–	4.26	17.96	13.70
F1-4	gw	4/28/2000 9:45	–	4.30	18.02	13.72
F4	sw	4/26/2000 15:10	13.02	–	–	–
F4-3	gw	4/26/2000 4:15	–	4.36	17.38	13.02
F4-4	gw	4/26/2000 3:45	–	4.58	17.57	12.99
S10C-A	gw	4/24/2000 11:50	–	6.40	22.21	15.81
S10C-B	gw	4/24/2000 13:00	–	7.74	22.92	15.18
S10C-C	gw	4/24/2000 14:13	–	7.05	21.64	14.59
S10C-HW	sw	4/24/2000 10:00	16.28	–	–	–
S10C-TW	sw	4/24/2000 14:00	15.02	–	–	–
S7E-1	gw	4/26/2000 13:25	–	3.50	16.43	12.93
S7E-2	gw	4/26/2000 11:30	–	3.48	16.45	12.97
S7E-3	gw	4/26/2000 10:35	–	4.12	16.43	12.31

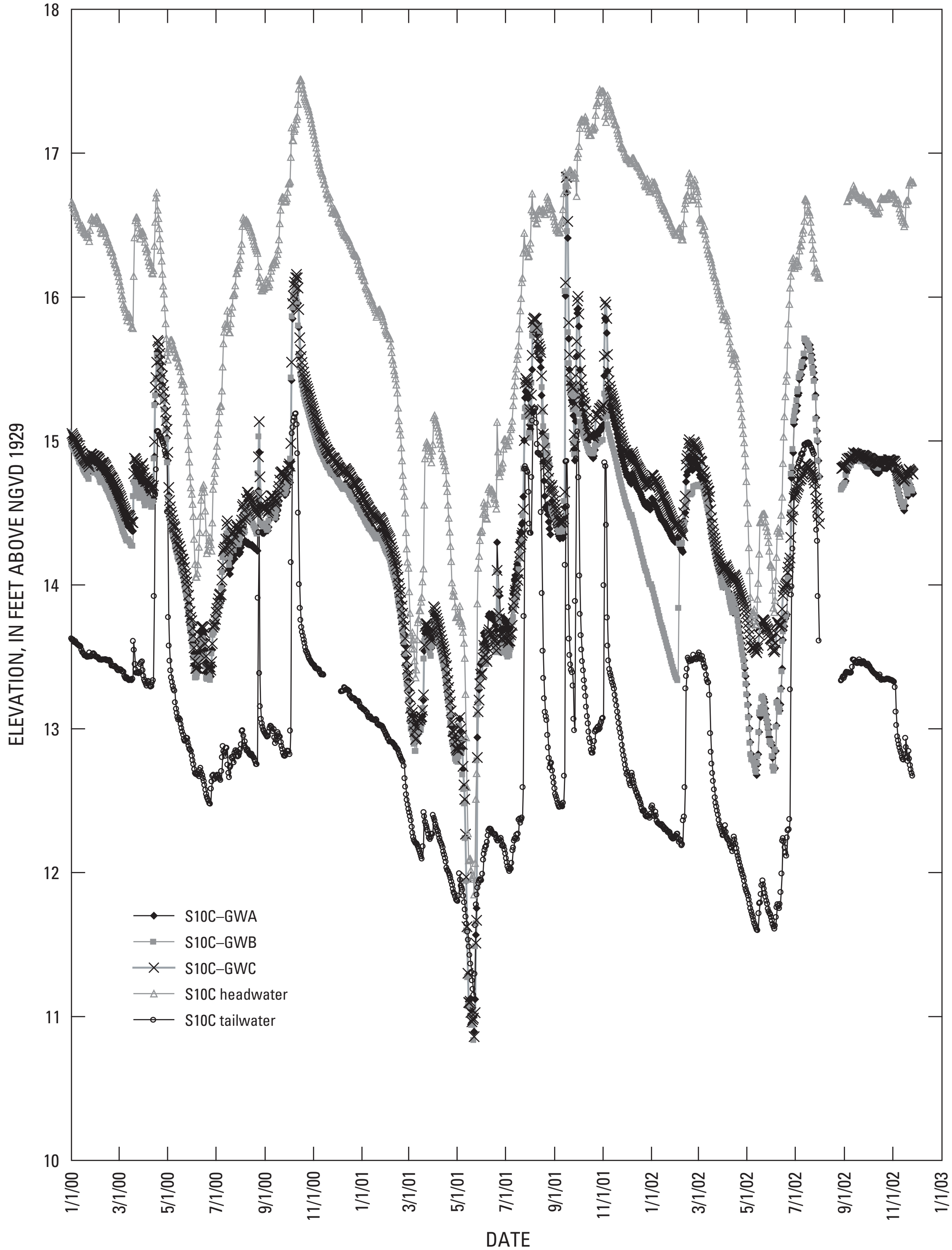
Appendix 3 Surface- and ground-water levels at sites in Water Conservation Area 2A, central Everglades, south Florida.—Continued

[NGVD 29; National Geodetic Vertical Datum of 1929; sw, surface water; –, not applicable; gw, ground water]

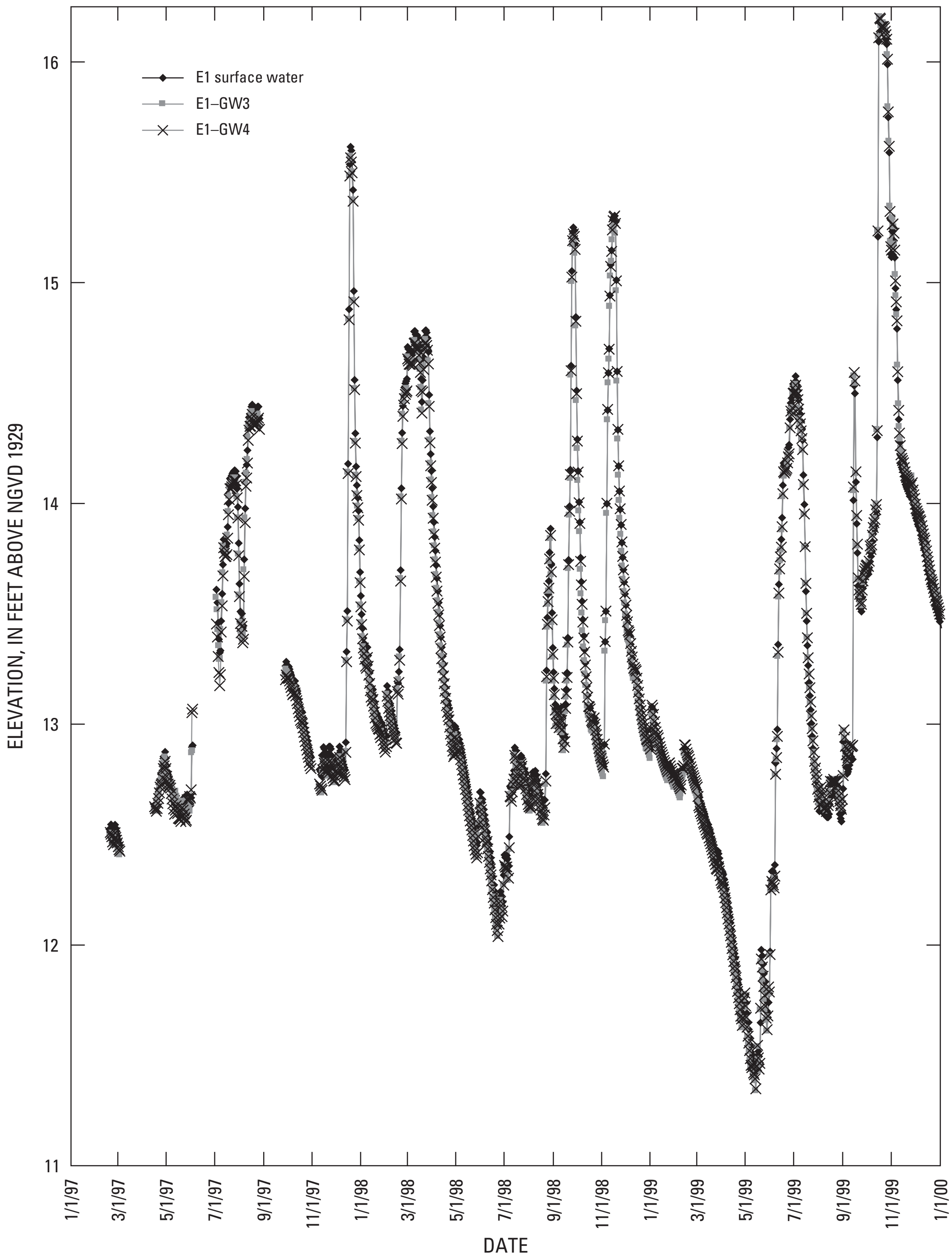
Site ID	Site type	Water-level observation date and time	Surface-water level,in feet above NGVD 29	Ground-water data		
				Tapedown, in feet	Reference elevation, in feet above NGVD 29	Hydraulic head, in feet above NGVD 29
S7E-4	gw	4/26/2000 9:15	–	4.10	16.46	12.36
U3	sw	4/27/2000 8:30	12.44	–	–	–
U3-3	gw	4/27/2000 10:15	–	4.79	17.23	12.44
U3-4	gw	4/27/2000 9:30	–	4.75	17.19	12.44
U3-5	gw	4/27/2000 15:05	–	2.45	18.38	15.93
U3-6	gw	4/27/2000 13:10	–	2.44	18.38	15.94
U3-7	gw	4/27/2000 11:50	–	3.45	18.28	14.83
U3-8	gw	4/27/2000 9:15	–	3.40	18.25	14.85
E4	sw	9/10/2000 12:00	12.32	–	–	–
E4-3	gw	9/10/2000 10:10	–	4.95	17.29	12.34
E4-4	gw	9/10/2000 9:40	–	4.94	17.28	12.34
E4-5	gw	9/10/2000 12:45	–	2.98	17.74	14.76
E4-7	gw	9/10/2000 11:30	–	3.28	17.58	14.30
E4-8	gw	9/10/2000 11:00	–	3.73	17.56	13.83
F1	sw	9/9/2000 12:00	12.96	–	–	–
F1-3	gw	9/9/2000 16:20	–	5.02	17.96	12.94
F1-4	gw	9/9/2000 16:00	–	5.07	18.02	12.95
U3	sw	9/9/2000 12:00	11.94	–	–	–
U3-3	gw	9/9/2000 10:20	–	5.30	17.23	11.93
U3-4	gw	9/9/2000 9:40	–	5.25	17.19	11.94
U3-5	gw	9/9/2000 13:25	–	3.56	18.38	14.82
U3-6	gw	9/9/2000 12:45	–	3.83	18.38	14.55
U3-7	gw	9/9/2000 11:30	–	6.33	18.28	11.95
U3-3	gw	9/25/2001 11:15	–	4.31	17.23	12.92
U3-4	gw	9/25/2001 12:05	–	4.27	17.19	12.92
U3-5	gw	9/25/2001 13:10	–	5.57	18.38	12.81
U3-6	gw	9/25/2001 14:10	–	5.98	18.38	12.40



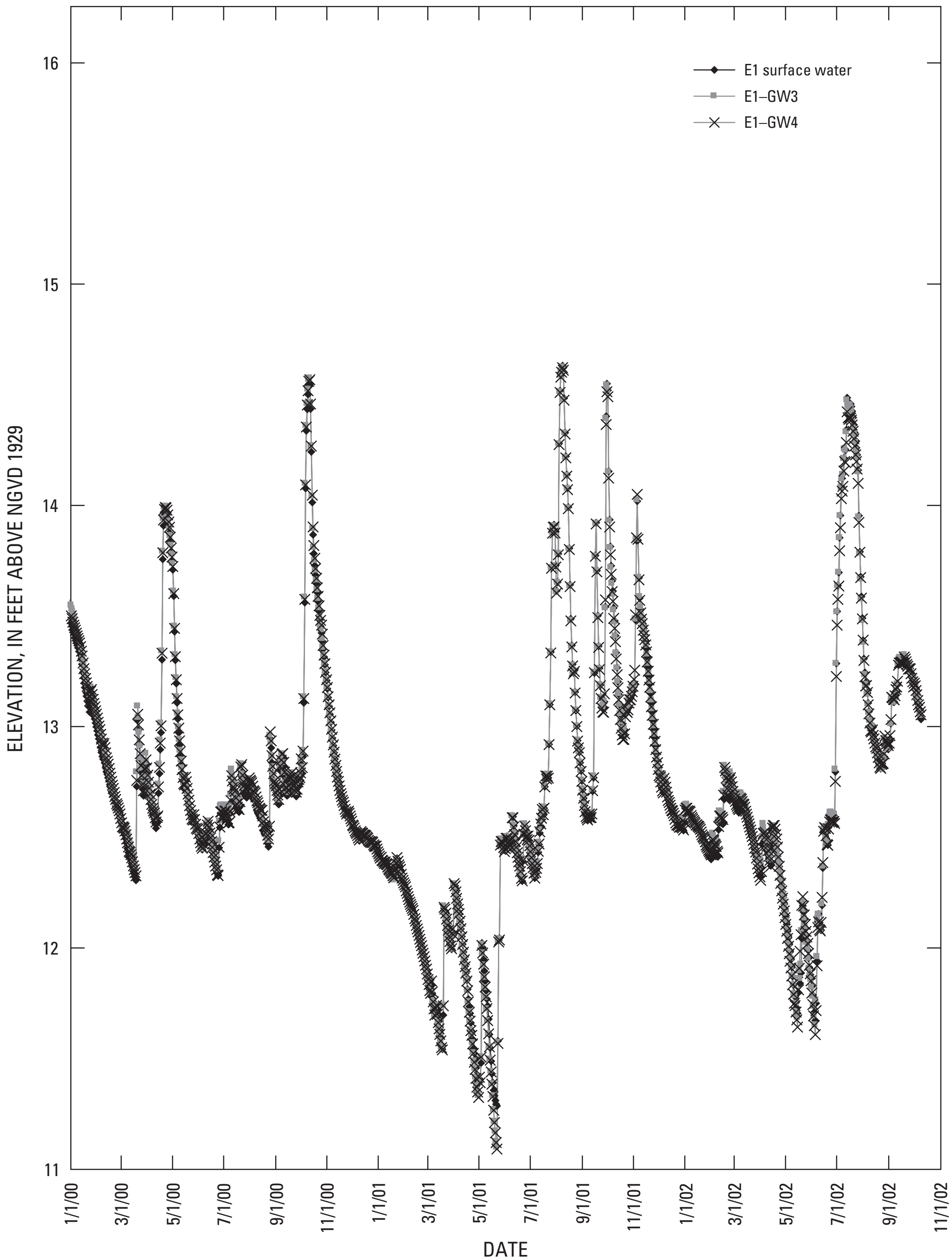
Appendix 4. Surface-water (headwater and tailwater) and ground-water levels (GWA, GWB, and GWC) in 1997, 1998, and 1999, for site S10C, central Everglades, south Florida.



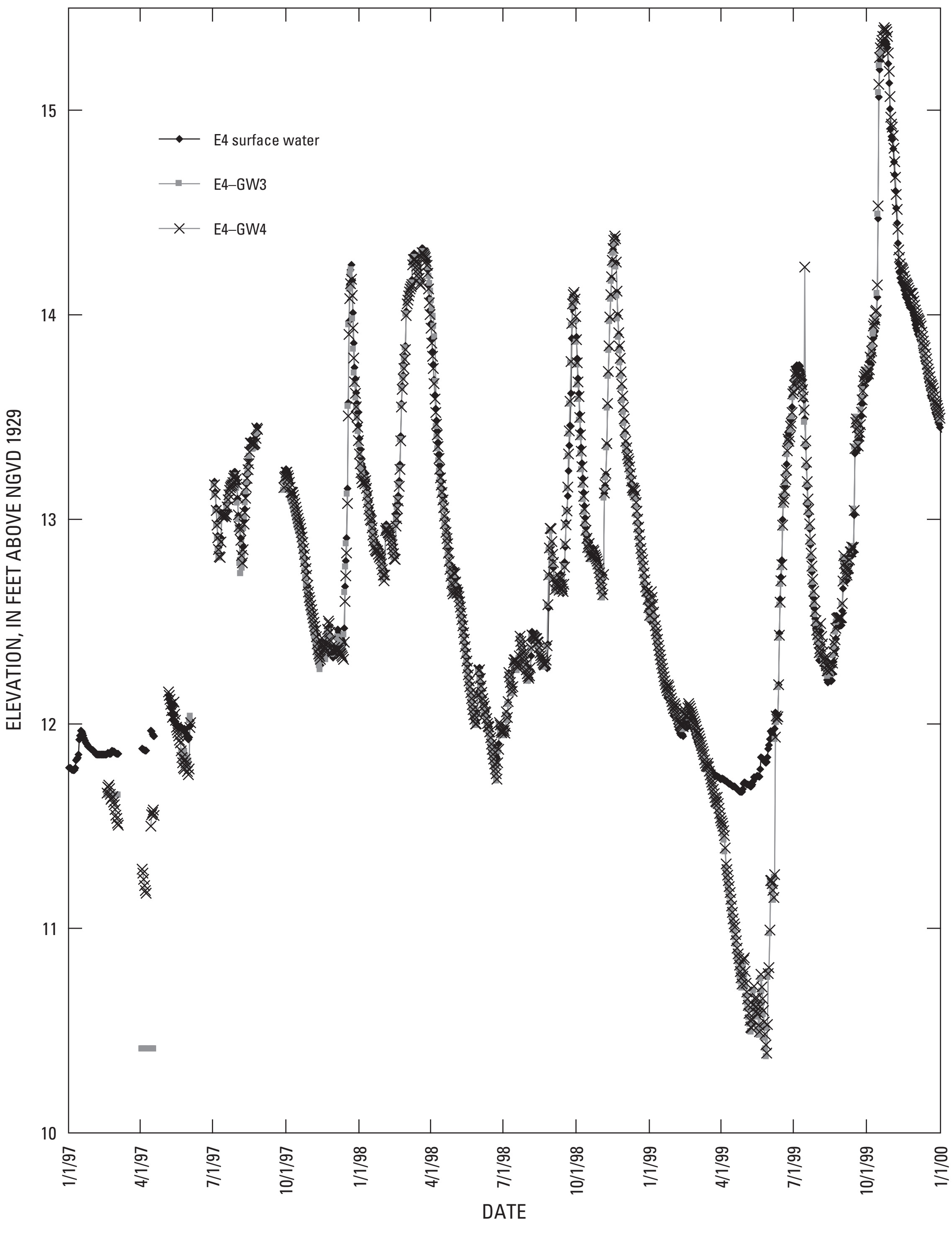
Appendix 5. Surface-water (headwater and tailwater) and ground-water levels (GWA, GWB, and GWC) in 2000, 2001, and 2002, for site S10C, central Everglades, south Florida.



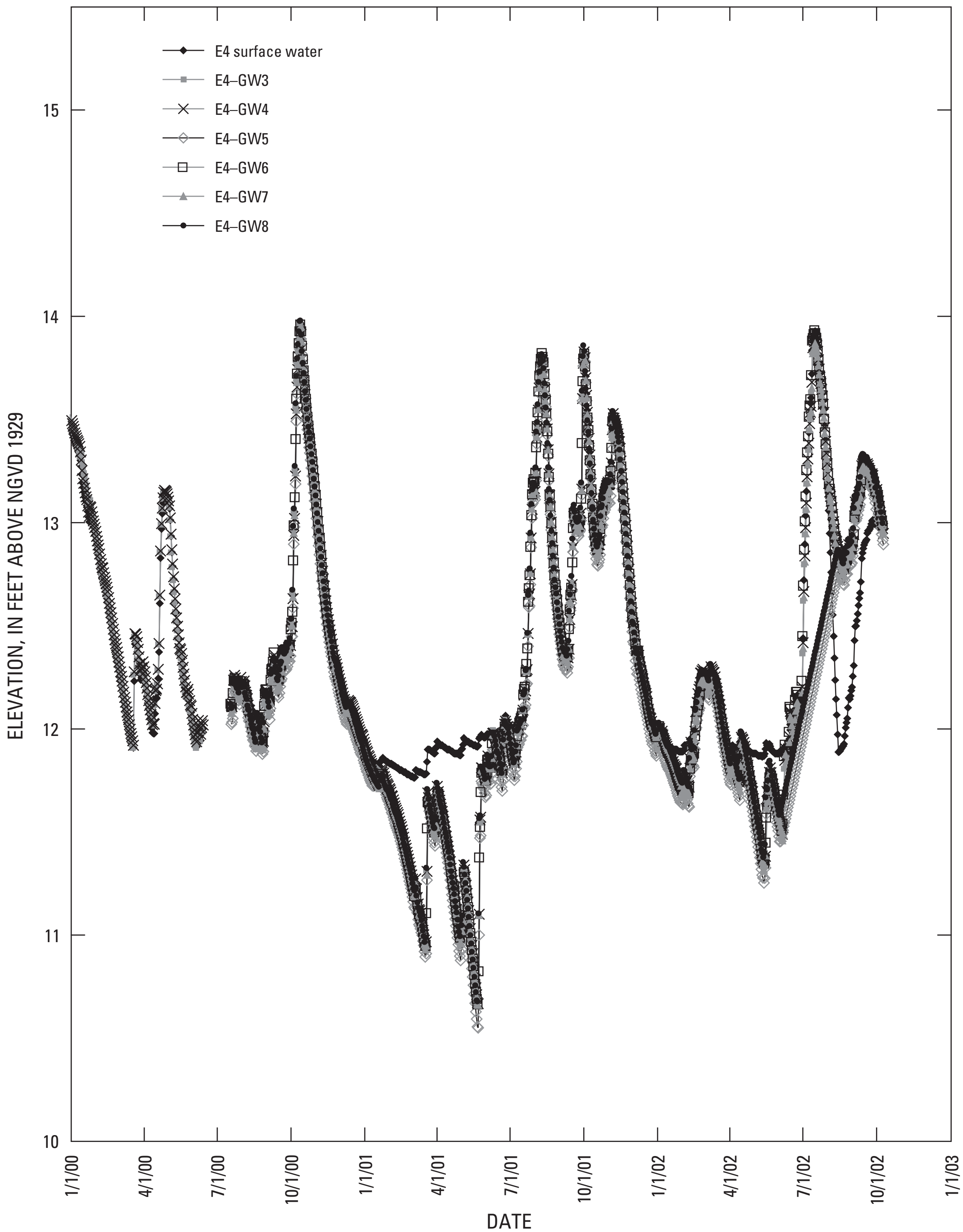
Appendix 6. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site E1, central Everglades, south Florida.



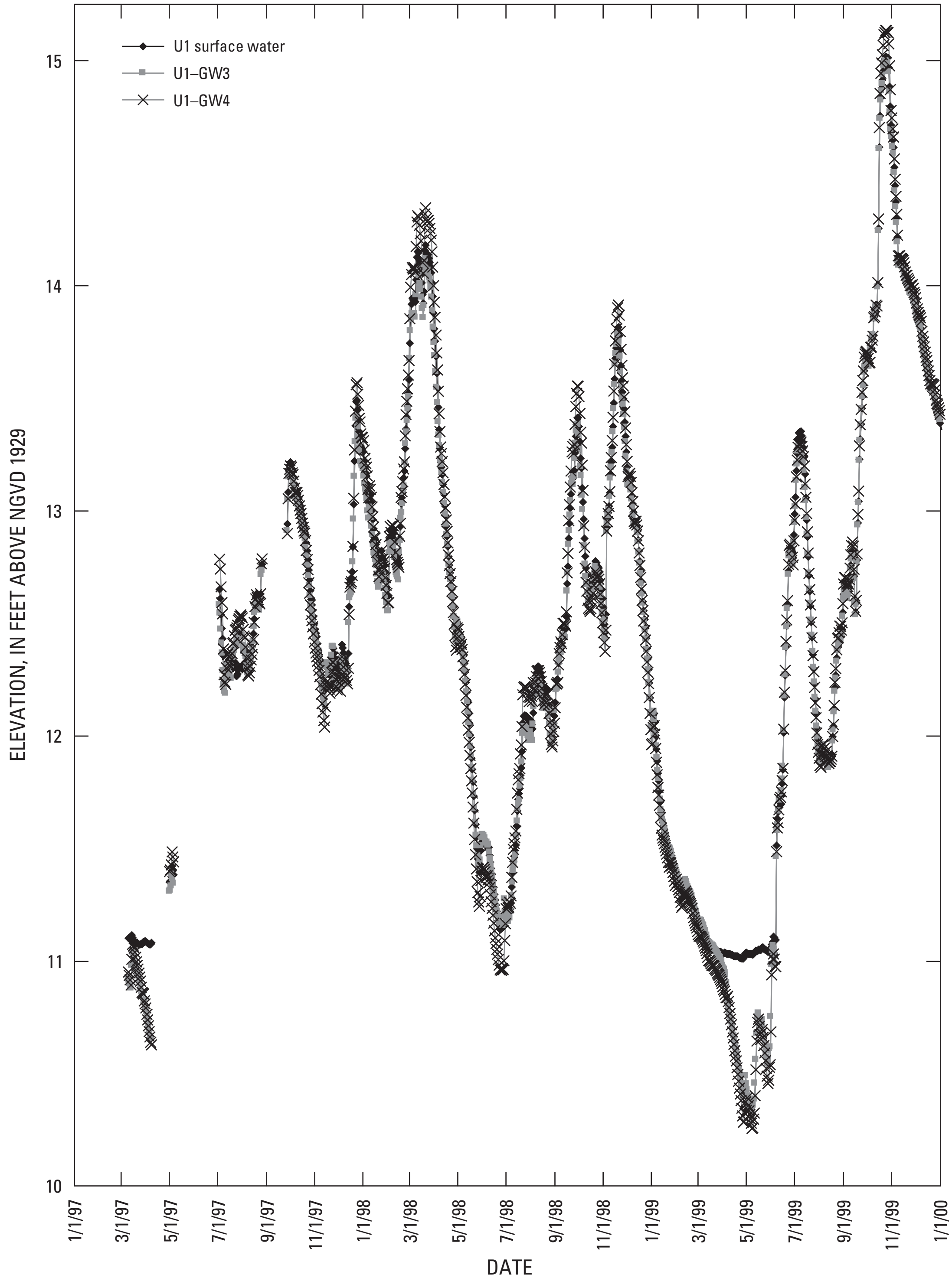
Appendix 7. Surface-water and ground-water levels (GW3 and GW4) in 2000, 2001, and 2002, for site E1, central Everglades, south Florida.



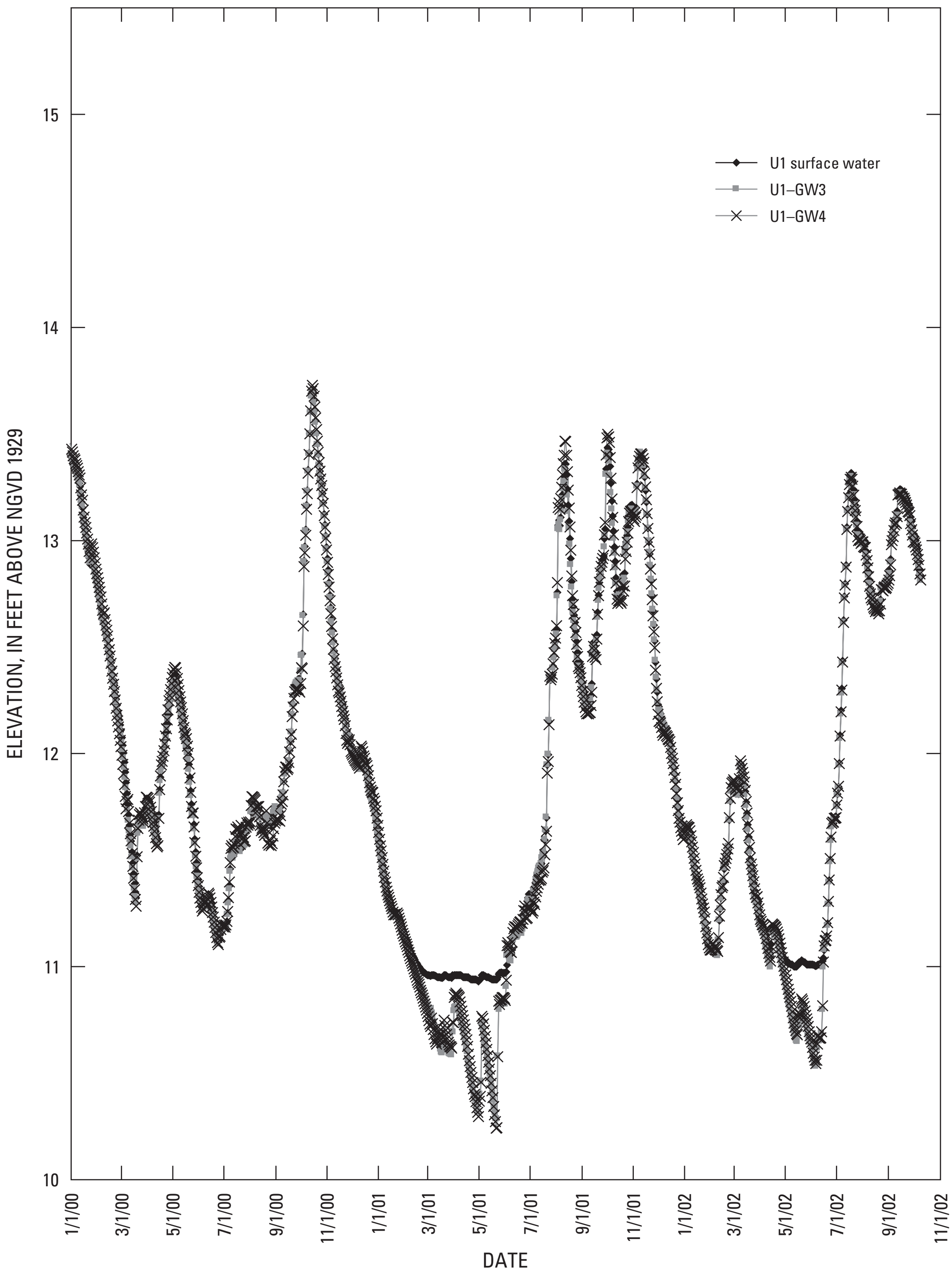
Appendix 8. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site E4, central Everglades, south Florida. Note that the GW4 data from 2/18/1997 to 7/14/1999 was adjusted by 1.42 feet (representing the change in datum due to resurveying). This adjustment is not currently reflected in the South Florida Water Management District database.



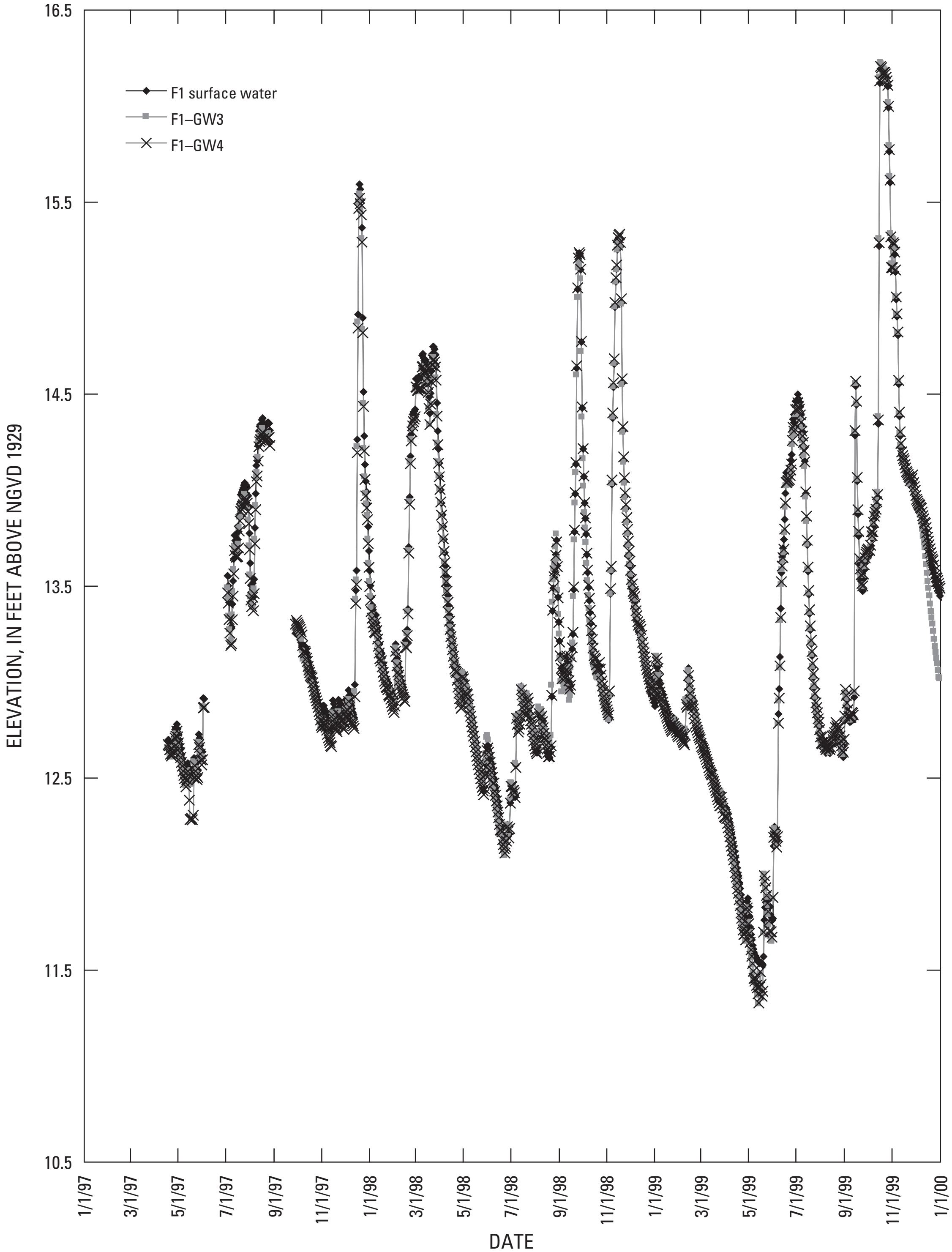
Appendix 9. Surface-water and ground-water levels (GW3, GW4, GW5, GW6, GW7, and GW8) in 2000, 2001 and 2002, for site E4, central Everglades, south Florida.



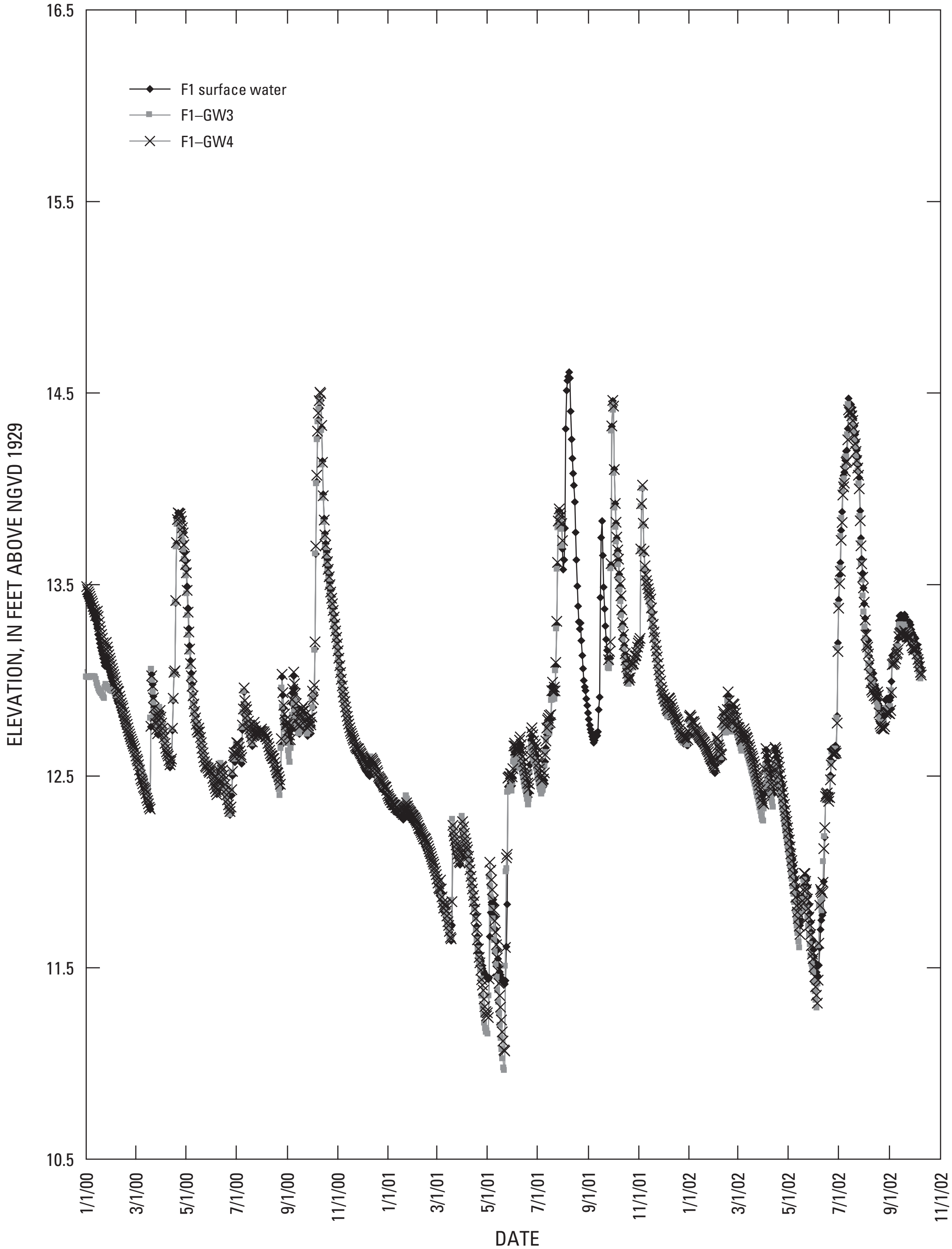
Appendix 10. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site U1, central Everglades, south Florida.



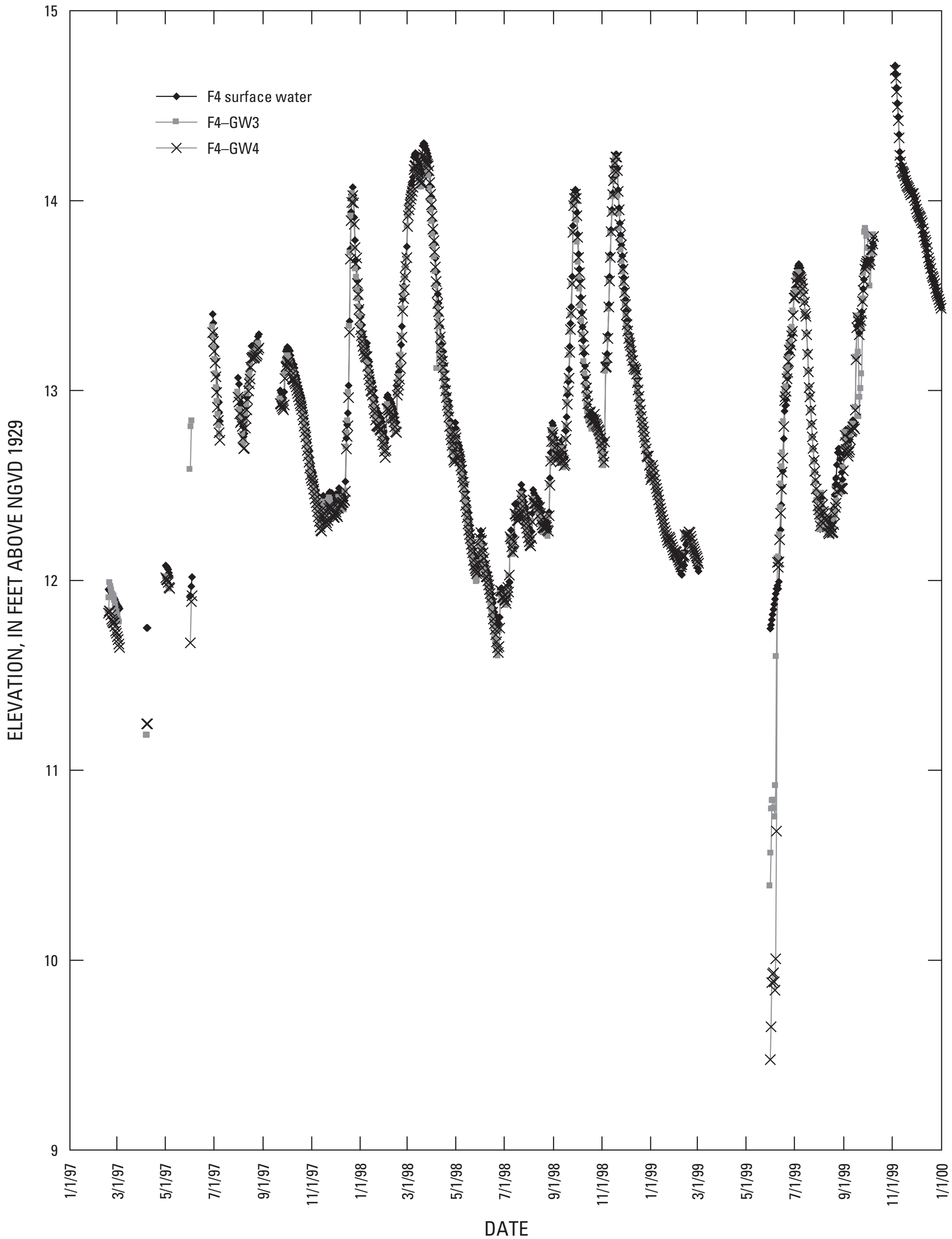
Appendix 11. Surface-water and ground-water levels (GW3 and GW4) in 2000, 2001, and 2002, for site U1, central Everglades, south Florida.



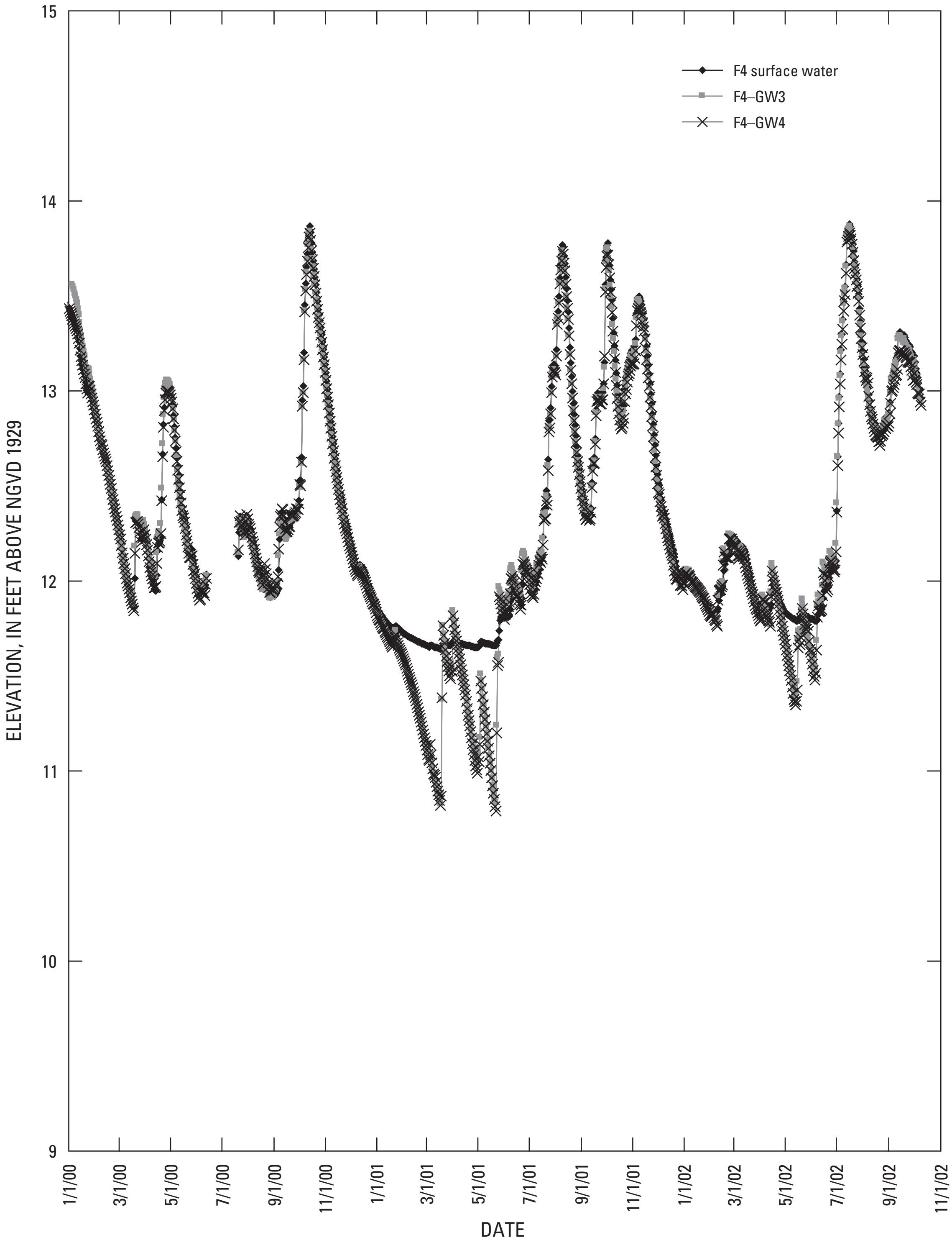
Appendix 12. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site F1, central Everglades, south Florida.



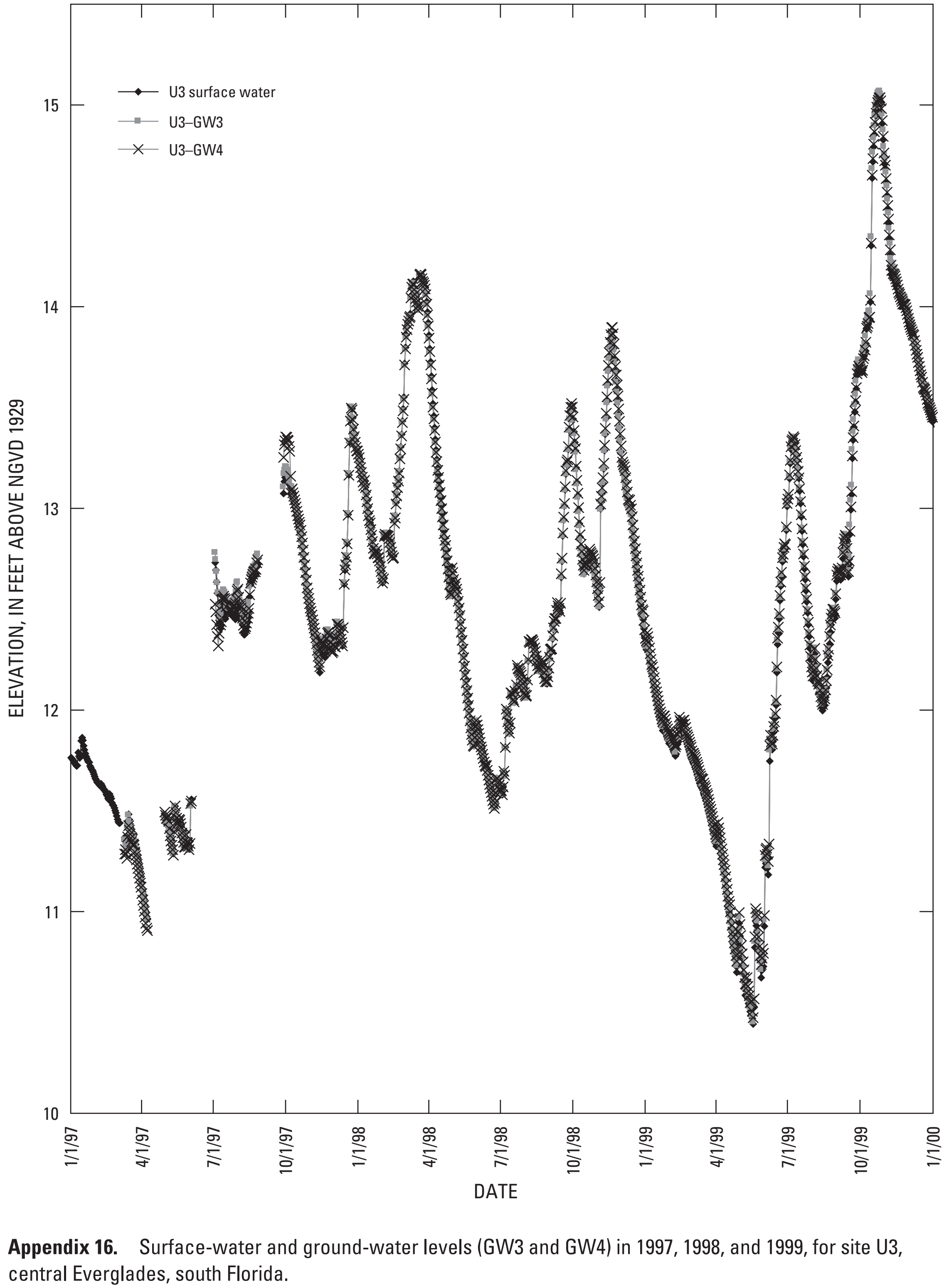
Appendix 13. Surface-water and ground-water levels (GW3 and GW4) in 2000, 2001, and 2002, for site F1, central Everglades, south Florida.



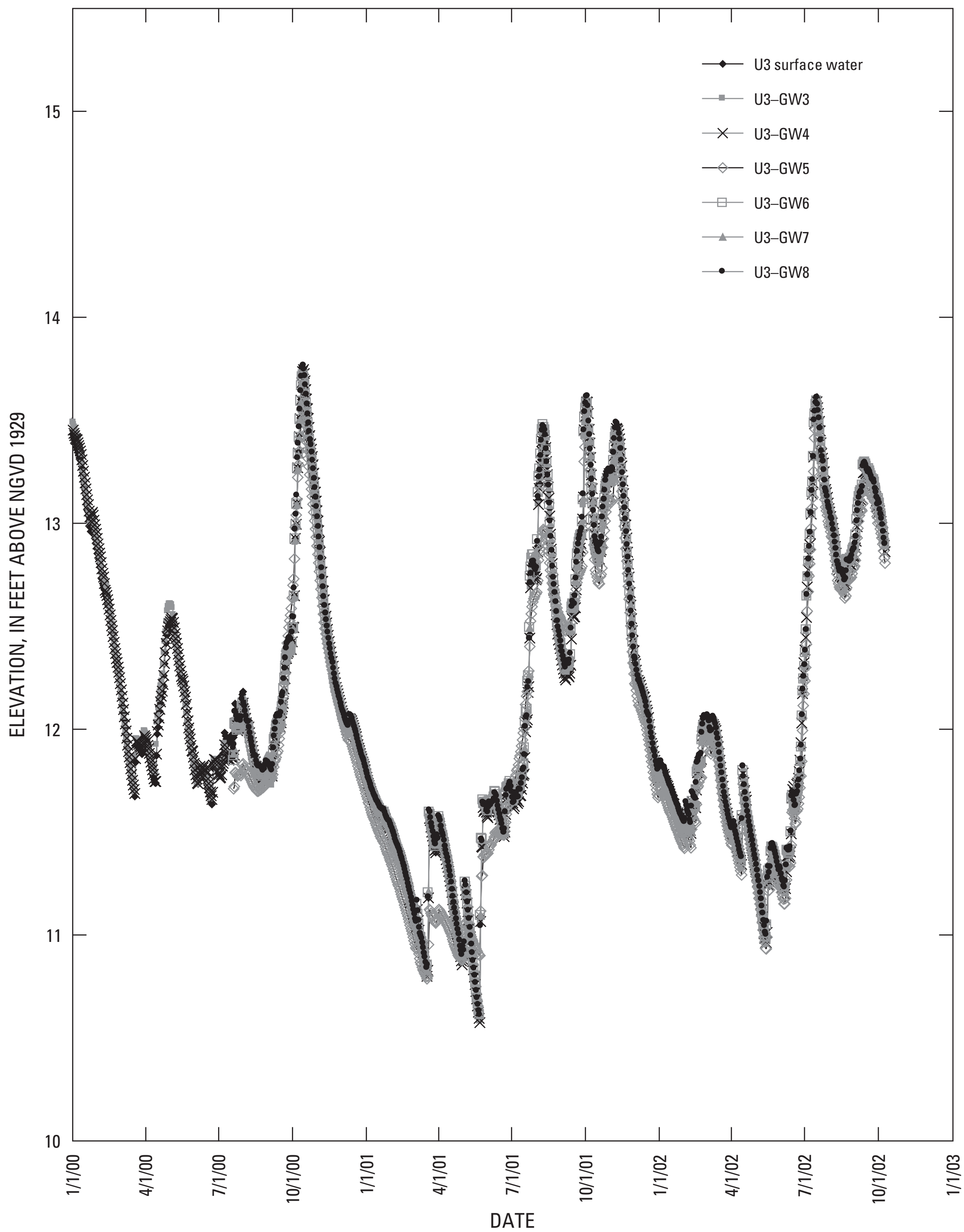
Appendix 14. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site F4, central Everglades, south Florida.



Appendix 15. Surface-water and ground-water levels (GW3 and GW4) in 2000, 2001, and 2002, for site F4, central Everglades, south Florida.



Appendix 16. Surface-water and ground-water levels (GW3 and GW4) in 1997, 1998, and 1999, for site U3, central Everglades, south Florida.



Appendix 17. Surface-water and ground-water levels (GW3, GW4, GW5, GW6, GW7, and GW8) in 2000, 2001, and 2002, for site U3, central Everglades, south Florida.

Appendix 18. Results of radium analyses of surface-water, ground-water, and peat pore water samples in central Everglades, south Florida, September 8-12, 2000.

[^{223}Ra, ^{224}Ra, ^{226}Ra, isotopes of radium; dpm/L, disintegration per minute per liter; ^{228}Th, isotope of thorium; ^{222}Rn, isotope of radon; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; sw, surface water; –, no sample, no measurement, no analysis, or not applicable; gw, ground water; pw-peat, pore water in peat layer; n.d., no data, lost sample; sw-mc, surface-water sample collected from Aquatic Cycling of Mercury in the Everglades mesocosm operated by U.S. Geological Survey Mercury Studies Team (http://sofia.usgs.gov/projects/evergl_merc/)]

Site ID	Site and sample type	Date	Depth, in meters[a]	^{223}Ra (dpm/100L)	^{223}Ra, in standard error	^{224}Ra (excess) (dpm/100L)	^{224}Ra, in standard error	^{228}Th (dpm/100L)	^{222}Rn (dpm/L)	^{222}Rn, in standard error	NH_4 (µM)	PO_4 (µM)	^{228}Ra (dpm/100L)	^{226}Ra (dpm/100L)
				Analyst										
				J. Krest, USGS							W. Orem, USGS		T. Kraemer, USGS	
E4	sw	9/10/00	–	0.01	0.01	5.6	0.24	–	23.0	1.40	0.29	<0.2	10.5	60.4
E4-5	gw	9/10/00	35.8	45.6	2.56	192	6.73	3.35	–	–	32.0	0.28	64.8	463
E4-7	gw	9/10/00	8.8	42.4	2.54	47.6	3.11	4.42	1,148	39	31.5	2.26	32.4	664
E4-8	gw	9/10/00	4.2	5.87	0.49	42.9	1.65	1.75	1,155	31	67.9	0.28	31.1	146
F1	sw	9/8/00	–	0.45	0.08	6.2	0.33	0.60	2.29	0.68	–	–	7.4	91.0
F1	sw	9/12/00	–	0.34	0.03	10.2	0.21	0.33	4.70	0.80	1.23	0.75	9.4	109
F1-50	pw-peat	9/11/00	0.50	0.65	0.22	19.2	1.15	1.46	52.0	15	12.1	1.34	15.6	234
F1-100	pw-peat	9/11/00	1.00	–	–	–	–	–	155	14	37.7	0.86	–	–
F1-125	pw-peat	9/11/00	1.25	1.35	0.34	46.6	2.22	–	94.0	11	48.6	4.19	47.8	153
F1-3	gw	9/9/00	7.9	–	–	–	–	–	3,192	80	50.0	0.85	–	–
F1-4	gw	9/9/00	2.0	4.07	0.45	25.1	1.26	0.27	579	28	78.9	0.28	20.0	79.7
F1-MC1	sw-mc	9/8/00	–	0.52	0.05	13.9	0.37	0.36	–	–	–	–	9.8	112
F1-MC1	sw-mc	9/12/00	–	0.42	0.04	5.9	0.23	0.30	–	–	29.2	0.45	4.9	53.6
F1-MC1 rerun	sw-mc	9/8/00	–	0.45	0.04	15.9	0.42	0.01	–	–	–	–	–	–
F1-MC2	sw-mc	9/12/00	–	0.09	0.02	3.3	0.17	0.03	2.00	0.60	–	–	4.0	42.1
S10C_HW	sw	9/11/00	–	1.37	0.18	5.2	0.33	0.28	–	–	–	–	17.4	132
U3	sw	9/8/00	–	0.13	0.05	3.1	0.21	0.28	6.50	0.60	0.75	0.33	4.0	54.3
U3	sw	9/12/00	–	0.02	0.02	3.6	0.23	0.61	3.40	0.80	0.73	0.23	1.9	–
U3-50	pw-peat	9/11/00	0.50	0.53	0.44	23.1	3.03	1.19	9.00	12	82.3	1.21	17.6	71.0
U3-100	pw-peat	9/11/00	1.00	–	–	–	–	–	35.00	13	89.7	<0.2	–	–
U3-112	pw-peat	9/11/00	1.12	3.91	0.47	56.7	2.12	3.09	n.d.	–	93.4	<0.2	45.5	53.0
U3-3	gw	9/9/00	8.0	82.1	2.46	32.2	3.00	7.61	2,190	27	42.3	0.53	12.4	1,312
U3-3 rerun	gw	9/9/00	8.0	72.9	2.92	45.1	8.00	7.58	–	–	–	–	–	–
U3-4	gw	9/9/00	1.6	8.02	0.67	19.7	3.00	0.12	796	40	59.8	<0.2	17.5	102
U3-MC3	sw-mc	9/8/00	–	0.17	0.04	4.0	0.26	0.08	–	–	12.4	<0.2	4.4	46.0
U3-MC3	sw-mc	9/12/00	–	0.07	0.01	1.4	0.07	0.15	–	–	11.9	<0.2	3.5	42.4
U3-MC4	sw-mc	9/12/00	–	0.24	0.05	5.4	0.28	0.02	4.80	0.80	–	–	5.1	70.5

[a] Measured relative to the peat surface. Positive values are below the peat surface.

Appendix 19. Results of chemical analyses from surface-water samples in central Everglades, south Florida, September 8-10, 1999.

[° C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; MDL, minimum detection limit; –, no sample, no measurement, no analysis, or not applicable]

Site ID	Date	Field parameters				Laboratory analyses[a,b]									Cation/anion balance[c] (percent)
		Temperature (°C)	pH	DO (mg/L)	Specific conductance (µS)	Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)	
						MDL									
						1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05	
1/2 Westgate to camp 6	9/10/1999	27.78	6.98	–	474	–	–	–	–	–	–	–	–	–	–
1/2 Westgate to south trail intersect	9/10/1999	29.06	7.2	–	930	–	–	–	–	–	–	–	–	–	–
1st trail split	9/10/1999	28.21	7.27	–	1,248	–	–	–	–	–	–	–	–	–	–
2nd trail split	9/10/1999	26.72	7.12	–	1,046	1,030	82	110	27	21	140	283	45	0.5	5.59
A1	9/8/1999	24.90	6.94	–	800	715	58	71	19	14	98	202	19	0.3	4.21
A3	9/8/1999	27.24	6.69	–	1260	–	–	–	–	–	–	–	–	–	–
A4	9/8/1999	27.73	7.3	–	585	574	49	49	16	12	67	178	14	0.1	3.04
A5	9/9/1999	26.53	7.27	1.75	597	574	50	50	16	16	70	181	11	0.1	2.73
Back in main trail	9/10/1999	26.56	7.11	–	944	–	–	–	–	–	–	–	–	–	–
Boat ramp	9/8/1999	30.21	8	–	1,218	–	–	–	–	–	–	–	–	–	–
Camp 6	9/9/1999	27.72	7.04	–	376	369	31	33	8.9	7	45	106	8.2	0.08	3.76
E4	9/9/1999	25.58	7.08	–	513	499	43	43	13	9.5	60	152	12	0.1	2.74
Emain junction	9/10/1999	26.97	7.32	–	600	593	51	52	15	12	74	183	12	2	1.59
E-S10 trail willow	9/9/1999	26.78	7.24	–	993	942	60	100	20	14	170	187	37	0.4	1.10
F4	9/9/1999	26.2	7.17	–	547	541	48	47	15	13	64	171	12	0.2	3.33
Left split main trail	9/10/1999	26.65	7.21	–	965	947	74	97	25	19	130	256	43	0.4	4.64
Left split willow	9/10/1999	27.73	7.28	–	773	759	60	73	20	17	100	209	28	0.4	4.12
Main trail offshoot	9/10/1999	26.63	7.28	–	864	–	–	–	–	–	–	–	–	–	–
Near F1	9/9/1999	28.97	7.51	–	808	792	62	85	20	18	120	214	17	0.3	4.03
Plane	9/9/1999	29.43	7.61	–	587	572	48	52	15	12	73	167	17	0.1	3.30
South trail intersect	9/10/1999	29.78	7.28	–	1,213	–	–	–	–	–	–	–	–	–	–
S10C-H	9/10/1999	28.13	7.42	–	1,391	1,200	110	130	37	26	180	361	80	0.6	4.94
S10C-T	9/10/1999	28.12	7.47	–	1,360	1,320	110	130	37	26	180	359	80	0.6	5.09
U3	9/8/1999	28.74	7.48	–	605	601	45	56	16	15	81	168	18	0.1	1.96
Unknown 1	9/8/1999	29.47	7.85	–	573	–	–	–	–	–	–	–	–	–	–
Westgate	9/10/1999	28	7.12	–	688	607	51	60	17	16	89	174	23	0.3	3.17
Willow head-main trail	9/10/1999	26.95	7.25	–	655	–	–	–	–	–	–	–	–	–	–

[a] QWSU, U.S. Geological Survey Water Quality Service Unit, Ocala, Florida

[b] Results below the MDL are listed as the MDL.

[c] Calculated using milliequivalents as (cations - anions)/(cations + anions) * 100

Appendix 20. Results of chemical analyses of surface-water and ground-water samples in central Everglades, south Florida, January 11-14, 2000.

[° C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; ORP, oxidation–reduction potential; mV, millivolt; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; δ^2H, isotopic ratio of hydrogen-2; °/oo, per mil; $\delta^{18}O$, isotopic ratio of oxygen-18; CH_4, methane; N_2, nitrogen; O_2, oxygen; Ar, argon; MDL, minimum detection limit; sw, surface water; gw, ground water; –, no sample, no measurement, no analysis, or not applicable]

			Field parameters					Laboratory analyses[b]										Laboratory analyses[b]							
								QWSU[c]										USGS[e]		USGS[f]		USGS[g]			
Site ID	Sample type	Date	Temperature (°C)	pH	DO (mg/L)	ORP[a] (mV)	Specific conductance (µS)	Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)	Cation/ anion balance[d] (percent)	NH_4 (µM)	PO_4 (µM)	δ^2H (°/oo)	$\delta^{18}O$ (°/oo)	CH_4 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)
								MDL										MDL							
								1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05		0.1	0.2	–	–	0.005	0.05	0.03	0.005
E4	sw	1/13/2000	18.50	7.42	1.78	12.6	864	874	71	76	23	17	110	238	41	0.3	3.52	0.5	0.2	-8.2	-1.5	0.042	14.33	0.06	0.551
E4-3	gw	1/13/2000	23.81	6.61	0.6	-69.5	2,189	2,180	150	270	27	14	460	441	1.2	1	-0.83	37.6	0.5	10.5	1.6	2.294	12.56	0.03	0.479
E4-4	gw	1/13/2000	23.50	6.6	0.62	-67.5	1,489	1,480	120	160	15	14	260	360	0.6	0.7	-1.25	54.9	0.3	11.3	1.79	4.634	13.06	0.03	0.488
E4-5	gw	1/14/2000	24.42	6.92	0.84	-213.2	5,827	5,150	190	940	88	20	1,500	485	300	3.2	3.12	22.4	0.3	3.6	0.12	0.021	15.87	0.05	0.569
E4-6	gw	1/14/2000	24.00	7.41	0.23	-237.4	4,364	4,370	150	730	42	38	1,100	420	150	2.4	2.65	23.0	0.5	4.8	0.5	0.050	14.82	0.06	0.554
E4-7	gw	1/14/2000	23.92	6.79	0.65	-191.6	3,407	3,390	160	500	39	15	810	481	45	1.3	0.23	31.9	3.4	8.2	1.07	0.076	15.45	0.08	0.541
E4-8	gw	1/14/2000	23.75	8.05	0.24	-207.7	1,803	1,770	130	220	17	18	280	383	6.1	0.9	5.60	52.9	0.4	11.6	1.72	3.297	13.25	0.03	0.495
F1	sw	1/13/2000	21.86	7.59	5.2	6.2	1,251	1,250	93	120	34	21	180	337	48	0.5	2.05	1.4	0.4	-4.4	-0.83	0.087	12.74	4.80	0.522
F1-3	gw	1/13/2000	23.34	6.63	0.78	-217.1	5,691	5,750	130	1,000	73	18	1,400	723	170	2.1	0.76	51.7	0.9	9.2	1.49	0.066	13.37	0.06	0.482
F1-4	gw	1/13/2000	23.33	6.61	1.68	-84.2	2,638	2,640	140	390	40	16	550	588	1	1.2	-0.08	–	–	7.2	0.88	2.188	13.11	0.03	0.479
F4	sw	1/14/2000	20	7.57	3.67	5	1,225	1,240	97	110	35	21	170	324	71	0.5	3.03	1.1	0.2	-2.2	-0.64	0.022	16.37	2.45	0.583
F4-3	gw	1/14/2000	23.65	6.76	0.45	-207.4	1,681	1,660	130	180	31	22	250	501	2.2	0.7	-0.65	49.0	0.6	10.8	1.45	6.703	11.36	0.03	0.448
F4-4	gw	1/14/2000	22.99	6.73	0.53	-78.9	1,728	1,720	140	190	28	22	260	516	0.2	0.7	-0.29	63.4	0.3	9.2	0.91	6.430	10.67	0.03	0.440
S10C-A	gw	1/11/2000	24	6.8	2.27	-304.6	1,304	1,290	110	120	30	21	150	433	13	0.5	0.76	70.4	0.2	6.3	0.82	14.625	6.17	0.12	0.262
S10C-A EB	blank	1/11/2000	–	–	–	–	–	1.2	0.02	0.1	0.003	0.2	0.1	2.9	0.2	0.05	–	0.1	0.2	–	–	–	–	–	–
S10C-A FB	blank	1/11/2000	–	–	–	–	–	1.5	0.03	0.1	0.007	0.2	0.1	3	0.2	0.05	–	0.1	0.2	–	–	–	–	–	–
S10C-B	gw	1/11/2000	25.4	6.9	0.06	-213.7	1,020	1,020	83	82	24	37	120	347	2.4	0.4	-3.28	143	0.5	7.4	0.67	12.817	7.98	0.11	0.349
S10C-B REP	gw	1/11/2000	–	–	–	–	–	1,020	85	81	25	37	120	345	5.2	0.4	-2.47	179	0.3	–	–	–	–	–	–
S10C-B SPLIT	gw	1/11/2000	–	–	–	–	–	1,020	84	81	24	37	120	347	1.9	0.4	-3.23	159	0.4	–	–	–	–	–	–
S10C-C	gw	1/11/2000	25.38	6.89	-0.01	-217.6	1,020	1,010	91	86	29	34	140	353	30	0.5	-2.51	111	2.1	3.1	0.39	3.376	10.74	0.03	0.409
S10C-HW	sw	1/11/2000	23.02	7.33	6.19	–	692	697	55	61	16	12	91	170	38	0.3	3.73	0.7	1.2	5.3	0.7	0.022	15.93	5.20	0.575
S10C-TW	sw	1/11/2000	–	–	–	–	–	810	64	72	19	14	100	211	36	0.3	3.94	5.2	0.3	4.2	0.61	0.223	13.54	3.04	0.516
S7E	sw	1/12/2000	21.58	7.65	6.63	223.4	1,087	1,090	85	100	29	22	150	290	57	0.3	2.58	0.9	0.2	-7.0	-1.14	0.043	12.85	4.35	0.494
S7E-1	gw	1/12/2000	25.22	6.88	3.45	-288.4	9,540	9,590	130	1,500	168	24	2,700	783	440	4.4	-5.19	32.0	2.1	4.1	0.45	0.064	14.97	0.07	0.547
S7E-2	gw	1/12/2000	25.18	6.91	0.65	-279.6	6,109	6,040	90	1,100	102	30	1,500	829	150	3.1	0.64	32.0	1.4	5.1	0.72	0.124	12.49	0.10	0.494
S7E-3	gw	1/12/2000	24.99	6.79	0.15	-196.5	2,783	2,790	100	410	68	27	560	633	11	1.4	-0.21	42.0	0.6	10.8	1.77	4.365	12.88	0.03	0.478
S7E-4	gw	1/12/2000	25.16	8.11	0.16	-194.3	1,800	1,720	130	210	28	20	290	552	4	0.8	-3.56	51.1	0.2	8.7	0.82	3.274	15.66	0.08	0.517
S7E-4 REP	gw	1/12/2000	–	–	–	–	–	1,660	100	220	26	20	300	403	4.9	0.8	0.42	–	–	–	–	–	–	–	–
S7E-4 SPLIT	gw	1/12/2000	–	–	–	–	–	1,710	130	210	28	20	300	558	4	0.8	-4.59	–	–	–	–	–	–	–	–
U3	sw	1/12/2000	21.80	7.79	5.37	-36.2	1,050	1,050	73	100	29	21	140	260	59	0.2	4.13	0.9	0.2	-1.6	-0.32	0.016	12.87	3.95	0.504

Appendix 20. Results of chemical analyses of surface-water and ground-water samples in central Everglades, south Florida, January 11-14, 2000.—Continued

[°C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; ORP, oxidation–reduction potential; mV, millivolt; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; δ^2H, isotopic ratio of hydrogen-2; °/oo, per mil; $\delta^{18}O$, isotopic ratio of oxygen-18; CH_4, methane; N_2, nitrogen; O_2, oxygen; Ar, argon; MDL, minimum detection limit; sw, surface water; gw, ground water; –, no sample, no measurement, no analysis, or not applicable]

			Field parameters					Laboratory analyses[b]										Laboratory analyses[b]							
								QWSU[c]										USGS[e]		USGS[f]		USGS[g]			
Site ID	Sample type	Date	Temperature (°C)	pH	DO (mg/L)	ORP[a] (mV)	Specific conductance (µS)	Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)	Cation/anion balance[d] (percent)	NH_4 (µM)	PO_4 (µM)	δ^2H (°/oo)	$\delta^{18}O$ (°/oo)	CH_4 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)
								MDL										MDL							
								1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05		0.1	0.2	–	–	0.005	0.05	0.03	0.005
U3-3	gw	1/13/2000	24.25	6.51	1.09	-237.8	2,386	2,390	120	310	56	21	470	560	5.3	1.1	-0.86	39.6	0.6	11.9	1.91	3.685	12.43	0.03	0.473
U3-4	gw	1/13/2000	24.78	6.53	0.73	-76.9	1,272	1,270	140	93	22	19	190	378	0.2	0.5	-0.31	64.8	0.2	11.3	1.36	8.754	10.01	0.05	0.408
U3-5	gw	1/13/2000	24.48	6.88	0.25	-260.8	7,982	3,250	52	560	59	18	780	285	220	1.5	4.20	18.1	0.2	-0.6	-0.79	0.246	15.80	0.19	0.579
U3-6	gw	1/13/2000	25.93	8.06	0.19	-289	4,503	4,380	56	800	75	18	1,000	595	140	1.6	3.15	28.4	0.2	7.9	1.07	0.124	17.41	0.12	0.611
U3-7	gw	1/12/2000	24.77	6.78	0.61	-271.3	2,501	2,460	120	330	59	23	470	545	18	1.2	1.84	37.8	0.5	8.6	1.44	2.338	13.11	0.03	0.492
U3-8	gw	1/12/2000	24.68	11.98	5.09	-99.8	7,910	7,840	640	170	0.1	1.6	180	1,650	23	0.5	1.45	28.8	0.2	9.0	1.16	6.195	18.19	1.20	0.601

[a] Measured with platinum electrode (pH corrected).

[b] Results below the MDL are listed as the MDL.

[c] U.S. Geological Survey Water Quality Service Unit, Ocala, Florida.

[d] Calculated using milliequivalents as (cations - anions)/(cations + anions) * 100

[e] U.S. Geological Survey Biogeochemistry Laboratory-Orem, Reston, Virginia.

[f] U.S. Geological Survey Water Stable Isotope Laboratory, Reston, Virginia. 2-sigma uncertainties are 2 and 0.2 °/oo for ^2H and ^{18}O, respectively.

[g] U.S. Geological Survey Chlorofluorocarbon Laboratory, National Research Program, Reston, Virginia. Dissolved gas samples were preserved with potassium hydroxide.

Appendix 21. Results of chemical analyses of surface-water and ground-water samples in central Everglades, south Florida, April 24-28, 2000.

[°C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; ORP, oxidation–reduction potential; mV, millivolt; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; δ^2H, isotopic ratio of hydrogen-2; °/oo, per mil; $\delta^{18}O$, isotopic ratio of oxygen-18; CH_4, methane; N_2, nitrogen; O_2, oxygen; Ar, argon; ^3H, tritium; TU, tritium units; MDL, minimum detection limit; –, no sample, no measurement, no analysis, or not applicable; sw, surface water; gw, ground water; < less than]

Site ID	Sample type	Date	Field Parameters: Temperature (°C)	pH	DO (mg/L)	ORP[a] (mV)	Specific conductance (µS)	Laboratory analyses[b] QWSU[c]: Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)	Cation/anion balance[d] (percent)	Laboratory analyses[b] USGS[e]: NH_4 (µM)	PO_4 (µM)	USGS[f]: δ^2H (°/oo)	$\delta^{18}O$ (°/oo)	USGS[g]: CH_4 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)	RSMAS[h]: ^3H (TU)
								MDL: 1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05		MDL: 0.1	0.2	–	–	0.005	0.05	0.03	0.005	0.1
E1	sw	4/28/2000	23.56	7.48	4.79	94.9	1,029	1,020	77	100	24	16	140	248	54	0.5	4.53	0.3	0.4	8.4	1	–	–	–	–	–
E1-3	gw	4/28/2000	23.5	6.61	0.9	-231.4	2,365	2,280	150	290	38	21	440	508	20	1.2	1.11	57.7	0.8	9.1	1.48	0.807	13.36	0.03	0.485	0.231
E1-4	gw	4/28/2000	23.2	6.5	0.73	-75.5	1,850	1,720	160	170	23	20	270	509	0.7	0.8	-1.51	52.0	0.5	5.5	0.32	–	–	–	–	2.478
E4	sw	4/25/2000	–	–	–	–	–	976	88	85	27	17	130	267	49	0.4	4.90	0.2	0.4	1.4	0.35	–	–	–	–	–
E4-3	gw	4/25/2000	23.99	6.80	0.23	-93.4	2,019	2,150	150	270	26	14	430	447	0.7	1.2	0.68	24.6	0.5	10.4	1.61	2.365	13.82	0.03	0.505	0.351
E4-4	gw	4/25/2000	22.97	6.84	0.47	-60.3	1,378	1,480	120	160	15	14	270	369	0.2	0.7	-2.80	37.9	0.4	11.3	1.77	4.808	11.84	0.03	0.465	0.05
E4-5	gw	4/25/2000	24.76	6.9	0.17	-206.3	5,367	5,770	200	930	91	20	1,500	486	300	3	3.37	18.2	0.5	2.3	-0.14	0.020	14.23	0.07	0.532	0.13
E4-6	gw	4/25/2000	27.82	8.62	0.95	22.5	3,862	3,560	25	710	12	23	980	81	110	2.4	4.85	20.7	0.4	5.8	0.65	0.044	10.83	0.08	0.462	–
E4-7	gw	4/25/2000	24.22	6.77	0.16	-157.8	3,134	3,390	170	490	41	17	800	490	41	2	0.76	22.0	1.7	9.0	1.1	0.066	15.58	0.09	0.542	0.201
E4-8	gw	4/25/2000	23.74	8.17	0.17	-239.9	1,594	1,650	120	220	15	18	330	331	2.9	0.8	2.56	51.7	0.6	12.2	1.7	3.479	14.18	0.03	0.514	0.381
F1	sw	4/28/2000	22.75	6.83	2.23	124.1	1,063	1,030	79	100	24	17	140	257	55	0.7	4.01	0.2	0.6	8.3	1	–	–	–	–	–
F1-3	gw	4/28/2000	23.46	6.66	1.6	-189.3	5,866	5,700	150	1,000	76	19	1,400	740	170	8.8	1.48	37.6	0.9	10.1	1.49	0.065	14.34	0.09	0.501	-0.08
F1-4	gw	4/28/2000	22.7	6.52	0.94	-58.2	2,791	2,750	150	400	41	17	550	596	2.9	1.5	1.43	58.3	0.5	6.5	0.97	1.998	13.59	0.03	0.486	2.147
F4	sw	4/26/2000	27.31	7.8	3.6	-45	1,270	1,380	100	150	32	20	210	320	73	0.6	4.88	0.3	0.6	3.3	0.28	–	–	–	–	–
F4-3	gw	4/26/2000	23.66	6.66	0.16	-176.3	1,496	1,640	140	180	31	22	250	511	0.7	0.7	0.26	27.3	0.4	9.9	1.48	6.946	13.35	0.03	0.491	2.588
F4-4	gw	4/26/2000	23.09	6.61	0.37	-75.8	1,582	1,720	150	190	29	22	260	537	0.2	0.8	0.17	48.9	0.4	8.0	0.9	6.743	13.79	0.03	0.513	3.19
S10C-A	gw	4/24/2000	24.99	6.73	-0.04	-289.1	1,225	1,280	110	120	31	22	150	437	35	0.5	0.18	72.8	0.7	5.8	0.82	13.541	5.14	0.03	0.254	3.611
S10C-A FB	blank	4/24/2000	–	–	–	–	–	1	0.02	0.1	0.002	0.01	0.1	4.7	0.2	0.05	–	0.1	0.2	-1.3	-0.61	–	–	–	–	–
S10C-B	gw	4/24/2000	25.42	6.85	0.04	-227.8	955	1,020	85	83	25	37	120	355	2	0.4	-2.88	144	0.4	5.3	0.6	12.844	6.08	0.04	0.300	2.528
S10C-C	gw	4/24/2000	25.29	7.17	-0.05	-228.5	813	849	74	75	23	30	110	251	25	3	3.02	76.6	1.6	-0.4	0.22	1.669	15.18	0.20	0.537	2.588
S10C-C EB	blank	4/24/2000	–	–	–	–	–	1.1	0.02	0.1	0.01	0.01	0.1	4.9	0.2	0.05	–	0.1	0.2	-1.0	-0.6	0.005	12.24	7.14	0.458	–
S10C-HW	sw	4/24/2000	26.57	7.85	7.21	53.5	614	714	57	62.5	18	9.1	95	178	33	0.2	4.26	0.2	0.3	9.2	1.24	–	–	–	–	–
S10C-TW	sw	4/24/2000	25.43	7.53	5.89	72.4	858	904	76	84	24	14	120	223	51	0.4	6.93	0.3	0.4	8.5	1.06	–	–	–	–	–
S7E	sw	4/26/2000	23.83	7.54	3.07	22	1,111	1,240	88	130	32	18	190	312	51	0.4	2.95	0.3	0.5	6.0	0.11	–	–	–	–	–
S7E-1	gw	4/26/2000	25.22	6.87	0.11	-286	8,795	9,680	130	1,900	170	23	2,700	760	450	4.8	4.35	27.6	1.1	7.0	0.6	0.070	17.67	0.10	0.585	0.06
S7E-2	gw	4/26/2000	24.52	6.82	0.26	-276.8	5,546	6,170	98	1,100	111	29	1,600	842	150	3.7	-0.94	17.4	1.1	6.9	0.88	0.136	17.51	0.06	0.581	0.236
S7E-2 REP	gw	4/26/2000	–	–	–	–	–	6,180	99	1,100	112	29	1,500	843	150	3.1	1.45	18.7	1.1	7.1	0.93	0.135	17.56	0.06	0.582	–
S7E-3	gw	4/26/2000	24.58	6.82	0.19	-197.3	2,502	2,740	98	410	66	28	530	652	8	1.5	0.18	35.5	0.6	12.0	1.8	4.194	14.21	0.03	0.503	0.532
S7E-4	gw	4/26/2000	24.37	8.11	0.24	-224.8	1,495	1,670	150	220	28	18	290	531	1.4	0.8	1.44	72.7	0.3	8.3	0.88	3.520	13.76	0.03	0.484	3.2

Appendix 21. Results of chemical analyses of surface-water and ground-water samples in central Everglades, south Florida, April 24-28, 2000.—Continued

[°C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; ORP, oxidation–reduction potential; mV, millivolt; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; δ^2H, isotopic ratio of hydrogen-2; °/oo, per mil; $\delta^{18}O$, isotopic ratio of oxygen-18; CH_4, methane; N_2, nitrogen; O_2, oxygen; Ar, argon; ^3H, tritium; TU, tritium units; MDL, minimum detection limit; –, no sample, no measurement, no analysis, or not applicable; sw, surface water; gw, ground water; < less than]

			Field Parameters					Laboratory analyses[b]										Laboratory analyses[b]								
								QWSU[c]										USGS[e]		USGS[f]		USGS[g]				RSMAS[h]
Site ID	Sample type	Date	Temperature (°C)	pH	DO (mg/L)	ORP[a] (mV)	Specific conductance (µS)	Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)	Cation/anion balance[d] (percent)	NH_4 (µM)	PO_4 (µM)	δ^2H (°/oo)	$\delta^{18}O$ (°/oo)	CH_4 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)	^3H (TU)
								MDL										MDL								
								1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05		0.1	0.2	–	–	0.005	0.05	0.03	0.005	0.1
U3	sw	4/27/2000	23.09	7.36	3.67	120	916	977	67	100	29	11	140	249	32	0.2	4.84	0.5	0.5	8.4	0.74	–	–	–	–	–
U3-3	gw	4/27/2000	24.32	6.64	0.13	-220.8	2,245	2,360	120	320	57	22	460	571	6.1	1.3	0.31	33.7	0.6	11.2	1.82	3.755	14.15	0.03	0.504	0.04
U3-4	gw	4/27/2000	23.56	6.58	0.33	-84.3	1,206	1,270	140	92	22	19	180	395	0.2	0.6	-0.70	52.5	0.3	11.5	1.38	9.421	12.90	0.03	0.482	1.585
U3-5	gw	4/27/2000	24.23	7.4	4.4	-128.5	7,860	2,260	150	1,200	159	21	2,000	135	470	4.4	7.64	15.0	0.8	-1.0	-0.14	0.925	17.38	0.03	0.608	1.264
U3-6	gw	4/27/2000	24.87	8.03	1.39	-162.1	5,021	4,760	110	830	90	17	1,100	730	120	2.3	2.64	27.4	0.6	8.5	1.22	0.124	16.62	0.06	0.565	0.13
U3-7	gw	4/27/2000	24.56	7.67	0.40	-137.2	2,677	2,490	120	340	61	26	480	589	12	1.3	0.76	34.2	0.7	9.4	1.84	2.623	14.58	0.03	0.512	0.171
U3-8	gw	4/27/2000	24.53	11.44	1.52	-39.2	7,654	7,330	670	140	<0.03[i]	3.3	190	1,760	4.3	0.5	-1.30	39.5	0.7	9.2	1.32	5.959	15.61	0.30	0.557	0.943

[a] Measured with platinum electrode (pH corrected).
[b] Results below the MDL are listed as the MDL.
[c] U.S. Geological Survey Water Quality Service Unit, Ocala, Florida.
[d] Calculated using milliequivalents as (cations - anions)/(cations + anions) * 100
[e] U.S. Geological Survey Biogeochemistry Laboratory-Orem, Reston, Virginia.
[f] U.S. Geological Survey Water Stable Isotope Laboratory, Reston, Virginia. 2-sigma uncertainties are 2 and 0.2 °/oo for ^2H and ^{18}O, respectively.
[g] U.S. Geological Survey Chlorofluorocarbon Laboratory, National Research Program, Reston, Virginia. Dissolved gas samples were preserved with potassium hydroxide.
[h] Tritium Laboratory, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida. 1-sigma uncertainties are 0.1 TU or 3.5 percent, whichever is greater.
[i] Result was flagged (for example, value is excessively low or high or not in keeping with history) and is suspect.

Appendix 22. Results of chemical analyses of surface-water and ground-water samples in central Everglades, south Florida, September 9-10, 2000.

[°C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; ORP, oxidation–reduction potential measured with platinum electrode (pH corrected); mV, millivolt; µS, microsiemens; Ca, calcium; Na, sodium; Mg, magnesium; SiO_2, silica; Cl, chloride; Alk, alkalinity; $CaCO_3$, calcium carbonate; SO_4, sulfate; Br, bromide; NH_4, ammonium; PO_4, orthophosphate; µM, micromolar; δ^2H, isotopic ratio of hydrogen-2; °/oo, per mil; $\delta^{18}O$, isotopic ratio of oxygen-18; CH_4, methane; N_2, nitrogen; O_2, oxygen; Ar, argon; MDL, minimum detection limit; sw, surface water; gw, ground water; –, no sample, no measurement, no analysis, or not applicable]

Site ID	Sample type	Date	Field parameters					Laboratory analyses[b]									Cation/anion balance[d] (percent)	Laboratory analyses[b]							
								QWSC[c]										USGS[e]		USGS[f]		USGS[g]			
			Temperature (°C)	pH	DO (mg/L)	ORP[a] (mV)	Specific conductance (µS)	Specific conductance (µS)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	SiO_2 (mg/L)	Cl (mg/L)	Alk. as $CaCO_3$ (mg/L)	SO_4 (mg/L)	Br (mg/L)		NH_4 (µM)	PO_4 (µM)	δ^2H (°/oo)	$\delta^{18}O$ (°/oo)	CH_4 (mg/L)	N_2 (mg/L)	O_2 (mg/L)	Ar (mg/L)
								MDL										MDL							
								1	0.02	0.1	0.001	0.01	0.1	1	0.2	0.05		0.1	0.2			0.005	0.05	0.03	0.005
E4	sw	9/10/2000	26.4	7.09	2.11	234.4	620	618	47	60	14	9.1	89	161	12	0.2	2.46	0.3	0.2	-0.58	-0.96	–	–	–	–
E4-3	gw	9/10/2000	23.83	6.54	0.41	-80.8	2,223	2,220	140	270	25	14	440[h]	452	0.2	1.1	-1.59	36.4	0.4	12.51	1.62	2.130	13.93	0.13	0.501
E4-4	gw	9/10/2000	24.61	6.63	0.49	-63	1,529	1,520	130	160	15	15	280	371	0.2	0.8	-2.14	44.5	0.2	11.79	1.69	4.409	9.92	0.05	0.415
E4-5	gw	9/10/2000	24.22	6.74	0.34	-177.3	5,821	5,850	190	900	89	20	1,500	487	290	4.1	1.68	31.6	0.3	2.24	-0.18	0.020	17.89	0.04	0.601
E4-7	gw	9/10/2000	24.04	6.59	0.38	-160.2	3,399	3,410	160	480	39	17	830	492	40	1.8	-2.24	31.4	2.3	4.16	1.11	0.066	15.06	0.05	0.525
E4-8	gw	9/10/2000	23.9	8.57	0.21	-189.8	1,717	1,740	120	220	14	16	360	342	1.3	0.8	-0.89	67.9	0.3	9.2	1.74	3.255	14.44	0.05	0.516
E4-EB	blank	9/10/2000	–	–	–	–	0	2	0.04	0.1	0.001	0.05	0.2	2.6	0.2	0.05	–	0.2	0.2	-3.42	-0.66	0.005	13.18	7.41	0.470
E4-FB	blank	9/10/2000	–	–	–	–	0	–	0.02	0.1	0.001	0.04	–	–	–	–	–	0.2	0.2	–	–	–	–	–	–
F1	sw	9/9/2000	27.84	7.98	–	-88.5	1,180	1,090	63	120	21	17	200	207	30	0.05	0.52	1.6	0.7	-7.13	-1.81	–	–	–	–
F1-3	gw	9/9/2000	23.83	6.33	–	-197.2	6,070	5,770	140	1000	72	19	1,500	738	170	2.9	-1.63	50.0	0.9	8.78	1.51	0.065	14.23	0.05	0.492
F1-4	gw	9/9/2000	24.18	6.31	–	-77.7	3,000	2,830	140	400	40	16	600	566	3.5	1.4	-1.07	79.0	0.3	6.37	1.06	1.554	13.14	0.05	0.476
U3	sw	9/9/2000	25.87	6.8	–	124.4	715	651	45	61	17	20	88	183	14	0.05	0.49	0.7	0.3	4.15	0.26	–	–	–	–
U3-3	gw	9/9/2000	24.74	6.24	–	-186.3	2,583	2,410	120	310	55	21	470	571	4.8	0.9	-1.47	42.3	0.5	12.62	1.89	3.877	13.62	0.05	0.493
U3-4	gw	9/9/2000	24.83	6.34	–	-91.6	1,390	1,290	140	89	22	19	190	402	0.2	0.05	-2.79	59.8	0.2	10.04	1.36	8.955	12.66	0.27	0.470
U3-5	gw	9/9/2000	24.24	6.47	–	-233.1	8,428	8,080	140	1400	155	21	2,000	725	450	4.2	4.24	28.9	0.7	3.35	0.3	0.054	17.67	0.06	0.586
U3-6	gw	9/9/2000	24.7	7.54	–	-226.8	4,921	4,500	67	810	57	15	1,100	599	110	2.1	-0.60	43.8	0.3	8.04	1.21	0.117	14.94	0.05	0.545
U3-7	gw	9/9/2000	24.68	5.8	–	-188.5	2,715	2,550	110	330	59	22	510	592	8.1	0.7	-3.10	41.8	0.6	11.68	1.77	2.776	13.43	0.05	0.489

[a] Measured with platinum electrode (pH corrected).
[b] Results below the MDL are listed as the MDL.
[c] U.S. Geological Survey Water Quality Service Unit, Ocala, Florida.
[d] Calculated using milliequivalents as (cations - anions)/(cations + anions) * 100
[e] U.S. Geological Survey Biogeochemistry Laboratory-Orem, Reston, Virginia.
[f] U.S. Geological Survey Water Stable Isotope Laboratory, Reston, Virginia. 2-sigma uncertainties are 2 and 0.2 °/oo for ^2H and ^{18}O, respectively.
[g] U.S. Geological Survey Chlorofluorocarbon Laboratory, National Research Program, Reston, Virginia. Dissolved gas samples were preserved with potassium hydroxide.
[h] Result was flagged (for example, value is excessively low or high or not in keeping with history) and is suspect.