ground water

Ground Water Recharge and Discharge in the Central Everglades

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Abstract

Rates of ground water recharge and discharge are not well known in the central Everglades. Here we report estimates of ground water recharge and discharge at 15 sites in the Everglades Nutrient Removal Project and in Water Conservation Area 2A (WCA–2A), along with measurements of hydraulic properties of peat at 11 sites. A simple hydrogeologic simulation was used to assess how specific factors have influenced recharge and discharge. Simulations and measurements agreed that the highest values of recharge and discharge occur within 600 m of levees, the result of ground water flow beneath levees. There was disagreement in the interior wetlands of WCA–2A (located > 1000 m from levees) where measurements of recharge and discharge were substantially higher than simulated fluxes. A five-year time series (1997 to 2002) of measured fluxes indicated that recharge and discharge underwent reversals in direction on weekly, monthly, and annual timescales at interior sites in WCA–2A. 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 by water managers. Discharge also tended to occur at sites in the wetland interior for ~1 week preceding the arrival of the surface water pulse. We conclude that ground water recharge and discharge vary cyclically in the interior wetlands of the central Everglades, 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.

Introduction

Past hydrological investigations in wetlands have mostly been conducted in relatively small systems, such as fringing wetlands at the margin of rivers or estuaries. Interactions between small wetland systems and surrounding terrestrial and aquatic systems have generally been found to be significant for water and chemical budgets in the wetlands (Brinson et al. 1983; Nuttle and Hemond 1988; Harvey and Nuttle 1995; Gerla and Matheney 1996; Hunt et al. 1999; Tobias et al. 2001). Large peatlands such as those in the northern midwestern United States and in southern Florida have received less attention, in part because of the difficulty and expense of fieldwork in expansive wetlands. Progress has been made over the past 20 years, especially in efforts to evaluate hydrologic connections of ground water and surface water in these systems. For example, the hydrology of the Glacial Lake Agassiz peatlands in northern Minnesota has been investigated for several decades using a broad array of field techniques and modeling (Siegel 1983; Reeve et al. 2000). Progress has also been made in the Everglades; however, many of the investigations were targeted specifically as support for water resources management and tended not to be as broad in scope (Sonenshein 2001). Recently, the number and scope of hydrological investigations in the Everglades has increased (Harvey et al. 2002; Price et al. 2003).

The Everglades is a subtropical coastal wetland that extends 160 km from Lake Okeechobee to Florida Bay in southeastern Florida (Figure 1). In the past, large quantities of fresh surface water moved southward by overland sheet flow through the broad wetland system, ultimately

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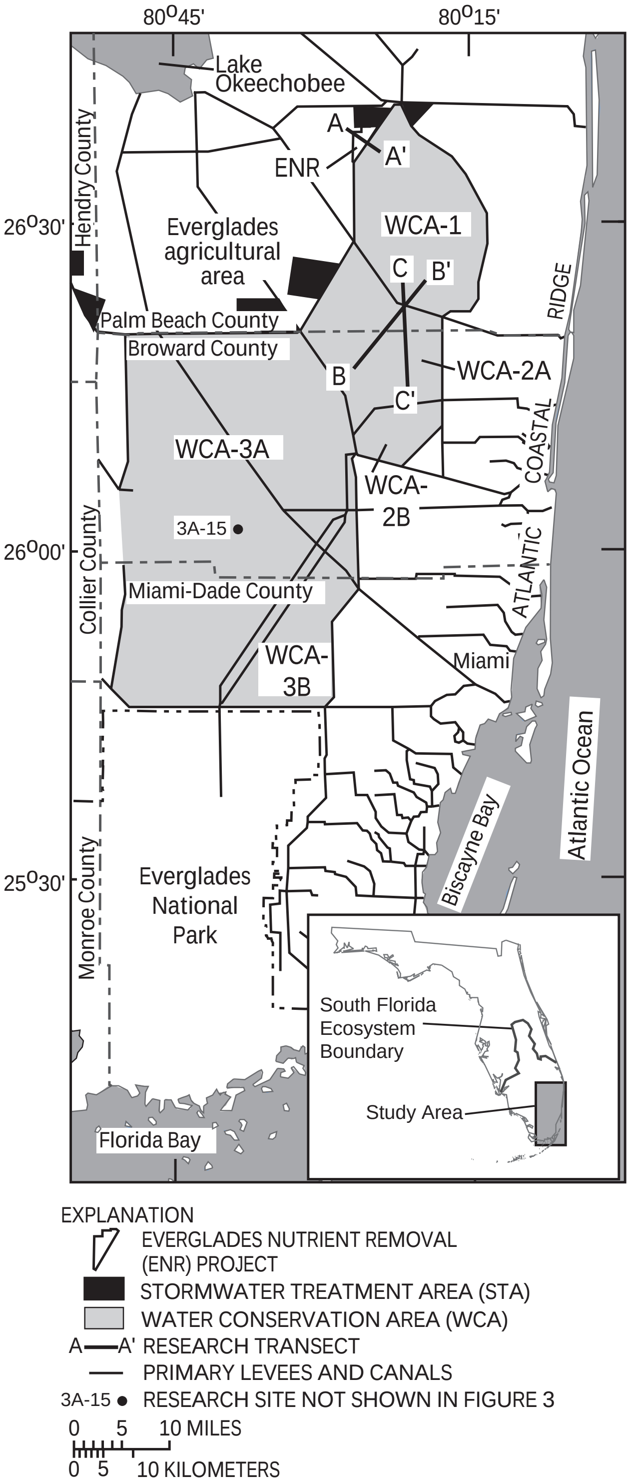

Figure 1. Central Everglades and adjoining areas, south Florida, showing locations of WCAs, ENR Project, and STAs.

discharging to the Atlantic Ocean, Florida Bay, or the Gulf of Mexico depending on the particular flowpath taken through the wetlands. Recharge and discharge fluxes under predrainage conditions are assumed to have been relatively low in the Everglades, due to small driving forces imposed by natural topographic gradients (Figure 2). Beginning about 1910, canals were constructed in the Everglades that extended southeast from Lake Okeechobee to the Atlantic Ocean (Light and Dineen 1994). Beginning in the 1950s, additional systems of canals and levees were built that narrowed the main flow-way and completely compartmentalized the central Everglades into a series of enclosed basins, called the Water Conservation Areas (WCAs).

Recharge and discharge have increased since predrainage times, in part due to the increased gradients driving recharge of surface water near the WCA boundaries. At those boundaries, levees separate the WCA wetlands from areas outside where water levels have been lowered by canal drainage, subsidence, or ground water pumping for water supply (Harvey et al. 2002). For example, significant recharge now occurs along the northern and western border of the Everglades as a response to 80 years of subsidence in the neighboring Everglades Agricultural Area, an area of former wetlands now managed for agriculture located northwest of the WCAs (Figure 1). Significant recharge also occurs on the eastern side of the Everglades, replenishing water-supply wells and draining to the ocean via canals. Another factor that may have increased recharge and discharge is the possible increase in fluctuations of surface water levels under water management. Several times each year, water managers release surface water through control structures to quickly move large quantities of water from upstream to downstream basins. The sudden releases of water create gravity waves that are sometimes higher than 1.2 m and propagate southward through the basins. Hydrologic simulations by the South Florida Water Management District (SFWMD) using the South Florida Water Management model and natural system model suggest that the range of annual surface water fluctuations in the WCA–2A interior may have increased by ~50% since predrainage times, from ~60 cm to 90 cm (Tarboton et al. 1999) (also see *www.sfwmd.gov/org/pld/restudy/hpm/index.html*). It is difficult to determine precisely how recharge and discharge have been affected by an increase in surface water level fluctuations. Our research focused on quantifying recharge and discharge that is presently occurring in the central Everglades. We attempted to identify the specific roles of different aspects of water management, including the role of levees, in causing increases in recharge and discharge near WCA basin boundaries, as well as the possible role of surface water level fluctuations resulting from the operation of water-control structures in causing increases in recharge and discharge in the interior wetlands.

Although most scientists acknowledge a connection between ground water and surface water in the Everglades, the locations of recharge and discharge, and the volumes of water exchanged between wetland surface water and aquifer, remain uncertain. Past investigations of recharge and discharge were mainly conducted on wetland areas in the immediate vicinity of canals (Klein and Sherwood 1961; Miller 1978; Swayze 1988; Chin 1990; Genereux and Slater 1999; Rohrer 1999; Nemeth and Solo-Garbriele 2001; Sonenshein 2001). Due in part to logistical constraints, investigations of surface water and ground water interactions in the vast interior areas of the Everglades are almost nonexistent. Until recently, it was still common for recharge and discharge in the Everglades to be computed as net estimates averaged over large areas and long time periods as part of regional surface water budgets (Fennema et al. 1994). Recharge and discharge were estimated in a smaller

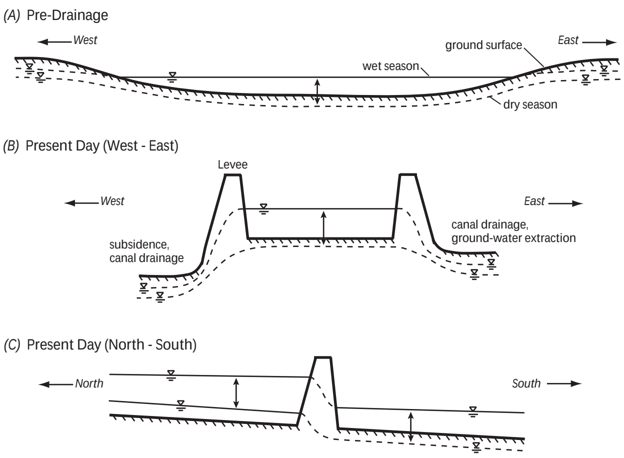

Figure 2. Schematic showing general relationships between topography, and surface water and ground water levels in (a) predrainage and (b and c) present-day hydrologic systems, central Everglades, south Florida. Approximate surface water levels (solid lines) and ground water levels (dashed lines) are shown for both wet and dry seasons. The vertical scale is substantially exaggerated to show detail. The predrainage wetland was relatively wide and surface water fluctuations were muted (a). Compartmentalization of the Everglades into enclosed basins narrowed the surface water flow-way, and increased surface water fluctuations. Subsidence, canal drainage, and ground water withdrawals on former wetlands to either side of the Everglades contributed to increased recharge in the wetlands, especially near levees (b). 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 downgradient side of levees (c). Under present-day management, when levee spillways are opened, a pulse of surface water is released that flows overland under the influence of gravity toward the basin interior. The pulsed behavior of surface water releases may play a role in driving cyclic reversals between recharge and discharge in the interior wetlands.

Everglades basin (Everglades Nutrient Removal [ENR] Project) using surface water and chloride budgets (Choi and Harvey 2000), but that work required exceptionally dense instrumentation and frequent hydrologic and chemical measurements. There is an increasing need for information about recharge and discharge in the interior wetlands of the central Everglades, such as the WCAs. Estimates of recharge and discharge in the interior basins are important because the dominant percentage of the wetlands is far from levees, so that even relatively small recharge or discharge fluxes in the wetland interior could be significant to overall water or chemical budgets.

The goal of our research was to estimate recharge and discharge, and delineate spatial and temporal patterns of those fluxes in the central Everglades using data collected over a five-year period (1997 to 2002). The study documented some of the factors influencing recharge and discharge, including effects of compartmentalizing the wetlands with levees (i.e., due to the effect on hydraulic driving forces), and the effect of movement of pulses of surface water released through water-control structures at levees into the interior areas of the basins.

Study Sites

The surficial aquifer is a principal source of fresh drinking water in south Florida. 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 surficial aquifer includes the highly transmissive Biscayne Aquifer, which underlies Miami-Dade County, Broward County, and eastern Palm Beach County. The Biscayne Aquifer is thickest beneath the Atlantic coastal ridge to the east of the Everglades, and it thins from east to west, disappearing beneath the north-central Everglades. Aquifers to the west of the Biscayne and beneath the Everglades generally have been ignored as potential sources of ground water, both because of the lower transmissivities (Fish 1988) and because of the higher total dissolved solids in ground water beneath the Everglades (Howie 1987).

Beyond these few studies cited here, there is relatively little comprehensive information available about the hydrogeology beneath the central Everglades in western Palm Beach and Broward counties. Miller (1988) illustrated some of the effects that water management has had on ground water levels in that part of the central Everglades. Recent work characterized the geology and hydraulic properties of

Table 1
Hydrolithogeological Properties of Surficial Aquifer, WCA–2A Central Everglades

Average Thickness (m)	Primary Lithology	Common Formation Name	Geologic Timescale	Hydraulic Conductivity K (cm/day)
1	Peat	Undifferentiated deposits	Holocene	60
1	Fresh water marl/sand	Undifferentiated deposits	Holocene	50
4.5	Sand	Fort Thompson	Pleistocene	2500
4	Limestone with sand stringers	Fort Thompson	Pleistocene	9000
7.5	Sand	Fort Thompson	Pleistocene	5000
9	Sand with fine sand layers	Tamiami	Pliocene	4000

Modified from Harvey et al. 2002 and Harvey et al. 2000 the surficial aquifer beneath the northern WCAs in greater detail than previously available (Harvey et al. 2002). The present study extended that work through collection of additional hydraulic conductivity data from shallow layers (1a and 1b, Table 1). Table 1 combines and summarizes basic hydrogeologic information collected beneath WCA–2A, which is representative of much of the central Everglades.

Everglades Nutrient Removal Project

The ENR Project was constructed and operated in the 1990s as a prototype to test the capacity of larger constructed wetlands, called storm water treatment areas, to remove nutrients from agricultural drainage waters (Figures 1 and 3a). ENR is comprised of a 1545 ha area that was formerly part of the Everglades, but was drained and farmed beginning in the mid–1900s, and then recently returned to management as a constructed wetland. The source of surface water to ENR is pumpage from agricultural land to the west and from surface water from Lake Okeechobee. ENR's location in the Everglades landscape affects interactions between surface water and ground water. To the east of ENR is WCA–1, where water surface elevations are maintained at relatively high elevations compared with the rest of the Everglades. To the west of the ENR is the Everglades Agricultural Area (EAA), where subsidence and canal drainage have substantially decreased the ground elevation and water table relative to WCA–1 and ENR. Proximity to the agricultural area has a significant effect on the ENR water budget, with recharge in ENR accounting for flow equal to 30% of the pumped inflow of surface water (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) than ENR (Figure 3b). 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 et al. 1993; Jensen et al. 1995). WCA–2A shares boundaries with WCA–1 and the EAA, lands developed for light industrial and residential areas to the east, and WCA–3A to the southwest. In the 1950s, construction began on a new system of levees and borrow 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 (Figure 3B).

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

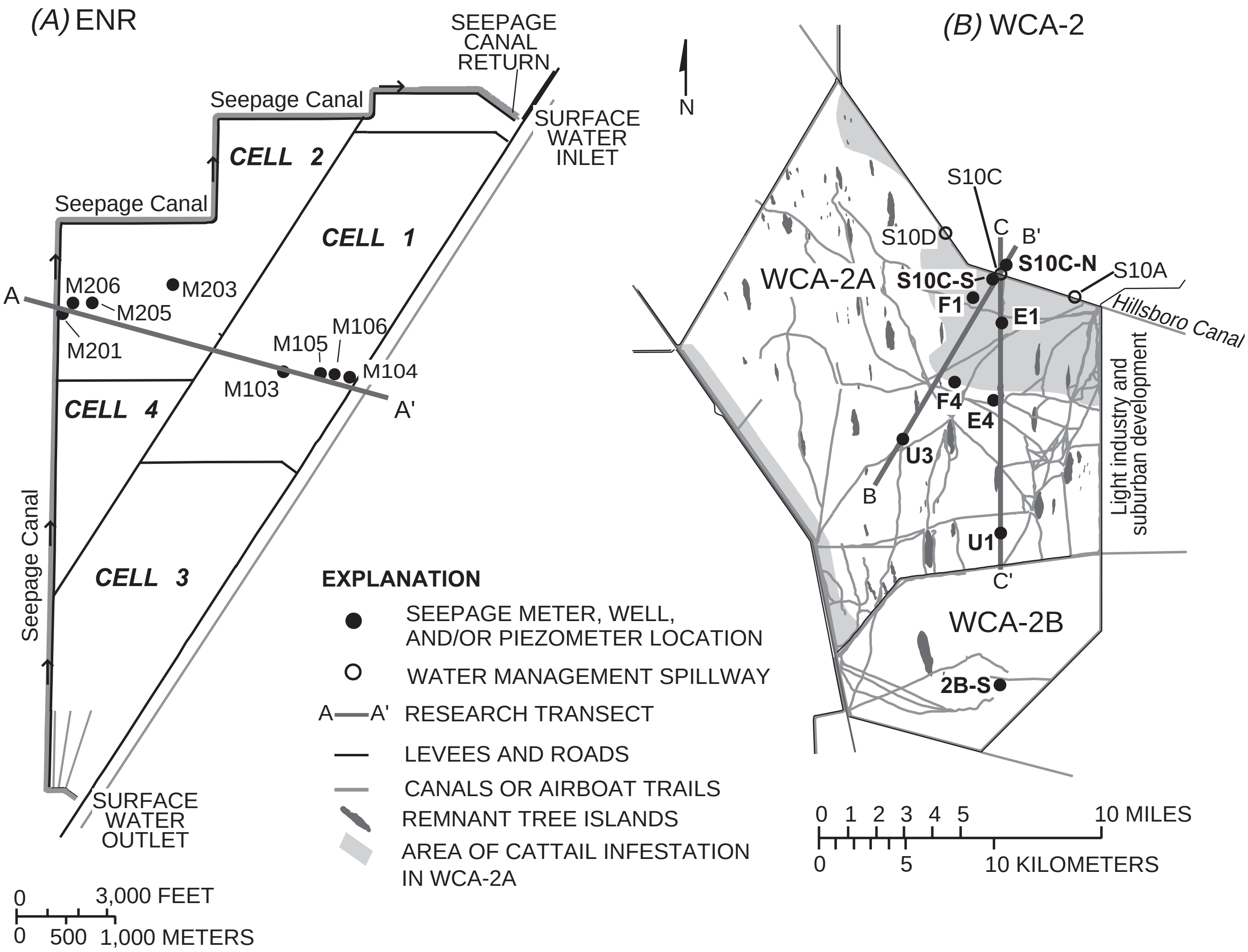

Figure 3. Research sites, instrumentation, and natural and manmade features in (a) ENR Project and (b) WCA–2, central Everglades, south Florida.

growth in some areas (Jensen et al. 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.

Methods

Three research transects with an orientation similar to local directions of ground water flow were selected for study—one in ENR, and two in WCA–2A (Figure 3). Transects were also selected to take advantage of existing infrastructure and to colocate our measurements with other complementary studies. In total, 10 sites on the ENR transect and seven sites on the two transects at WCA–2A were investigated. Some additional measurements were also collected at single sites in WCA–3A and WCA–2B (Figures 1 and 3b). Research sites had instrumentation including (in various combinations) a surface water stage recorder, one or more research monitoring wells emplaced in the surficial aquifer underlying the Everglades, one or more shallow drivepoints emplaced in the peat, and two or more seepage meters installed in wetland peat.

Six research monitoring wells (3.2 or 5.1 cm nominal outside diameter) with 60 cm screens were emplaced in the surficial aquifer at a depth of ~2 m below the ground surface. Shallow drivepoints (0.95 to 1.9 cm nominal outside diameter) with 1 to 5 cm screens were emplaced in peat and in the underlying organic/marl/sand transitional sediments to depths ranging from 0.1 to 2 m. More details on well and drivepoint construction, installation procedures, exact locations of instruments, and measurement techniques are given in Harvey et al. (2000).

Hydraulic Conductivity and Recharge/Discharge Estimates

Hydraulic conductivity of the sand and limestone aquifer beneath WCA–2A and ENR was estimated by a previous study (Harvey et al. 2000). Hydraulic conductivities of Everglades' peat and the organic/marl/sandy sediments immediately underlying the peat were determined as part of the present study using either a constant-head, pump-out method (Tavenas et al. 1990; Brand and Premchitt 1980) or a bail-test method (Luthin and Kirkham 1949) in piezometers. Slug tests are usually thought to be more sensitive to horizontal hydraulic conductivity, which could bias results if used to compute a vertical flux. We used our slug test results as direct estimates of vertical hydraulic conductivity because, to our knowledge, a more reliable method has not been demonstrated for peat. An alternative approach to estimating vertical hydraulic conductivity, i.e., applying corrections to horizontal hydraulic conductivities in the manner typically used in granular sediments, was judged to be inappropriate for peat, because those approaches do not consider special features such as the possibility of preferred flowpaths created by vertical growth of roots. To be consistent with units of reporting recharge and discharge estimates, all hydraulic conductivity values used in the present study are reported in units of cm/day.

Seepage meters were used to obtain direct estimates of vertical water fluxes (i.e., recharge and discharge) through the peat at sites in ENR. Our seepage meters were designed similarly to the Lee-type meter (Lee 1977), but instead of cutoff drums, we built seepage meters from 0.64 cm thick, high-density polyethylene (HDPE) by creating rings (76 cm diameter by 30 cm wall height), attaching an HDPE conical dome, and installing a PVC bulkhead fitting with a 1.9 cm port on top of the dome for quick connections and disconnections of a prefilled seepage bag. Simultaneous seepage-meter measurements using replicate meters at a single site had an average uncertainty of ± 50%. A more limited data set on recharge and discharge was collected using seepage meters at sites WCA–2BS (Figure 3b) and WCA–3A–15 (Figure 1). More detailed information on seepage meters, including emplacement and operation, and precision and limit of detection, are given in Harvey et al. (2000).

Limited access to more remote wetland sites in WCA–2A required a method other than seepage meters to estimate vertical recharge and discharge fluxes. Daily-averaged surface and ground water level measurements were combined with estimates of peat hydraulic conductivity to compute recharge and discharge in WCA–2A. Calculations were made by multiplying the average hydraulic conductivity of peat at a site by the vertical hydraulic gradient measured at that site. The vertical gradient was estimated as the difference between the surface water stage and the ground water elevation in the shallowest monitoring well (~2 m below the peat surface). For the denominator in the hydraulic gradient, the thickness of peat was used. This assumed that head changed linearly through the peat and that the head measurement in the well was a good estimate of head at the base of the peat. The sign convention for fluxes was a positive flux and negative hydraulic gradient when discharge occurred (i.e., upward flow from ground water to surface water), and a negative flux and positive hydraulic gradient when recharge occurred (i.e., downward flow from surface water to ground water). Our calculations further assumed that head changes in surface water or ground water were rapidly transmitted through the peat without significant time lag, thus maintaining the linear head distribution assumed by Darcy's law. That approximation was justified by the relative timescales involved, i.e., the timescale for pressure propagation through the peat (minutes) compared with a timescale of days to weeks for changing surface water levels (which control head at the peat surface). We estimated the characteristic time of pressure propagation through the peat, t_p, using the equation $t_p = 1/2 \times L^2 \times S_s/K_{peat}$, where L is the approximate thickness of the restricting layer (1.5 m), S_s is the specific storativity of peat (0.001/m), and K_{peat} is the approximate hydraulic conductivity of the restricting layer (0.3 m/day) (Thibodeaux 1996).

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) provided a solution to the problem based on a one-dimensional (horizontal) flow assumption through the aquifer with uniform hydrogeologic properties, and with vertical leakage across the aquitard (envisioned as Everglades' peat in our case). Because of one-dimensional flow, the head at the left boundary of the aquifer (in contact with the canal) was equal to the canal water level and was constant with depth. That boundary condition represented the hypothetical situation where the canal fully penetrated the aquifer, which was not the situation in WCA–2A where the surficial aquifer was ~60 m thick and the canal was ~4 m in depth. Despite the fact that the canal only partially penetrates the aquifer, the fully penetrating assumption was judged sufficient for our purposes because of its simplicity and because it successfully has been used in the past as a first order approximation of boundary conditions for situations that were in reality more complicated. The governing equations for the hydrogeologic model are as follows:

$$\frac{\partial^2 h}{\partial x^2} = \frac{S_s}{K_x}\frac{\partial h}{\partial t} + q' \quad (1)$$

$$\frac{\partial^2 h'}{\partial z^2} = \frac{S_s'}{K'}\frac{\partial h'}{\partial t} \text{ for the domain } b \leq z \leq (b + b') \quad (2)$$

$$q' = -\frac{K'}{K_x b}\left(\frac{\partial h'}{\partial z}\right)_{z=b} \quad (3)$$

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 $x_o \leq x \leq \infty$; 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

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

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

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

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

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

An analytical solution for these equations exists, but we chose to solve our problem using the numerical code called STLK1 provided by Barlow and Moench (1998).

The simple hydrogeologic simulation described here was used to try 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). The model ignored other possible influences, such as climatic factors, surface water pumping, and operation of water-control structures, as well as 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 away from the levee of recently discharged ground water. 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 restricting layer. 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 (peat) was initially set to 30 cm/day, 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 (Anderson and Woessner 1992). Other parameter values used in model simulations were aquifer depth 60 m, peat depth 1 m, and K_{aquifer} 3000 cm/day. For the purpose of testing sensitivity to the value of K_{peat}, two additional simulations were run using values of K_{peat} = 0.3 and 3000 cm/day, respectively.

Results

Hydraulic conductivities of peat (K_{peat}) are reported as geometric means for three areas of the central Everglades in Table 2. In the WCA–2A interior, 19 measurements were made at four sites in the wetland interior, and near the WCA–2A levee seven measurements were made at one site. In ENR, 17 measurements were made at six sites. No obvious vertical pattern was seen in the vertical distribution of K_{peat} estimates (Figure 4), which supports the simple approach of using the geometric mean of all K_{peat} estimates from a site as a reasonable characterization of vertical hydraulic conductivity at the site. There was a trend toward higher values of K_{peat} in the WCA–2A interior (geometric mean of 55 cm/day) compared with ENR (6 cm/day). Values of K_{peat} at sites near the Hillsboro levee in WCA–2A (24 cm/day) were intermediate between interior WCA–2A and ENR. A tendency toward lower K_{peat} values in ENR may be the result of irreversible compaction of peat that probably occurred there due to decades of drainage and farming before the site was reconverted to a wetland (Harvey et al. 2002). That interpretation is consistent with bulk density measurements which indicate that peat sediments in ENR are a factor of three denser than in the WCA–2A interior. Finding lower K_{peat} near the WCA–2A levee compared to values from the WCA–2A interior is consistent with the higher bulk density of peat measured near the levee (Table 2), which may be the result of interactions with the nearby canal, where frequent overbank flooding over the past 30 years is likely to have delivered large amounts of fine-grained

Table 2
Measured Physical Properties and Hydraulic Conductivity of Peat and Underlying Transitional (Fresh Water Marl/Sand) Sediments in WCA–2A and ENR, Central Everglades

Location	Number of Sites	Number of Observations	Mean Depth (cm)	Hydraulic Conductivity (cm/day)			Bulk Density (g/cm^3)
				Mean	Min	Max	
Peat							
WCA-2A interior	4	18	120	59	7	1400	0.06
WCA-2A–near levee	1	4	80	26	17	42	0.09
ENR	6	11	110	6	0.2	110	0.20
Transitional							
WCA-2A interior	2	8	n.d.	61	15	420	n.d.
WCA-2A–near levee	1	7	> 100	6	1	20	1.1
ENR	5	5	n.d.	18	4	46	1.1

All means are geometric means.
n.d. means no data.

mineral sediments into the wetlands. Probably as a result of being less disturbed by human activities, interior areas of WCA–2A appeared to have a higher K_{peat} that was more representative of predrainage conditions in the central Everglades (Gleason and Stone 1994).

At some sites, we also estimated hydraulic conductivity in the fresh water marl/sand layer immediately underlying the peat. Average hydraulic conductivities in transitional layers at WCA–2A interior, WCA–2A levee, and ENR sites were 61, 6, and 18 cm/day, respectively (Figure 4 and Table 2). K in the transitional layer therefore did not differ greatly from K_{peat} above. K values were 2000 and 900 cm/day near the top of the surficial aquifer at WCA–2A and ENR, respectively (Harvey et al. 2000). Finding that hydraulic conductivity in the surficial aquifer was one to two orders of magnitude higher than in the peat or fresh water marl/sand transition layer indicated that peat, along with the transitional matrix, function together as a layer restricting vertical fluxes of water by recharge and discharge.

Spatial and Temporal Variability of Measured Recharge and Discharge Fluxes

Recharge and discharge fluxes were greater near levees compared with interior sites in wetlands (Table 3 and Figure 5). Fluxes at those sites (within 1000 m of levees) also

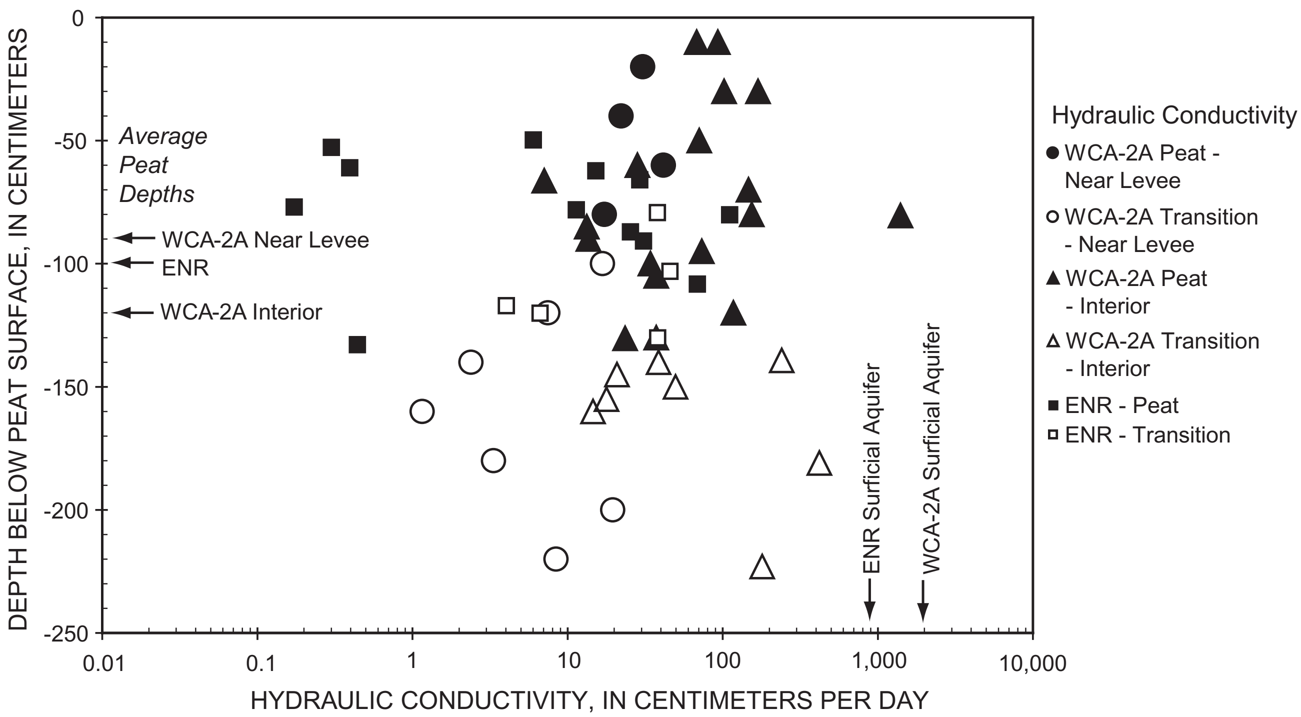

Figure 4. Hydraulic conductivity of wetland peat and fresh water marl/sand layers that are transitional to the underlying surficial aquifer, ENR Project and WCA–2A, central Everglades, south Florida.

tended to be unidirectional with time (i.e., always recharge or discharge, depending on position upgradient or downgradient of a levee) (Figure 5a). At near-levee sites, the median (50th percentile) values of vertical fluxes ranged in magnitude from 0.03 to 4 cm/day. 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-S in WCA–2A (Figure 5a). The highest value of recharge occurred in ENR at the site that was closest to the levee bordering the agricultural area (site M201) (Figure 5a).

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. This was because those 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 (< 0.06 cm/day), while the 25th and 75th percentile fluxes better represented the typical magnitudes of recharge and discharge (on the order of 0.5 cm/day).

Interior sites at ENR had even smaller median fluxes (approximately 0.03 cm/day). Also, rather than experiencing changing directions of fluxes, vertical fluxes at the interior sites in ENR experienced recharge ~90% of the time (Figure 5c).

Hydrogeologic Simulation

The hydrogeologic simulation suggested that surface water level differences across levees can drive vertical fluxes across the peat surface as large as 10 cm/day near the levees, and that fluxes decline exponentially with distance and become negligible beyond 1000 m (Figure 6). The model performed reasonably well simulating data collected near levees (within 1000 m). All data collected near levees in ENR and WCA–2A plotted within an envelope describing sensitivity of the model to a range of vertical values of K_{peat} (0.003 to 30 m/day). 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 was large, with 25th and 75th percentile fluxes being much larger in magnitude (0.1 to 1 cm/day) than their corresponding median fluxes (~0.06 cm/day). Higher magnitudes of fluxes on the quartiles resulted from switching of vertical fluxes back and forth between recharge and discharge at most sites, averaging to a net flux of approximately zero. The hydrologic simulation predicted a zero vertical flux at all times in the interior wetlands, which vastly underpredicted the observed recharge and discharge fluxes. These results suggest that a time-dependent factor must exist that drives alternating periods of recharge and discharge in the interior of WCA–2A.

Table 3
Vertical Fluxes Across the Peat Surface Measured at Wetland Sites in WCA–2A and ENR Project, Central Everglades, South Florida

	Site	Distance from Levee (m)	Period of Record	Number of Observations	Vertical Flux (cm/day) Percentile 10%	25%	50%	75%	90%
WCA-2A	S10C-S	50	9/9–11/02	1651	1.5	2.3	2.9	3.7	4.0
WCA-2A	E1	2191	2/97–10/02	1945	–0.9	–0.7	–0.03	0.3	0.6
WCA-2A	E4	6915	2/97–10/02	1679	–1	–0.4	0.00	0.4	0.8
WCA-2A	U1	14,447	2/97–10/02	1741	–0.8	–0.4	–0.06	0.2	0.6
WCA-2A	F1	1968	2/97–10/02	1885	–0.7	–0.4	0.04	0.3	0.4
WCA-2A	F4	6906	2/97–10/02	1616	–1.0	–0.8	–0.5	–0.08	0.2
WCA-2A	U3	11,075	2/97–10/02	1955	–0.3	–0.1	0.02	0.2	0.5
ENR East	M104	50	10/96–4/98	110	0.2	0.3	0.7	1.1	1.3
ENR East	M106	132	3/7–4/98	43	0.2	0.2	0.3	0.8	4.7
ENR East	M105	257	12/96–4/98	40	0.1	0.2	0.4	2.3	4.7
ENR East	M103	867	6/96–4/98	37	–0.2	–0.1	–0.04	0.01	0.02
ENR West	M201	50	8/96–4/98	68	–12	–9.6	–3.3	–2.3	–1.1
ENR West	M206	180	3/97–4/98	14	–0.7	–0.1	–0.07	–0.06	–0.04
ENR West	M206	359	10/96–4/98	43	–0.4	–0.2	–0.07	–0.05	–0.02
ENR West	M203	1027	6/96–4/98	53	–0.2	–0.06	–0.03	–0.01	0.01

Five-year (WCA-2A) and two-year (ENR) time periods were investigated, with fluxes reported by percentiles.
Discharge fluxes are positive and recharge fluxes are negative.
Vertical fluxes in WCA-2 and ENR were estimated by seepage meter and Darcy-flux calculations, respectively.

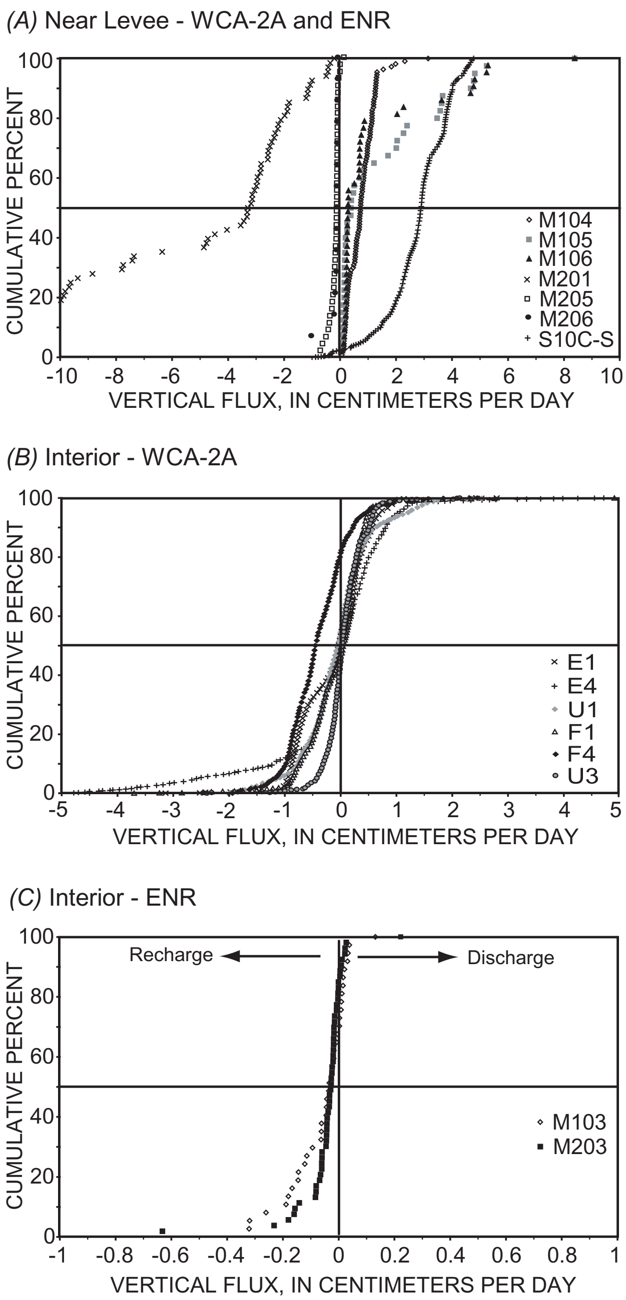

Figure 5. Cumulative distributions of vertical fluxes across the peat surface at wetland sites (a) near levees, (b) interior sites in WCA–2A, and (c) interior sites in ENR Project, central Everglades, south Florida. Vertical fluxes in WCA–2A and ENR were estimated by seepage meter and Darcy-flux calculations, respectively. Note the two times and 10 times exaggeration of vertical flux (x-axis) in (b) and (c), respectively.

Temporal Trends in Recharge and Discharge in Interior Wetlands of WCA–2A

During a five-year measurement period at site U3, vertical fluxes varied cyclically back and forth between recharge and discharge (Figure 7). The temporal record was based on daily calculations of Darcy-flux, which was based on measured surface water levels and ground water head at the site. Unfortunately, a simple correlation was not evident between the fluctuating pattern of recharge and discharge, and measured fluctuations in surface water. Instead, the direction of vertical fluxes alternated on annual, monthly, and weekly timescales. Trends for each timescale are described separately, beginning with annual trends. The years 1997 to 2002 were a time of average wetness in WCA–2A with a slight (interannual) trend toward drying out over the five-year period (-3×10^{-5} m/day). The first half of the record followed a wetter period in the mid-1990s and was a time of average wetness. During that time, the annual trend in recharge and discharge was weighted toward ground water discharge. Recharge and neutral fluxes occurred more often in the second half of the record (2000 to 2002), which was a time of transition to drier conditions in WCA–2A (Figure 7).

Viewed from a monthly perspective, the most obvious repeating features are the ~14 peaks in surface water level that last from several weeks to several months (Figure 7). Plotting the times of spillway discharges from site S10C (Figure 3b) on Figure 7 suggested that most of those peak water levels (above 3.8 m NGVD [National Geodetic Vertical Datum of 1929]) were a direct result of the movement of a pulse of surface water released from the S10 spillways into the central wetland where U3 is located. It appears that the ~8 smaller peaks in surface water elevation (below 3.8 m NGVD) were not associated with surface water pulses, but rather with periods of heavy precipitation near the end of the dry season (Figure 7).

The weekly pattern of vertical flux began with many missing values, and was then 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

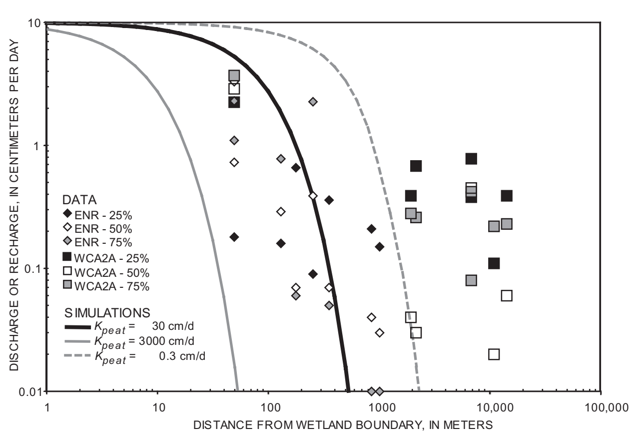

Figure 6. Magnitude of observed discharge and recharge fluxes and simulated fluxes vs. distance from levees in ENR Project and WCA–2A, central Everglades, south Florida.

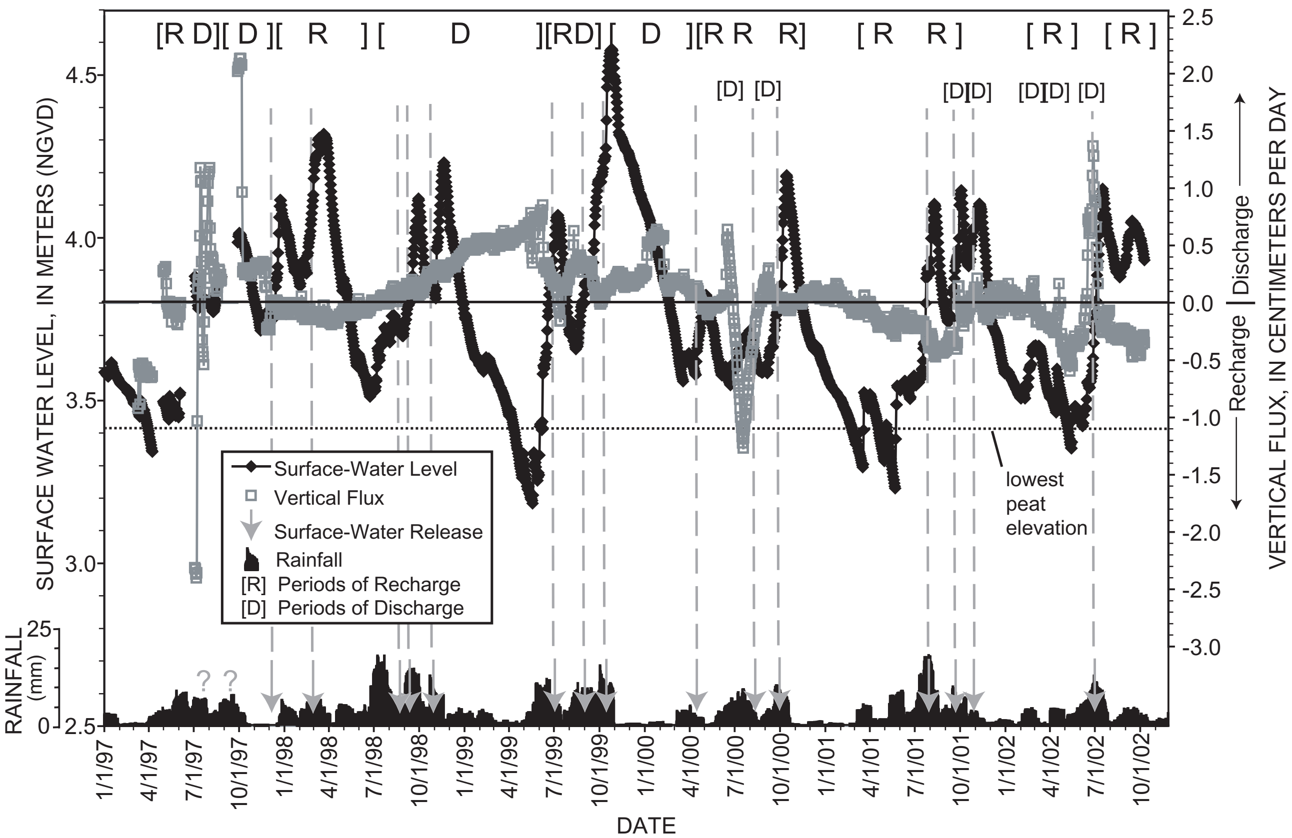

Figure 7. Surface water level fluctuations and vertical fluxes (discharge and recharge) observed over a five-year period at site U3 in the interior of WCA–2A, central Everglades, south Florida. The solid horizontal line separates discharge (positive) from recharge (negative) fluxes. The same horizontal line also indicates the long-term (1951 to 2002) mean water level at U3 (3.8 m NGVD). The dashed horizontal line shows the elevation at which the water level has declined below the lowest measured peat surface at the site. Timing of surface water releases from S10C spillways (vertical gray dashed lines with arrowheads) and a record (29-day running average) of precipitation (small vertical bar graph at bottom of figure) are also shown.

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.

Controls on Reversals Between Discharge and Recharge in Interior Wetlands

Reversals between recharge and discharge were commonly associated with peat rewetting events. Peat rewetting is the process of refilling of unsaturated pore spaces and reflooding the wetland following a dry period when ground water levels decline below the sediment surface. With a maximum drawdown of the water table of ~0.24 m below the wetland surface elevation, 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. Specific factors involved in peat rewetting probably involve a combination of processes, including ground water discharge and infiltration of surface water from surface water flowing across what had just previously been relatively dry or variably saturated wetland sediment. The effects of peat rewetting at site U3 were easiest to visualize in Figure 7 during the periods March through July 2001, and March through June 2002.

Peat rewetting and fluctuations in surface water levels in WCA–2A were affected by precipitation and evapotranspiration, and also by spillway operations that released water from WCA–1. Precipitation and evapotranspiration were the primary controls on water levels when water-control structures were inactive. At those times, surface water levels in the northern (higher elevation) areas of WCA–2A were usually similar to topographic slopes, whereas in the southern areas surface water tended to be ponded (i.e., zero surface water 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 wavelike 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.

There is a potential for surface water pulses to influence surface water 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. We characterized the previous examples as the ground water lag mechanism of driving vertical exchange. Evidence for the ground water lag mechanism was apparent in the five-year record at site U3, particularly in the many recharge events that occurred simultaneously with peak surface water levels (Figure 7). Conversely, discharge tended to occur both on the falling limb of surface water levels and (for short periods encompassing several weeks or less) prior to the arrival of the surface water pulse (Figure 7). While 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 was 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 through the aquifer compared with moving with surface water across the top of the wetland. What we observed at site U3 in the interior of WCA–2A were approximately seven instances when a few days or weeks of discharge occurred immediately preceding the arrival of a surface water pulse at site U3 (Figure 7). Pressure must have traveled faster in the aquifer to cause discharge (for even a short-lived period) before the surface water pulse arrived. This mechanism is referred to here as the ground water pressure-wave mechanism of driving vertical exchange. Although we believe our explanation is plausible, we acknowledge that more field data and model simulations are needed to confirm our interpretation. Once the peak of the surface water pulse arrived, then the direction of vertical flux tended to reverse to recharge as anticipated by the ground water lag effect (Figure 7).

Discussion

Hydraulic conductivity of Everglades' peat was ~30 cm/day, which was more than a factor of 30 less than the hydraulic conductivity of sand and limestone sediments of the surficial aquifer. Lower hydraulic conductivity of peat in some areas of the central Everglades appears to be explained by human alterations of the wetlands, with the lowest average hydraulic conductivity measured in ENR, an area of former wetlands that was farmed for decades and then only recently converted back to wetlands. Transitional organic/marl/sand sediments beneath the wetland peat had hydraulic conductivities that were similar to peat, indicating that the layers restricting recharge and discharge fluxes may be thicker than the peat itself. The depth of the transitional layer was uncertain at most of our sites and should be more rigorously determined in future studies.

Model simulations were consistent with field data in suggesting that recharge and discharge were highest near levees. Modeled vertical fluxes declined exponentially and were not significant beyond 600 m. In the wetland interior

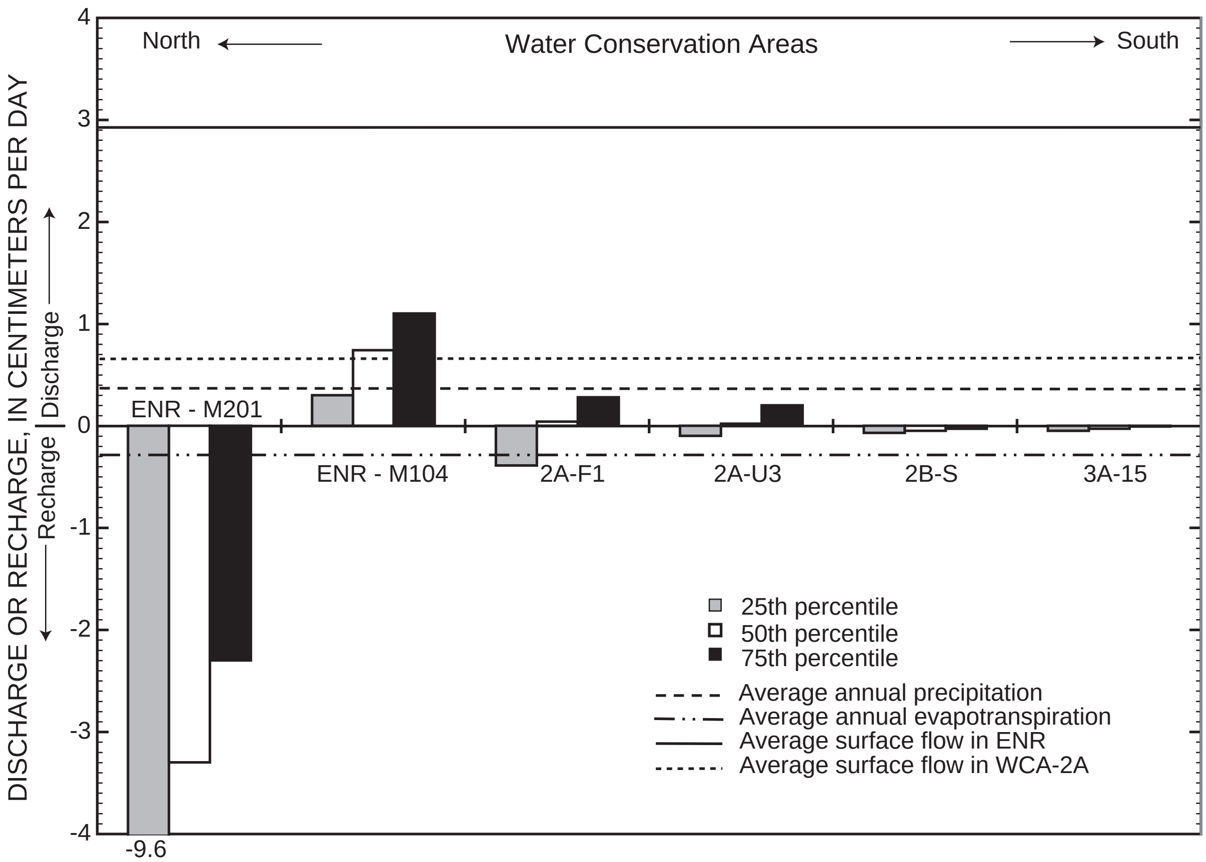

Figure 8. Spatial trends in discharge and recharge in central Everglades, south Florida. Time-averaged values of precipitation, evapotranspiration, and surface flows in ENR Project (Choi and Harvey 2000) and WCA–2A (SFWMD 1999) are plotted for comparison.

(farther than 1000 m), our measurements of recharge and discharge were significantly higher than simulated fluxes, and our observation in interior wetlands therefore could not be accounted for as a direct effect of ground water flow beneath levees. Field observations showed that most interior sites also demonstrated cyclic changes from recharge to discharge and vice versa, with reversals occurring on monthly or longer timescales.

Estimates of recharge and discharge from a subset of our sites in the central Everglades are summarized in Figure 8 and contrasted with average precipitation, evapotranspiration, and basin-averaged surface flows in the central Everglades (SFWMD 1999). Recharge and discharge were greatest in the smaller basins (ENR and the Stormwater Treatment Areas [STAs]) of the north-central Everglades. At some sites in ENR, recharge was larger than precipitation and evapotranspiration, and was also significant relative to surface flows (Figure 8). Choi and Harvey (2000) showed that recharge in ENR accounted for a flux of water equal to 30% of surface flow. Farther south in the much larger WCAs, area-averaged recharge and discharge were smaller, although the fluxes were still significant relative to other water balance fluxes (Figure 8). The trend of decreasing vertical fluxes farther south in the central Everglades is probably the result of several factors, including larger basin size (and correspondingly less effect of ground water flow beneath levees) and also a smaller overall driving force for recharge due to surface water levels in the wetlands that are not as high relative to areas outside of the wetlands compared with wetlands farther north (Miller 1988).

Recharge and discharge are important to water budgets in the central Everglades. Over the long term, recharge generally exceeds discharge (Harvey et al. 2002). The present research suggests that in addition to net, long-term recharge, there are alternating periods of recharge and discharge in the interior wetlands. These fluxes cancel out in long-term hydrologic budgets, but they are of great potential importance to seasonal water balances and water quality. For example, seasonal recharge during rising surface water levels transports surface water (and surface water contaminants) into peat porewater and the aquifer (Harvey et al. 2002). The stored water is later released by ground water discharge during falling surface water levels, supplementing low flows and perhaps exporting subsurface constituents back to surface water. In this way, alternating periods of recharge and discharge can be viewed as a natural process of aquifer storage and recovery that may be important to ecosystem processes as well as storage and return of dissolved contaminants to surface water.

Comparison with Predrainage Conditions

Knowing exactly how recharge and discharge have changed since predrainage times in the central Everglades is impossible, which means that present-day spatial trends are the best source of information to extrapolate backward to estimate predrainage conditions. The best modern analog for recharge and discharge relationships in the central Everglades to represent predrainage conditions is probably WCA–3A, where driving forces for recharge and discharge by natural topographic gradients are small, and great distances from levees and water-control structures reduce the effects of increased surface water level fluctuations. Recharge and discharge in WCA–3A were the smallest measured in our study. We conclude that in most areas of the central Everglades, particularly the much smaller basins (thousands of hectares) near the northern and northwestern boundaries (i.e., ENR and the STAs), recharge and discharge have vastly increased due to the effects of water resources management. Our work confirms that isolation of surface water at different levels in basins surrounded by levees creates significant driving forces for recharge and discharge. Our work also identifies that, perhaps for the first time, greater surface water level fluctuations associated with water resources management have also played a role in increasing recharge and discharge in the interior areas of the central Everglades.

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References

Anderson, M.P., and W.W. Woessner. 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport.* San Diego: Academic Press.

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

Brand, E.W., and J. Premchitt. 1980. Shape factors of cylindrical piezometers. *Geotechnique* 30, 369–384.

Brinson, M.M., H.D. Bradshaw, and R.N. Holmes. 1983. Significance of floodplain sediments in nutrient exchange between a stream and its floodplain. In *Dynamics of Lotic Ecosystems*, 199–221. Ann Arbor, Michigan: Ann Arbor Science.

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.

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

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, T.K. MacVicar, and W.A. Perkins. 1994. Computer model to simulate natural Everglades hydrology. In *Everglades: The Ecosystem and Its Restoration*, ed. S.M. Davis and J.C. Ogden, 249–290. Boca Raton, Florida: St Lucie Press.

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.

Genereux, D., and E. Slater. 1999. Water exchange between canals and surrounding aquifer and wetlands in the southern Everglades, U.S.A. *Journal of Hydrology* 219, 153–168.

Gerla, P.J., and R.K. Matheney. 1996. Seasonal variability and simulation of ground water flow in a prairie wetland. *Hydrological Processes* 10, no. 7: 903–920.

Gleason, P.J., and P. Stone. 1994. Age, origin, and landscape evolution of the Everglades peatland. In *Everglades: The Ecosystem and Its Restoration*, ed. S.M. Davis and J.C. Ogden, 149–198. Boca Raton, Florida: St Lucie Press.

Harvey, J.W., and W.K. Nuttle. 1995. Fluxes of water and solute in a coastal wetland sediment, 2. Effect of macropores on solute exchange with surface water. *Journal of Hydrology* 164, no. 1–4: 109–125.

Harvey, J.W., S.L. Krupa, C. Gefvert, J. Choi, R.H. Mooney, and J.B. Giddings. 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.

Harvey, J.W., S.L. Krupa, C. Gefvert, R.H. Mooney, J. Choi, S.A. King, and J.B. Giddings. 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.

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.

Hunt, R.J., J.F. Walker, and D.P. Krabbenhoft. 1999. Characterizing hydrology and the importance of ground water discharge in natural and constructed wetlands. *Wetlands* 19, no. 2: 458–472.

Jensen, J.R., K. Rutchey, M.S. Koch, and S. Narumalani. 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* 61, no. 2: 199–209.

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

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography* 22, 140–147.

Light, S.S., and J.W. Dineen. 1994. Water control in the Everglades—A historical perspective. In *Everglades: The Ecosystem and Its Restoration*, ed. S.M. Davis and J.C. Ogden, 47–84. Boca Raton, Florida: St Lucie Press.

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

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.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.

Nemeth, M.S., and H.M. Solo-Gabriele. 2001. Evaluation of the use of reach transmissivity to quantify exchange between groundwater and surface water. *Journal of Hydrology* 274, 145–159.

Nuttle, W.K., and H.F. Hemond. 1988. Salt marsh hydrology: Implications for biogeochemical fluxes to the atmosphere and estuaries. *Global Biogeochemical Cycles* 2, no. 2: 91–114.

Perkins, R.D. 1977. Depositional framework of Pleistocene rocks in south Florida. In *Quaternary Sedimentation in South Florida: Geological Society of America Memoir 147*, ed. P. Enos and R.D. Perkins, 131–196. Boulder, Colorado: Geological Society of America Inc.

Price, R.M.. J.D. Happell, Z. Top, and P.K. Swart. 2003. Use of tritium and helium to define groundwater flow conditions in Everglades National Park. *Water Resources Reseach* 39, no. 9: 1267-1280.

Reeve, A.S., D.I. Siegel, and P.H. Glaser. 2000. Simulating vertical flow in large peatlands. *Journal of Hydrology* 227, no. 1–4: 207–217.

Rohrer, K.P. 1999. Hydrogeological characterization and estimation of ground water seepage in the Everglades nutrient removal project. SFWMD WRE–372.

Romanowicz, E., and C.J. Richardson. 2000. Modeling hydroperiods and flooding depths in the northern Everglades, Water Conservation Area 2A. In *INTECOL VI: Millennium Wetland Event and 21st Annual Meeting of the Society of Wetland Scientists, August 6–12, Quebec City, Program with Abstracts*, 324. International Association of Ecology.

Siegel, D.I. 1983. Ground water and the evolution of patterned mires, Glacial Lake Agassiz peatlands, northern Minnesota. *Journal of Ecology* 71, 913–921.

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.

SFWMD. 1999. A primer to the South Florida Water Management Model (version 3.5). http://www.sfwmd.gov/org/pld/hsm/models/sfwmm/v3.5/wmmpdf.htm.

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.

Tarboton, K.C., C.J. Neidrauer, E.R. Santee, and J.C. Needle. 1999. Regional hydrologic modeling for planning the management of South Florida's water resources through 2050. American Society of Agricultural Engineers paper no. 992062.

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

Thibodeaux, L.J. 1996. *Environmental Chemodynamics: Movement of Chemicals in Air, Water, and Soil*. New York: John Wiley and Sons.

Tobias, C.R., J.W. Harvey, and I.C. Anderson. 2001. Quantifying ground water discharge through fringing wetlands to estuaries: Seasonal variability, methods comparison, and implications for wetland-estuary exchange. *Limnology and Oceangraphy* 46, no. 3: 604–615.

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