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QUANTIFYING TIME-VARYING GROUND-WATER DISCHARGE AND RECHARGE IN WETLANDS OF THE NORTHERN FLORIDA EVERGLADES

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Abstract: Developing a more thorough understanding of water and chemical budgets in wetlands depends in part on our ability to quantify time-varying interactions between ground water and surface water. We used a combined water and solute mass balance approach to estimate time-varying ground-water discharge and recharge in the Everglades Nutrient Removal project (ENR), a relatively large constructed wetland (1544 hectare) built for removing nutrients from agricultural drainage in the northern Everglades in South Florida, USA. Over a 4-year period (1994 through 1998), ground-water recharge averaged 13.4 hectare-meter per day (ha-m/day) or 0.9 cm/day, which is approximately 31% of surface water pumped into the ENR for treatment. In contrast, ground-water discharge was much smaller (1.4 ha-m/day, or 0.09 cm/day, or 2.8% of water input to ENR for treatment). Using a water-balance approach alone only allowed net ground-water exchange (discharge − recharge) to be estimated (−12 ± 2.4 ha-m/day). Discharge and recharge were individually determined by combining a chloride mass balance with the water balance. For a variety of reasons, the ground-water discharge estimated by the combined mass balance approach was not reliable (1.4 ± 37 ha-m/day). As a result, ground-water interactions could only be reliably estimated by comparing the mass-balance results with other independent approaches, including direct seepage-meter measurements and previous estimates using ground-water modeling. All three independent approaches provided similar estimates of average ground-water recharge, ranging from 13 to 14 ha-m/day. There was also relatively good agreement between ground-water discharge estimates for the mass balance and seepage meter methods, 1.4 and 0.9 ha-m/day, respectively. However, ground-water-flow modeling provided an average discharge estimate that was approximately a factor of four higher (5.4 ha-m/day) than the other two methods. Our study developed an initial understanding of how the design and operation of the ENR increases interactions between ground water and surface water. A considerable portion of recharged ground water (73%) was collected and returned to the ENR by a seepage canal. Additional recharge that was not captured by the seepage canal only occurred when pumped inflow rates to ENR (and ENR water levels) were relatively high. Management of surface water in the northern Everglades therefore clearly has the potential to increase interactions with ground water.

Key Words: wetland, constructed wetland, water balance, ground-water discharge and recharge, Florida Everglades, ground-water/surface-water interactions

INTRODUCTION

Recognition of the importance of wetlands to wildlife and to water quality has accelerated research on the role of hydrology as a driving force for wetland processes (Good et al. 1978, Ivanov 1981, Carter 1986, Hemond and Benoit 1988). Hydrologic fluxes in lakes and wetlands often include surface inflow and outflow, precipitation, evapotranspiration, and exchange between surface water and ground water. Of these, the interaction between surface water and ground water is generally recognized as the most difficult flux to estimate because it is often relatively small compared to other components of the water budget (Kadlec 1983, LaBaugh 1986). However, even a small flux between surface water and ground water might be very crucial to biogeochemical processes due to the typical sharp contrast between chemistry of surface water and ground water in wetlands (Howes et al. 1996). As a result, ground-water and surface-water interactions have the potential to vastly alter redox-sensitive solutes or contaminant mass balances in wetlands.

Exchange of water between ground water and surface water is difficult to quantify in wetlands because it cannot usually be measured directly. Rather, ground-water exchange fluxes must be inferred from related hydrologic and chemical measurements. In the past, wetland/ground-water exchange fluxes sometimes were assumed to be insignificant, or estimated as a residual term in wetland surface-water balances, or determined by Darcy flux calculations using relatively limited data sets. Progress in quantifying the water balance of lake systems provided useful guidance for wetland research (Crowe and Schwartz 1985, Stauffer 1985, Krabbenhoft and Anderson 1986). More recent approaches in wetlands used water or solute mass balances in the subsurface (Harvey and Odum 1990, Nuttle and Harvey 1995, Hunt et al. 1996). Mass balance calculations in the wetland subsurface have the possible advantage of improved accuracy over surface-water mass balances, but the results from a particular location cannot be easily extrapolated to other areas of the wetland. Ground-water-flow modeling offers a means to extrapolate site-specific results to larger wetland areas (Hunt et al. 1996, Guardo and Prymas 1998). A drawback is that reliable modeling often requires extensive installation of wells, which still may not be enough to characterize aquifer heterogeneity adequately (Krabbenhoft and Anderson 1986). Also, hydraulic conductivity estimates in peat are sometimes unreliable (Ingram et al. 1974, Hemond and Goldman 1985, Nuttle and Harvey 1995). Common to all methods is the difficulty of quantifying the uncertainties in ground-water discharge and recharge estimates.

The present study was undertaken in the Everglades Nutrient Removal area, a 1544-hectare wetland constructed in 1994 to test the removal efficiency for nutrients in agricultural runoff. The ENR is located in south Florida, USA (26° 38′N, 80° 25′W) between the eastern edge of the Everglades Agricultural Area (EAA) and the western edge of Everglades Water Conservation Area 1 (WCA-1) (Figure 1a). The ENR area is primarily covered by peat soils with very small topographic relief and an average ground elevation of 3 m NGVD. The peat layer is underlain by layers of permeable sand and limestone that comprise the surficial aquifer. The ENR project area is mainly covered with either monospecific stands of cattails, mixtures of many macrophytes including cattails, or open water with submerged vegetation.

Like other wetlands constructed for water treatment, ENR is often subjected to higher surface-water flows and more frequent fluctuations in water level compared with natural wetlands. In addition, the supply waters for treatment wetlands can vary substantially, representing vastly different source waters with different chemistry. Because of these unstable hydrologic and chemical conditions, time-varying estimates of ground-water fluxes were essential to understand the ground-water interactions in the ENR.

Ground-water interactions at the ENR were examined in several previous investigations (Hutcheon Engineers 1996, Guardo and Prymas 1998). Those authors estimated wetland/ground-water exchange using water-level data, hydraulic conductivity estimates, and ground-water-flow modeling. Guardo (1999) and Moustafa (1999) made use of those results in their water balance and nutrient balance studies at ENR. However, neither of previous ground-water investigations simultaneously estimated discharge and recharge, and no uncertainties were estimated. As a result, there is still some question whether previous estimates of ground-water interactions are reliable or not. Due to the above considerations, reliable estimates of ground-water discharge and recharge are still needed at ENR.

In this study, we estimated time-varying ground-water discharge and recharge in the ENR using a coupled water and solute (chloride) mass balance approach. We estimated the error in our analysis, and we examined individual components in mass balance to identify the key contributors to uncertainty. Also, we compared our results with other approaches used at ENR, including our past results using seepage meters as well as ground-water-flow modeling results from past studies. Through comparison, we identified the most reliable estimates of ground-water interactions and applied that knowledge to develop an initial understanding of how the design and operation of the ENR increases interactions between ground water and surface water.

METHODOLOGY

Water Budget

The water-budget equations that apply to the surface-water/ground-water interaction at the ENR are presented here. Using the conceptual model of water flow in the ENR (Figure 2) and mass conservation, the governing water-budget equation is

$$\frac{dV}{dt} = \frac{V(t) - V(t-1)}{\Delta t} = S_i + P + R_i + L_i + G_i - S_o - ET - R_o - G_o \quad [1]$$

where S_i and G_i are the rates of surface-water inflow and ground-water discharge, respectively, and S_o and G_o are the rates of surface-water outflow and ground-water recharge, respectively. P and ET are the rates of precipitation and evapotranspiration, respectively. V is the volume of water in the ENR at the present and previous time step, and t and Δt are time and time interval, respectively. There are also several measured fluxes that are unique to the ENR site that must be included in the balance. L_i is shallow seepage through the L-7 levee collected by a ditch and delivered by culverts into ENR. In addition, R_i is the rate of surface-water pumping to the ENR from a seepage canal that collects ground water on the western and northern side of the ENR. R_o is the rate of surface-water outflow

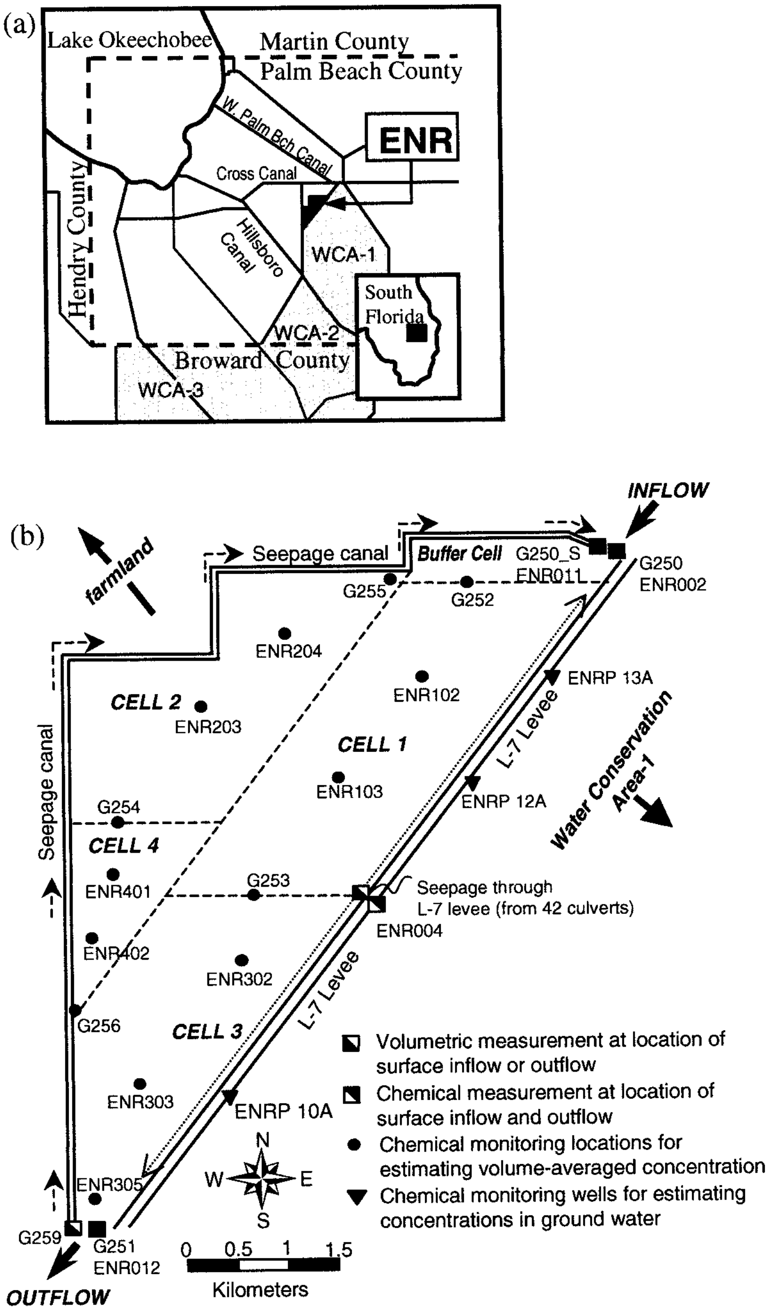

Figure 1. (a) Palm Beach County and vicinity showing location of ENR relative to Everglades Agricultural Area (EAA) and Water Conservation Area (WCAs). (b) Location map illustrating hydrologic and chemical monitoring sites in Everglades Nutrient Removal (ENR) project.

from the ENR to the seepage canal (R_o is almost always zero).

For our water balance, we used four years of data (1994–1998) that were supplied to us by the South Florida Water Management District. Among the main components of water balance, areal average precipitation was computed as a Thiessen-weighted average of a seven-gage network. Daily evapotranspiration was computed based on percent type of vegetative cover and the area of each cell. A Penman-Monteith model was used to determine evapotranspiration for cattails and mixed macrophytes, and a Penman-Combination model was used for shallow open water. The reader is refered to Abtew and Mullen (1997) for a more complete description of hydrologic monitoring at ENR. For our study, all components of input and output (L^3/T) are averaged over two-week periods in order to consider both the hydrologic residence time of approxi-

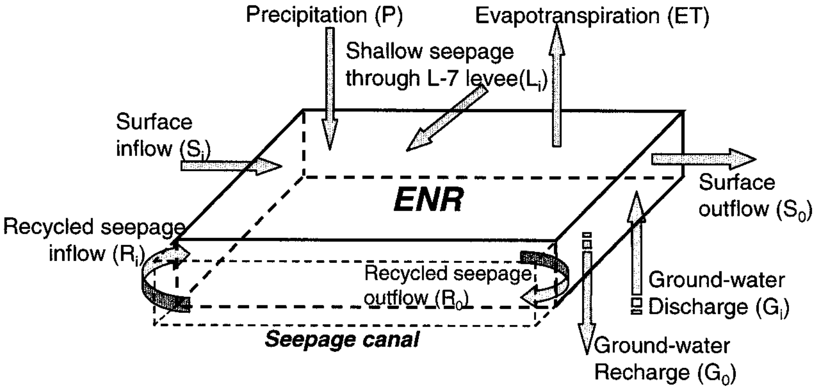

Figure 2. Conceptual model of water flows in the ENR.

mately 20 days in surface water (Guardo 1999) and time interval of chemical monitoring by South Florida Water Management District (14 days). We chose to use units of flow (hectare-meter/day) that were consistent with the data base of South Florida Water Management District (1 hectare-m/day = 0.116 m^3/second). Using the 14-day averaged fluxes, equation [1] is rewritten as

$$V(t) = V(t-1) + \Delta t \cdot \{\bar{S}_i + \bar{P} + \bar{R}_i + \bar{L}_i + \bar{G}_i - \bar{S}_o - \overline{ET} - \bar{R}_o - \bar{G}_o\} \quad [2]$$

where Δt equals 14 days and the overbars denote 14-day averaged fluxes. Using equation [2], we can solve for the two unknowns (G_i and G_o) in terms of a net exchange between ENR surface water and ground water by substituting $V(t) - V(t-1)$ by ΔV and rearranging [2] to yield

$$\bar{G}_i - \bar{G}_o = \frac{\Delta V}{\Delta t} - \bar{S}_i - \bar{P} - \bar{R}_i - \bar{L}_i + \bar{S}_o - \overline{ET} + \bar{R}_o. \quad [3]$$

Combined Water and Solute Mass Balance

Using only the surface-water-budget balance data, we cannot take the further step of partitioning the net ground-water exchange ($G_i - G_o$) to solve for G_i and G_o individually. In order to solve for the two unknowns (G_i and G_o), we need a second mass balance equation, such as one for solute tracer. Using the same conceptual model for water fluxes in the ENR, the solute mass balance for a solute in surface water is

$$\frac{dM}{dt} = \frac{V(t)\cdot C(t) - V(t-1)\cdot C(t-1)}{\Delta t} = \bar{S}_i\cdot\bar{C}_{S_i} + \bar{P}\cdot\bar{C}_P + \bar{R}_i\cdot\bar{C}_{R_i} + \bar{L}_i\cdot\bar{C}_{L_i} + \bar{G}_i\cdot\bar{C}_{G_i} - \bar{S}_o\cdot\bar{C}_{S_o} - \bar{R}_o\cdot\bar{C}_{R_o} - \bar{G}_o\cdot\bar{C}_{G_o} \quad [4]$$

where

M is the mass storage of the designated solute in the ENR,
$C(t)$ is the area-averaged solute concentration in ENR surface water at time t,
$\bar{C}_{S_i}$ is the solute concentration in surface inflow from ENR supply canal,
$\bar{C}_P$ is the solute concentration in precipitation,
$\bar{C}_{R_i}$ is the solute concentration in surface inflow from seepage canal,
$\bar{C}_{L_i}$ is the solute concentration in shallow seepage collected by L-7 culverts,
$\bar{C}_{G_i}$ is the solute concentration of ground-water discharge into ENR,
$\bar{C}_{S_o}$ is the solute concentration of surface outflow from ENR
$\bar{C}_{R_o}$ is the solute concentration of surface outflow to seepage canal, and
$\bar{C}_{G_o}$ is the solute concentration of ground water recharge from ENR.

Being able to calculate G_i and G_o is the main advantage of the combined approach using water and solute mass balance relationships. This is accomplished by rearrangement of [3] and substitution for G_o in [4]

$$\bar{G}_i = \left\{\frac{1}{\Delta t}\cdot(V_0 + \Delta V)\cdot C_t - \frac{1}{\Delta t}\cdot V_0\cdot C_0 - \bar{S}_i\cdot\bar{C}_{S_i} - \bar{P}\cdot\bar{C}_P - \bar{R}_i\cdot\bar{C}_{R_i} - \bar{L}_i\cdot\bar{C}_{L_i} + \bar{S}_o\cdot\bar{C}_{S_o} + \bar{R}_o\cdot\bar{C}_{R_o} + \bar{S}_i\cdot\bar{C}_{G_o} + \bar{P}\cdot\bar{C}_{G_o} + \bar{R}_i\cdot\bar{C}_{G_o} + \bar{L}_i\cdot\bar{C}_{G_o} - \bar{S}_o\cdot\bar{C}_{G_o} - \overline{ET}\cdot\bar{C}_{G_o} - \bar{R}_o\cdot\bar{C}_{G_o} - \frac{1}{\Delta t}\cdot\Delta V\cdot\bar{C}_{G_o}\right\} \bigg/ (\bar{C}_{G_i} - \bar{C}_{G_o}) \quad [5]$$

The result for $\bar{G}_i$ from equation [5] can be substituted back into equation [3] to compute ground-water recharge.

The following steps were undertaken in the estimation procedure. First, hydrologic and chemical data were acquired for the ENR from the South Florida Water Management District (Table 1 and Figure 1b).

Table 1. Monitoring locations of hydrologic and chemical components in the ENR.

Hydrologic Components		Chemical Components	
Variables	Location	Variables	Location
S_i	G-250	C_{Si}	ENR002
S_o	G-251	C_{So}	ENR012
R_i	G-250_S	C_{Ri}	ENR011
R_o	G-259	C_{Ro}	ENR012
L_i	L7a (culverts)	C_{Li}	ENR004
		C_{Gi}	ENRP10a, 12a, 13a
		C_{Go}	ENR(203, 204), G254(B & D), G255
		C_t	Buffer Cell: G252C, G252G Cell 1: ENR (102, 103), G252(C & G), G253(C & G) Cell 2: ENR(203, 204), G254(B & D), G255 Cell 3: ENR(302, 303, 305), G253(C & G) Cell 4: ENR(401, 402), G254(B & D), G256

The initial volume of surface water in ENR (V_o) was estimated using measurements of surface-water depth (ranging from 0.5 m to 0.8 m) and the area of each cell. Chemical concentrations monitored by the South Florida Water Management District were available on approximately biweekly basis at each surface input and output flow locations and at each interior site in ENR (Table 1 and Figure 1b). We evaluated several potential tracers (Cl, Na, Mg, and Ca) for the present study and selected chloride as the best ionic solute tracer for the ENR.

The average Cl concentration in surface water of the ENR (C_t) was estimated using water-volume fractions in each cell and average Cl concentrations in each cell determined from 3 or 4 representative monitoring sites in each cell (Table 1 and Figure 1b). The Cl concentration of ground-water discharge (C_{G_i}) was estimated by averaging the Cl measurements from 3 wells located on the eastern side of the ENR (near L-7 Canal) (Figure 1b). Boreholes were drilled by the mud-rotary drilling method and wells emplaced with 0.6-m screen located at approximately 9 m below land surface in a limestone layer with interbeded sand lenses (Harvey et al. 2000). In addition, the Cl concentration of ground-water recharge (C_{G_o}) was estimated from average concentration of surface water in cell 2, where hydraulic gradient and seepage-meter data suggest that most ground-water recharge is likely to occur (Harvey et al. 2000). Using the combined hydraulic and chemical data set and equations [3, 4, and 5], the ground-water discharge (G_i) and recharge (G_o) were estimated every 14 days over the study period of 4 years (1994 to 1998).

Uncertainty Analysis

A general characteristic of hydrologic mass balance equations is that they appear deceptively simple, i.e., mass in equals mass out plus or minus change in storage (Equation [1] and [4]). In reality, however, the errors in inputs to the mass balance equations affect the reliability of the outcome. Errors are usually generated from three major sources: first, measurement errors from imperfect instruments and inadequate sampling design and data collection procedures; second, interpretation errors resulting from spatial interpolation of point data; and third, model errors that are caused by inaccurate statement of the problem, for example, not including an important flux in the mass balance equation. Ideally, all of these errors should be assessed before final conclusions are drawn. For this study, we estimated the uncertainty of net ground-water exchange and ground-water discharge using standard techniques for propagating error through numerical calculations. For the case where a quantity y is determined as a function of multiple variables $x_1, x_2, \ldots, x_n$, the uncertainty in y is expressed by following (Meyer 1975, Taylor 1982)

$$\epsilon_y = \sqrt{\left(\frac{\partial y}{\partial x_1}\epsilon_{x_1}\right)^2 + \left(\frac{\partial y}{\partial x_2}\epsilon_{x_2}\right)^2 + \left(\frac{\partial y}{\partial x_3}\epsilon_{x_3}\right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n}\epsilon_{x_n}\right)^2} \tag{6}$$

where ϵ_y represents the uncertainty in a calculated variable y and $\epsilon_{x_1,x_2,\ldots,x_n}$ represent uncertainties of measured variables $x_1, x_2, \ldots, x_n$. The relative contribution of each variable to uncertainty in calculated variable y can be determined by comparing ϵ_y^2 and each term under the square root of the right hand side of equation [6]. In the present study, we adhered to the usual assumption in hydrologic studies that the uncertainty of each variable was independent of that of other variables (Winter 1981). Equation [6] is therefore the simplified form of the more general expression that considers covariance between variables (i.e., where the

Table 2. Estimated uncertainties involved in hydrologic and chemical components.

Hydrologic Components		Chemical Components	
Components	Uncertainty (%)	Components	Uncertainty (%)
S_i	10.0	C_t and C_o	15.0
S_o	10.0	C_{Si}	10.0
R_i	10.0	C_{So}	10.0
R_o	10.0	C_{Ri}	10.0
L_i	10.0	C_{Ro}	10.0
P	8.5	C_P	15.0
ET	20.0	C_{Li}	10.0
ΔV	15.0	C_{Gi}	15.0
V_o	15.0	C_{Go}	20.0

uncertainty in one variable depends on another) (Winter 1981). We referred to previous works (e.g., Winter 1981, Nuttle and Harvey 1995) in developing our uncertainty estimates of hydrologic components, such as precipitation, evapotranspiration, and surface-flow measurements (Table 2). However, to our knowledge, an equally defensible approach to define uncertainty of chemical measurements originating from both instrument error and interpolation error has not been attempted (LaBaugh 1985, Stauffer 1985, LaBaugh et al. 1997). Therefore, we estimated uncertainties of measured chemical variables at ENR by using our best judgment to qualitatively estimate instrument errors and interpolation errors associated with averaging point data to represent larger area of the ENR.

RESULTS

Water Budget and Coupled Mass Balance

Our analysis of surface-water and ground-water interaction in the ENR began with estimation of the net ground-water flux ($G_i - G_o$) for the study period (1994–1998) using equation [3]. The magnitude of the net ground-water flux ($G_i - G_o$) varied from −27.5 to −1.1 ha-m/day, with an average over time of −12.0 ha-m/day (Figure 3a). Estimated net ground-water fluxes are almost entirely negative values, which means that the ground-water recharge generally exceeded ground-water discharge. Therefore, ENR loses water on a net basis due to interaction with a ground-water aquifer. First-order error analysis indicated that uncertainty in estimated net ground-water flux varied from ± 0.5 to 4.5 ha-m/day (Figure 3a), with an average over time of 2.4 ha-m/day.

On the other hand, our initial estimates of ground-water discharge derived from the combined water and solute mass balance (Eq. [5]) fluctuated greatly. In the computation of ground-water discharge, the difference, $\bar{C}_{G_i} - \bar{C}_{G_o}$, sometimes approaches zero. During those periods, even a small relative error in either $\bar{C}_{G_i}$ or $\bar{C}_{G_o}$ an cause ground-water discharge (G_i) to be computationally inflated. We attempted to reduce uncertainty by filtering out those two-week periods when a reliable estimate of ground-water discharge was obviously impossible. To accomplish this, we excluded cases for which the difference of $\bar{C}_{G_i}$ and $\bar{C}_{G_o}$ was less than 15 mg/L (30% of observations). After filtering was completed, discharge estimates were still unrealistically large, ranging between −235.0 and 220.0 ha-m/day (Figure 3b) with an uncertainty averaging 54 ha-m/day and ranging between ± 20.0 and 215.0 ha-m/day (Figure 3b). We attempted to further improve our estimate of ground-water discharge by selecting an optimal time period with relatively lower uncertainty (period II in Figure 4a and b). During period II, ground-water discharge averaged 1.4 ha-m/day (Table 3) with uncertainty averaging 37.0 ha-m/day. Since the uncertainty was still large compared to the average estimate of ground-water discharge, we were forced to conclude that time-varying ground-water discharge could not be estimated by the combined mass balance alone. However, we hoped that our best estimate of average ground-water discharge (1.4 ha-m/day or 0.9 cm/day) would prove to be reliable, as shown by com-

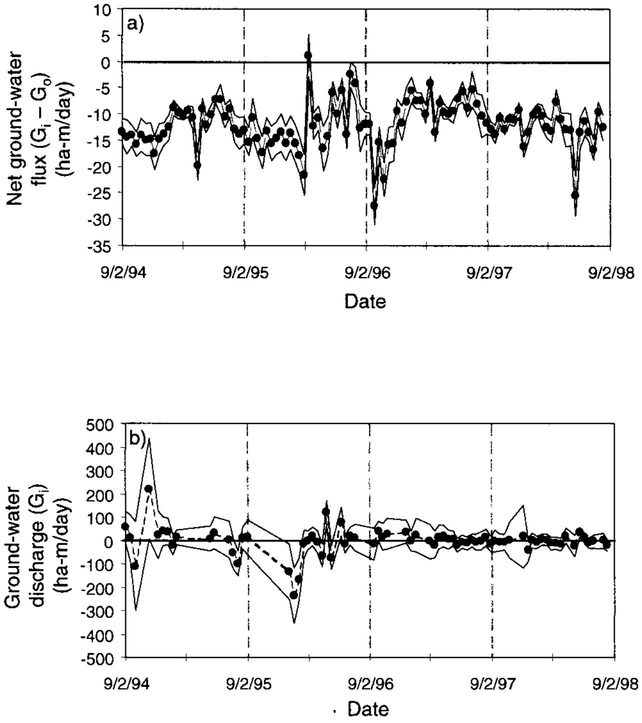

Figure 3. (a) Net ground-water flux and (b) ground-water discharge into ENR estimated from combined water and solute mass balance. Upper and lower ranges of the estimations indicated by solid lines show the uncertainty.

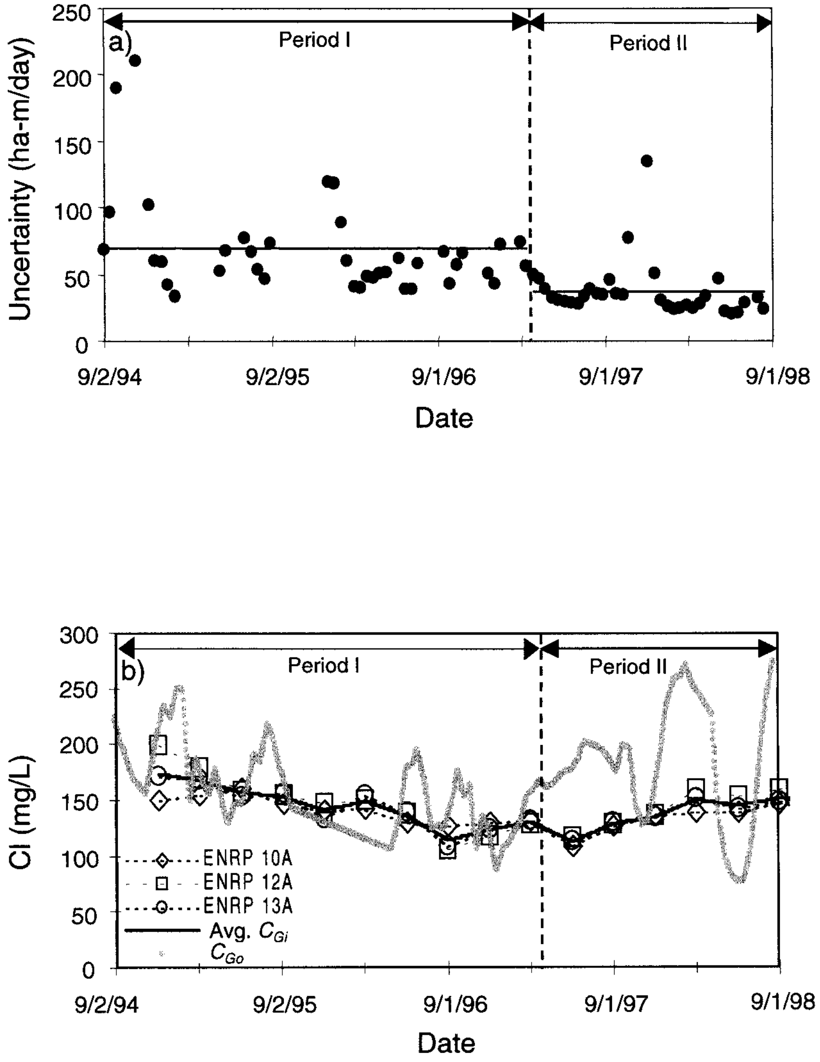

Figure 4. Uncertainty in (a) estimated ground-water discharge and (b) comparison of uncertainty in estimated ground-water discharge and chemical difference between ground-water recharge ($\bar{C}_{G_o}$) and discharge ($\bar{C}_{G_i}$). The greater the difference between Cl concentrations in ground water ($\bar{C}_{G_i}$) and surface water ($\bar{C}_{G_o}$), the lower the uncertainty in estimated ground-water discharge rate.

Table 3. Water-balance fluxes in ENR from coupled water-solute mass balance: 8/19/94–8/19/98.

	Description	Fluxes (ha-m/day)	Percent (%) of Inflow Pump
Inflow	Inflow pump (S_i)	43.1	100.0
	Inflow from seepage canal (R_i)	9.4	21.9
	Precipitation (P)	6.2	14.5
	Shallow seepage inflow (L_i)	1.6	3.8
	Ground-water discharge (G_i)	1.4	2.8
Outflow	Outflow pump (S_o)	42.5	98.6
	Outflow to seepage canal (R_o)	0.6	1.4
	Evapotranspiration (ET)	5.6	12.9
	Ground-water recharge (G_o)	13.4	31.0
	Change in storage (ΔV)	−0.3	0.7

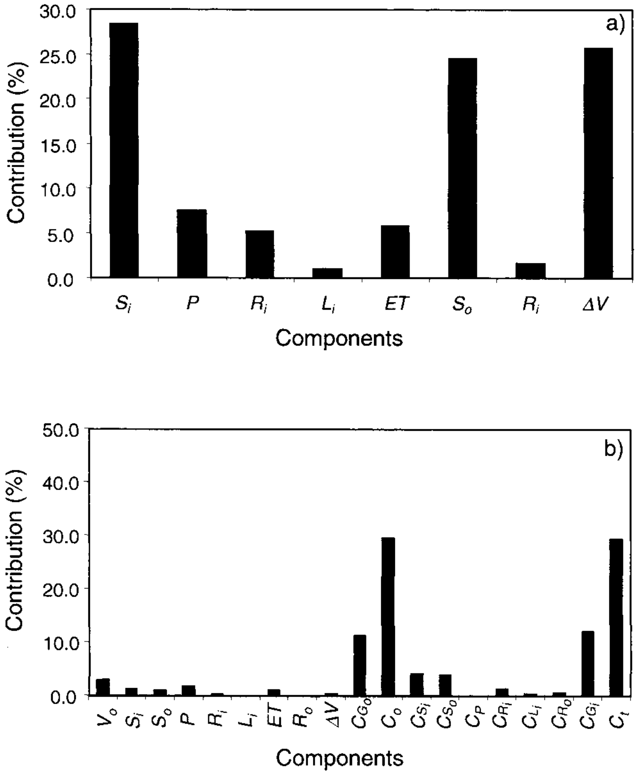

Figure 5. Contributions (%) of individual uncertainties of hydrologic and chemical measurements to the overall uncertainty in estimating (a) net ground-water exchange and (b) ground-water discharge into ENR.

parisons with other independent estimations of ground-water discharge.

Sources of Uncertainty

What are the individual sources of uncertainty in estimating ground-water interactions by the combined mass balance approach? Sources of uncertainty were separately identified by inspecting the uncertainty of each component in the water and combined water and solute mass balances, respectively. Results showed that most uncertainty in estimating net ground-water flux ($G_i - G_o$) was due to the uncertainties in S_i, S_0, and ΔV. However, uncertainty in estimating ground-water discharge was mainly controlled by chemical (Cl) variables in equation [5], such as C_0, C_t, C_{G_o}, and C_{G_i}. The relative contributions of all variables to uncertainties are shown in Figure 5.

Which physical or chemical attributes of the ENR wetland were most important in controlling overall uncertainties? In order to answer this question, uncertainties in $G_i - G_o$ and G_i were compared with key hydrologic and chemical variables. For example, the uncertainty in estimating net ground-water flux was compared with daily surface inflow rate and daily change in surface-water storage during the study period. Both of those comparisons show that uncertainty in estimated $G_i - G_o$ increases with higher surface-water inflow rate and higher change in surface-water storage. These relationships indicate that it becomes increasingly difficult to estimate the net ground-water flux ($G_i - G_o$) with accuracy when the system is actively responding to change in surface-water pumping rate. On the other hand, the uncertainty in estimating ground-water discharge (G_i) was mainly controlled by the difference in chloride concentration between ground-water discharge and ground-water recharge ($C_{G_i} - C_{G_o}$) (Figure 4a and b).

Ground-water discharge can more reliably be estimated during a subset of the 4-year period at ENR when the tracer concentration in ground water differed markedly from that in surface water. For example, the uncertainty in estimated ground-water discharge was relatively high during period I when $C_{G_i} \approx C_{G_o}$ while the uncertainty was lower during period II when $C_{G_i} \ll C_{G_o}$ or $C_{G_i} \gg C_{G_o}$. As explained in previous section, our best estimate of ground-water discharge was derived by average data for period II that had the lowest uncertainty.

DISCUSSION

Surface-water and ground-water interactions in a constructed wetland were estimated using simple mass balance calculations. Our approach combined hydrologic and chemical data in order that both ground-water discharge and recharge could be determined. Net ground-water flux (discharge—recharge) was reliably estimated from water-budget balance with relatively low uncertainty, but uncertainty in estimating ground-water discharge using a combined water and solute (tracer) mass balance was very high. Time-varying surface-water flows, water levels, and chemical concentrations in this constructed wetland all contributed to the relatively high uncertainty in our estimates of ground-water discharge. In order to improve our confidence in our estimate of ground-water interactions, it was necessary to compare with estimates obtained from other independent approaches including seepage meters and ground-water-flow modeling. Here, we make that comparison and discuss how ground-water interactions are increased by management of surface-water flows at ENR.

Comparison with Independent Measurements

Seepage Meters. Even our best estimates of ground-water discharge determined from mass balance approach had relatively high uncertainty. For that reason, we compared results with independent estimates based

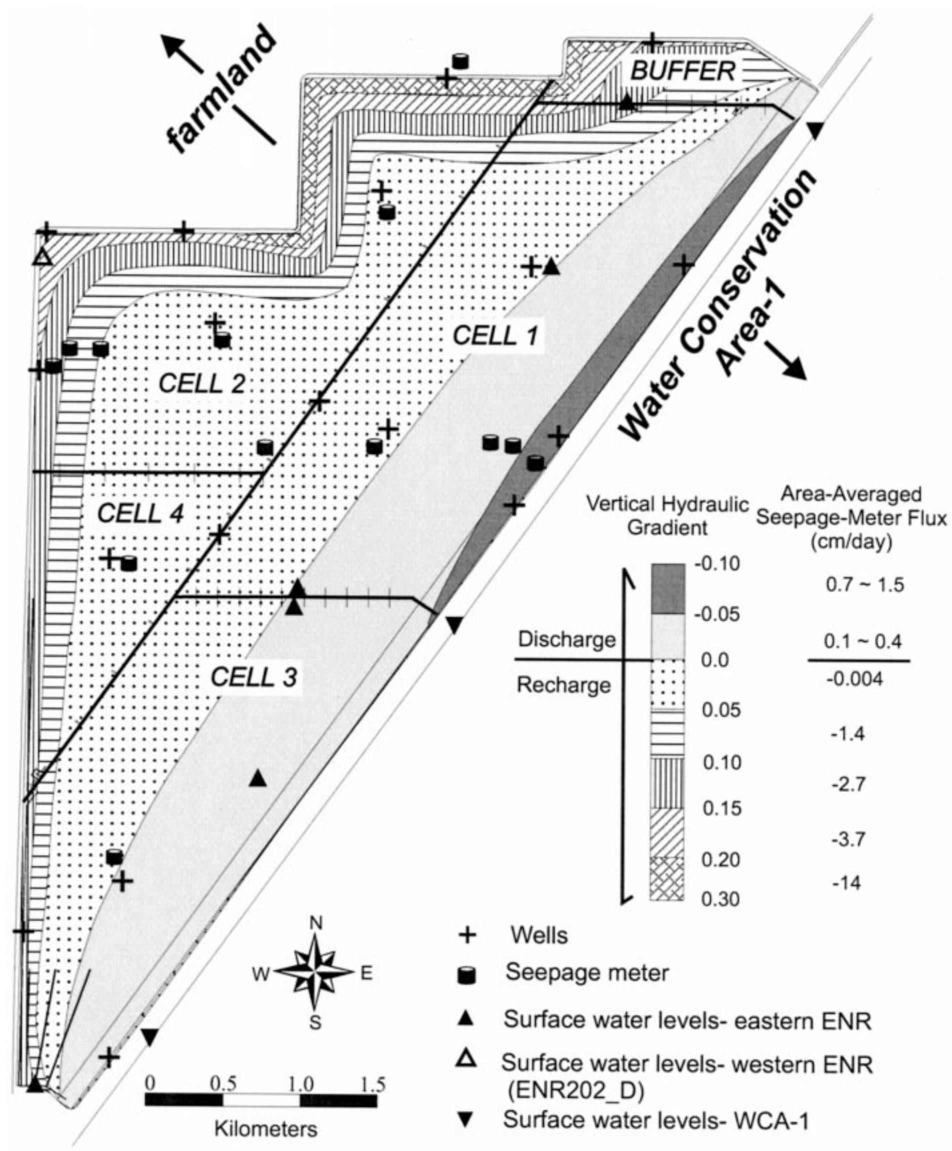

Figure 6. Locations of seepage meters, distribution of vertical hydraulic gradient, and estimation of area-averaged seepage-meter fluxes in ENR.

on measured vertical hydraulic gradients and seepage fluxes determined from seepage meters (Harvey et al. 2000). The seepage meters were constructed from 0.64-cm high density polyethylene sheets molded into conical domes (0.76-m diameter) with a circular ring (0.3-m high) that could be pushed into the peat sediments (Harvey et al. 2000). Between two and four seepage meters were installed at each of twelve sites in ENR (Figure 6). Meters were operated by attaching prefilled bags for periods ranging between 1 hour and 1 week, depending on the rate of change of water volume in the bag. In order to determine area-averaged fluxes by extrapolating to areas without seepage meters, the results from several seepage meters at each site were first averaged. Then those results were combined by grouping and averaging sites that had a similar vertical hydraulic gradient, as determined from wells (Figure 6). Those area-averaged estimates of discharge ranged from 0.3 to 2.4 ha-m/day for four different days that spanned the extremes of differences in surface-water levels between ENR and Water Conservation Area-1 to the east. The four discharge fluxes were regressed against corresponding water-level differences in ENR and WCA-1 (Figure 7a). The best-fit relationship ($r^2 = 0.984$) was used to extrapolate the ground-water discharge for the 4-year period of interest (Figure 7b). The average ground-water discharge estimated from the above approach was 0.9 ha-m/day (or 0.06 cm/day). The ground-water recharge was also estimated by seepage-meter measurements in the west-

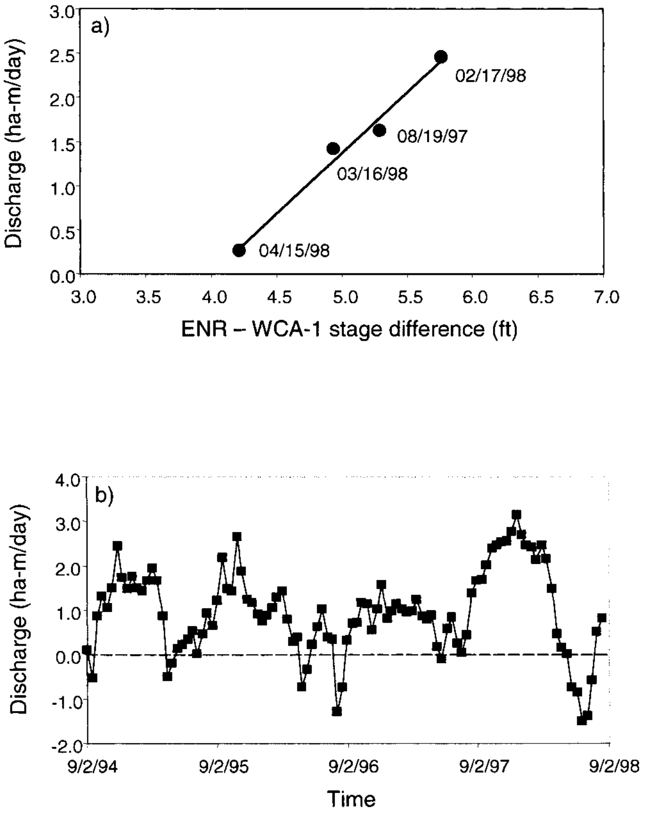

Figure 7. Independent estimate of ground-water discharge using seepage meters. (a) Regression of seepage-meter estimates of ground-water discharge against water-level differences between eastern ENR and WCA-1 ($r^2 = 0.984$). (b) Ground-water discharge computed for 4-year study period (two-week interval) using regression equation from seepage-meter estimates.

ern part of the ENR where strong downward hydraulic gradients indicate that recharge occurs (Figure 6). The estimated ground-water recharge was 13.0 ha-m/day (or 0.84 cm/day). The seepage-meter-derived estimates were quite similar to our coupled mass balance estimates, which increased our confidence that discharge and recharge are reliably estimated (Table 4).

Ground-water Modeling. Ground-water modeling was used previously at ENR to estimate ground-water interactions (Guardo and Prymas 1998). Subsurface seepage into the ENR was estimated by calibrating a two-dimensional, steady-state seepage model, Fast-SEEP/SEEP2D (Biedenharn and Tracy 1987, BYU 1993). After selecting appropriate hydraulic conductivity values by calibrating against measured hydraulic heads, the model was run to obtain simulation values of seepage flow. Regression analysis (simulated seepage flow against corresponding water-level difference between WCA-1 and ENR, $r^2 = 0.96$) was used to extrapolate results for a 2-year (1994 to 1996) period (Guardo and Prymas 1998). We used the empirical equation developed by Guardo and Prymas (1998) to calculate ground-water discharge into the ENR for our 4-year study period. The estimated ground-water discharge varied between 2.9 and 7.8 ha-m/day and averaged 5.4 ha-m/day (or 0.35 cm/day) over time, which is approximately a factor of 4 higher than the estimates from coupled mass balance and the seepage-meter-derived estimates (Table 4). In addition, the ground-water recharge on the western side of ENR was estimated by Hutcheon Engineers (1996) using a similar ground-water-flow modeling approach. When extrapolated for the four-year study period, the estimated ground-water recharge was 13.9 ha-m/day (or 0.9 cm/day), which is relatively close to the estimates from mass balance and seepage-meter measurements (Table 4).

The coupled mass balance and seepage-meter measurements showed good agreement in estimates of both ground-water discharge and recharge. In addition, the net ground-water flux ($G_i - G_o$) calculated from seepage-meter-derived estimates (−12.1 ha-m/day) was very well matched with the mass balance estimate (12.0 ha-m/day). However, ground-water-flow modeling estimated a net ground-water flux of −8.5 ha-m/day, which is approximately 30% less than both seepage and mass balance estimates (Table 4). We believe that the disagreement was caused by an unrealistically

Table 4. Comparison of ground-water fluxes estimated from coupled water-solute mass balance approach, seepage-meter measurements, and ground-water-flow modeling.

	Mass Balance Approach (ha-m/day)	Seepage-Meter Measurement (ha-m/day)	Ground-Water-Flow Model (ha-m/day)
Ground-water discharge (G_i)	1.4 (3)[1]	0.9 (2)	5.4[3] (13)
Ground-water recharge (G_o)	13.4[2](31)	13.0 (30)	13.9[4] (32)
Net ground-water flux (G_i–G_o)	−12.0	−12.1[2]	−8.5[2]

[a] Numbers in parenthesis indicate percent of inflow pump rate.
[2] Estimated by difference between other two estimates in each column.
[3] Estimated using results from Guardo and Prymas (1998).
[4] Estimated using results from Hutcheon Engineers (1996).

high estimate of ground-water discharge by the ground-water-flow modeling method (Table 4). It is easy to envision a large potential error in the ground-water-flow modeling approach due to difficulty in accurately estimating vertical hydraulic conductivity. Errors in estimating hydraulic conductivity of the wetland peat could be particularly troublesome, since the peat acts as a restricting layer for vertical flow in this system (Harvey et al. 2000).

Are Managers Increasing Ground-water Recharge through Design and Operation of Constructed Wetlands?

Recharge from ENR surface water to the aquifer was the most significant hydrologic interaction with ground water over the 4 years of the study period. Recharge in constructed wetlands is very important because it can potentially transport contaminants, such as nutrients and mercury, into the underlying aquifer. The seepage canal, which is located on the western and northern sides of the ENR, was designed to prevent flooding of adjacent agricultural fields by capturing and returning the recharged ground water to the ENR (Figure 2). The flux of water captured by the seepage canal is significant (22% of pumped inflow from seepage canal). However, the returned inflow from the seepage canal is mostly lower than the estimated ground-water recharge flux (Figure 8a), which indicates that there is a component of recharged ground water that is not captured by the seepage canal. The difference between recharged ground water and recycled seepage canal flow is greatest when the water level in ENR is highest (Figure 8a). In order to determine the control that managers have over the extent of ground-water recharge, our estimate of ground-water recharge was plotted against the rate of surface-water inflow by pumping from the supply canal (Figure 8b). Recharge was positively correlated with the pumping rate of surface water from the supply canal into ENR. This demonstrates that the relatively high surface-water inputs to this constructed wetland have the unintended effect of increasing ground-water recharge.

The effect of ground-water recharge on contaminant mass balance has not been fully investigated. Contaminants such as nutrients and mercury recharged in the wetland could have unexpected transport paths and fates in the aquifer. For example, recharged water that is not captured by the seepage canal could take unexpected pathways and possibly discharge outside of treatment wetland, releasing contaminants to surface water. It is also possible that certain contaminants could be retained or transformed by interaction with aquifer solids within the aquifer. The answers to these questions are certainly important at ENR, where such a large proportion of the water intended for treatment is recharged.

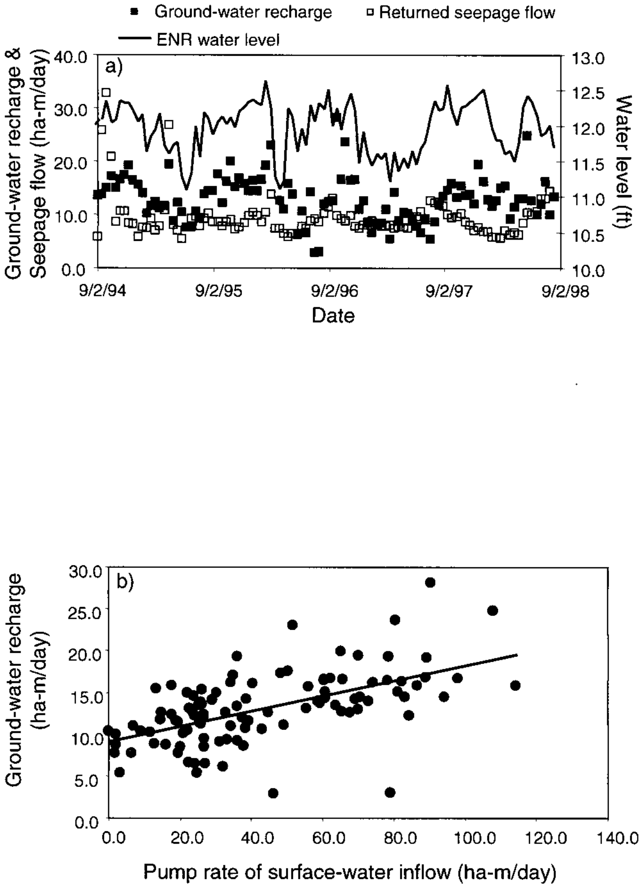

Figure 8. Comparison of estimated ground-water recharge with (a) returned flow from seepage canal (G-250_S) and water level in ENR (ENR202D) and (b) inflow rate of surface water from supply canal into ENR (G-250).

CONCLUSION

A combined water and solute mass balance approach with uncertainty analysis was used to estimate time-varying ground-water fluxes at a constructed wetland (ENR). The combined water and solute mass balance was needed in order to estimate both ground-water discharge and recharge, rather than just the net exchange. However, reliable estimation of both ground-water recharge and discharge required comparisons with other independent approaches, because of the high uncertainty in estimating ground-water discharge. In the ENR, the main hydrologic interaction with ground water is recharge of surface water to the underlying aquifer system (approximately 31% of water supplied for treatment). Ground-water discharge was almost negligible in comparison (approximately 2.8%). In this constructed wetland, we found that time-varying pumping rates from a supply canal and highly fluctuating water levels within the wetland greatly affected the rate of recharge of surface water (and possibly contaminants) into the subsurface aquifer. Our finding suggests that hydrologic managers of wetlands constructed for water treatment might be able to use this knowledge to construct accurate water and contaminant mass balances and possibly to optimize performance of constructed wetlands by minimizing the migration of contaminants from treatment wetlands into adjacent hydrologic systems.

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