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Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (U.S.A.)

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Abstract. Hydrological restoration of the Southern Everglades will result in increased freshwater flow to the freshwater and estuarine wetlands bordering Florida Bay. We evaluated the contribution of surface freshwater runoff versus atmospheric deposition and ground water on the water and nutrient budgets of these wetlands. These estimates were used to assess the importance of hydrologic inputs and losses relative to sediment burial, denitrification, and nitrogen fixation. We calculated seasonal inputs and outputs of water, total phosphorus (TP) and total nitrogen (TN) from surface water, precipitation, and evapotranspiration in the Taylor Slough/C-111 basin wetlands for 1.5 years. Atmospheric deposition was the dominant source of water and TP for these oligotrophic, phosphorus-limited wetlands. Surface water was the major TN source of during the wet season, but on an annual basis was equal to the atmospheric TN deposition. We calculated a net annual import of 31.4 mg m^{-2} yr^{-1} P and 694 mg m^{-2} yr^{-1} N into the wetland from hydrologic sources. Hydrologic import of P was within range of estimates of sediment P burial (33–70 mg m^{-2} yr^{-1} P), while sediment burial of N (1890–4027 mg m^{-2} yr^{-1} N) greatly exceeded estimated hydrologic N import. High nitrogen fixation rates or an underestimation of groundwater N flux may explain the discrepancy between estimates of hydrologic N import and sediment N burial rates.

Introduction

The coupling of wetlands with adjacent aquatic ecosystems provides a source of materials for new production within the wetland, and energy subsidies from wetland to the adjacent ecosystems (Odum 1971; Odum & Heald 1972). Inputs of allochthonous materials to wetland ecosystems can occur via geologic and biologic pathways, though hydrologic sources usually dominate (Likens et al. 1977). Understanding hydrology is key to discerning what controls the productivity, organic matter accumulation, nutrient cycling and transport within a wetland ecosystem. Wetland water and chemical budgets are a useful method to assess the relative importance of allochthonous exchanges versus intrasystem recycling on productivity (Mitsch & Gosselink 1993). They also clarify information gaps required to understand ecosystem function. Despite their utility, relatively few coastal wetland water or chemical budgets exist in the literature, in part because of the extensive data required for their construction (e.g. Boynton et al. 1995).

The Everglades is a unique wetland ecosystem in North America due to its carbonate sedimentary environment and sub-tropical climate (Davis 1940; Lugo & Snedaker 1974; Light & Dineen 1994). Phosphorus (P) is the limiting macronutrient in this oligotrophic system, due to the strong affinity of carbonate minerals for P (de Kanel & Morse 1978). Its availability and distribution strongly control productivity of the Everglades freshwater wetlands (Craft et al. 1995) and mangrove forests (Koch 1996). The degradation of the Everglades and the adjacent Florida Bay ecosystems has been attributed to changes in watershed land use over the past century (Light & Dineen 1994). These activities have resulted in wetland loss, increased nutrient inputs, and diversion of freshwater to the Atlantic coast by canals. Hydrological restoration of the Southern Everglades, which began in October 1997, will increase freshwater flow to these wetlands, and ultimately, to Florida Bay (SFWMD 1990). Evaluating the relative importance of upland freshwater inputs on the hydrologic and nutrient budgets of Southern Everglades allows us to better understand the effect of restoration activities on wetland productivity and nutrient transport through this landscape.

Atmospheric deposition is an important source of nutrients to oligotrophic ecosystems (Cole et al. 1990; Jassby et al. 1995; Prospero et al. 1996). In the Everglades, several factors point to the importance of atmospheric deposition as a source of P. First, Everglades wetlands in general are very shallow with ambient total P levels at or below 10 μg/L (McCormick et al. 1996). Thus, atmospheric deposition of even low levels of P can provide an important subsidy of this limiting nutrient. Second, the meteorological conditions of south Florida are ideal for atmospheric deposition. Rainfall can scavenge aerosol P and N (Poleman et al. 1995), a pathway may be enhanced during convection thunderstorms common in South Florida during the rainy season.

Ground water seepage can also be an important source of water and nutrients to wetlands. Ground water inputs are a significant portion of the N budget of Massachusetts salt marshes (Valiela et al. 1978; Valiela & Teal 1979). Ground water flow is thought to play a major role in the hydrologic budget of the Everglades wetlands because the porous nature of the limestone bedrock enhances hydraulic conductivity (Fennema et al. 1994). Despite the importance of this flow, understanding of wetland-ground water interactions and their contribution to the nutrient budget of the Everglades is limited. Based on simulations using the Natural Systems model, Fennema et al. (1994) concluded that the southern Everglades is an important source of ground water recharge to the Biscayne Aquifer, the main source of water to the lower east coast of Florida. Estimates of submarine ground water flux to Florida Bay based on natural chemical tracers and seepage measurements suggest that this source may provide as much N and P as surface water runoff from the Everglades (Corbett et al. 1999).

We hypothesized that in the oligotrophic Southern Everglades wetlands, atmospheric deposition is a more important P source than surface fresh-water input because the canal water nutrient concentrations are generally low (<10 μg/L). To address this hypothesis, we conducted a 1.5 yr study of the seasonal and annual water and nutrient budgets of the Taylor Slough/C-111 basin wetlands. We used these budgets to understand the relative importance of atmospheric deposition versus surface water and ground water inputs as sources of nutrients to these wetlands. In addition, we assessed the magnitude of these source and loss terms versus literature values for sediment N and P burial, N fixation, and denitrification in this basin.

Methods

Site description

The freshwater and mangrove wetlands of the Southern Everglades are located at the southernmost extent of the Florida peninsula, and border Florida Bay, a large, shallow, sub-tropical embayment bounded on the south and east by the Florida Keys (Figure 1). The climate of Florida Bay and the southern Everglades is characterized as a sub-tropical savanna with distinct rainy and dry seasons (Hela 1952). The wet season extends from June through November, while the dry season is December through May (Jordan 1984). The geology of this region is characterized by surface carbonate and silici-clastic sedimentary deposits that may be greater than 200 m thick in some areas (Randazzo & Jones 1997). The highly permeable Biscayne Aquifer system crops out on the southeast Florida Peninsula, and occurs at shallow depths everywhere within the study area (Randazzo & Jones 1997). Below this lies the Floridan Aquifer, the largest aquifer system in the southeastern United States.

The 460 km^2 study area is comprised of two sub-basins, Taylor Slough and the wetland area south of the C-111 canal (herein referred to as the Taylor Slough/C-111 basin). Taylor Slough historically was the major conduit for freshwater flow to Florida Bay (McIvor et al. 1994). During the past century,

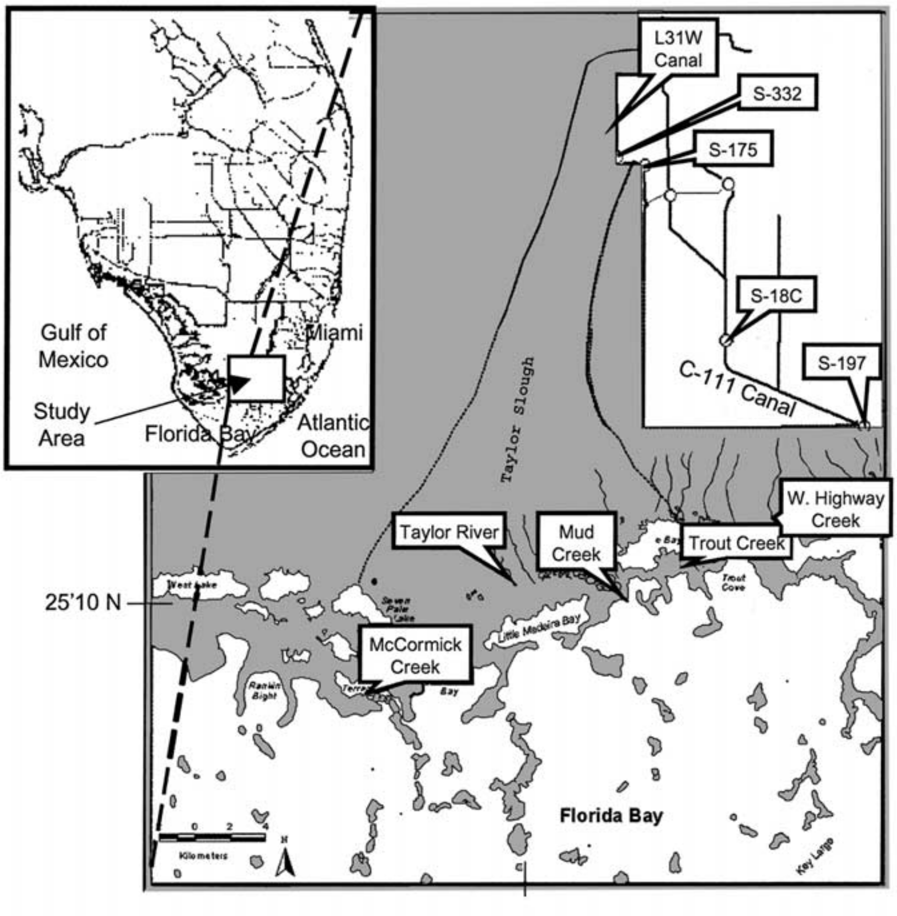

Figure 1. Location of Taylor Slough/C-111 basin in Southern Everglades, Florida.

surface water flow into the slough was drastically reduced by upland water management practices. Currently, the major upland flows into this system are controlled inputs from a series of water control structures on the L31W and C-111 canals, managed by the South Florida Water Management District (SFWMD; Figure 1). Taylor Slough's western boundary is a slightly elevated ridge that delineates it from Shark River Slough. The southern levee from the C-111 canal has been partially removed as part of restoration efforts in the Southern Everglades. As a result, water flows into wetlands south of the C-111 canal towards Florida Bay. As surface water from Taylor Slough and the C-111 canal flows south towards the bay, it becomes increasingly channelized, and drains into five major creek systems that discharge to Florida Bay. At the wetland-bay interface, the creeks cut through an area of relatively high topographical relief called the 'Buttonwood Ridge.' This ridge restricts the overland flow of water, making the five creeks major point source inputs of freshwater to Florida Bay.

Hydrologic budget calculation

Seasonal and annual water budgets for the Taylor Slough/C-111 basin wetlands were calculated for the time period of June 1996 through December 1997, which captured two rainy seasons and one dry season. The sources and sinks of water for a hydrologic budget of the study area are given as (Eq. 1):

$$GW_i + SW_i + P - GW_o - SW_o - ET \pm \triangle S = 0 \qquad (1)$$

where GW_i and GW_o are ground water input and output terms, SW_i and SW_o are the surface water input and output terms, P is precipitation; ET is evapotranspiration; and $\triangle S$ is the change in storage. $\triangle S$ represents a net change in water volume within the basin for a given time period. The methodology used to derive each term and its error are given below.

Surface water exchange with a wetland can be a combination of channelized and overland flow. In the Taylor Slough/C-111 basin, studies of surface water hydrology have shown that overland flow from west is negligible (E. Swain, pers. comm.). Therefore, surface water inflow (SW_i) is limited to anthropogenically controlled inputs from the L31W in northern Taylor Slough and from the C-111 canal to the east. SW_i was calculated as the sum of the discharge from the S332, S175, and S18C Water Management District control structures minus the discharge from the S197. S197, when open, discharges to Biscayne Bay on the eastern coast of Florida. Error in estimated discharge from the four water control structures ranged from 13 to 31%. This estimate of surface water input to Taylor Slough/C-111 basin is likely to be a maximum value, since some flow may recharge the aquifer and return via localized ground water flow from the wetlands back to canals.

Overland flow to Florida Bay is negligible. The Buttonwood ridge restricts overland flow from the Taylor Slough/C-111 wetlands to Florida Bay, thus confining most of the flow to several creeks that cut through the ridge. Since 1996, the U.S. Geological Survey (USGS) has measured the discharge of the five major creeks that drain the Taylor Slough/C-111 basin. These include Taylor River, McCormick, Trout, Mud, and West Highway Creeks (Figure 1). Surface water output (SW_o) was calculated as the sum of daily discharge of these five creeks. Daily relative error associated with measurement of surface water outputs from the five creeks averaged 5%.

Inputs to the water budget from precipitation were calculated from daily rainfall data at 15 gauges in the study area. These gauges are not evenly distributed, so the precipitation data were area-weighted using the Thiessen polygon method. The precipitation estimate was multiplied by the surface area of the basin to arrive at a volume input. A major source of variability in precipitation estimates arises from the spatial variability in rainfall. This error decreases with the length of the time period for which precipitation is estimated (Winter 1982). Gauge density in this study was 30 km^2/gauge. Monthly sampling error with a gauge density of 60 to 120 km^2/gauge ranged 4 to 6%. Based on this work, we assumed error in our estimate would be 5%.

Actual evapotranspiration (ET) data, measured by the Bowen ratio method in Taylor Slough from January 1996 to December 1997, was procured from USGS for a site in Everglades National Park (site P33; German et al. in press). The average annual ET rate for this time period was estimated as 162 cm yr^{-1} with an error of 10%. Change in storage ($\triangle$S) was calculated as the average change in daily mean water level at eight locations in the study area over the time period of interest, multiplied by the surface area of the basin. The standard error of these the eight estimates of water level change was used as the error of $\triangle$S. Net ground water contribution to the budget ($GW_i - GW_o$) was estimated as the difference between the input, output, and storage terms in Eq. 1. Error in this estimate ($E(GW_i - GW_o)$) was the propagation of error estimates of other terms in the equation, given by Eq. 2.

$$E(GW_i - GW_o) = [E(P)^2 + E(ET)^2 + E(SW_i)^2 + E(SW_o)^2 + E(\triangle S)^2]^{0.5} \quad (2)$$

Nutrient mass balance calculations

The total nitrogen (N) and total phosphorus (P) budgets for the Taylor Slough/C-111 basin were calculated as the contribution of each nutrient from each of the terms in the water budget, as given by equations 3 and 4:2

$$N_{GW_i - GW_o} + N_{SW_i} + N_P - N_{SW_o} \pm N_{\triangle S} = N_{Res} \quad (3)$$

$$P_{GW_i - GW_o} + P_{SW_i} + P_P - P_{SW_o} \pm P_{\triangle S} = P_{Res} \quad (4)$$

where the terms on the left-hand side of the equations represent the sources and sinks of N and P associated with each term in the water budget. N_{Res} and P_{Res} represent the residual terms for the N and P budgets respectively. Assuming that no net loss of N or P occurs over an annual cycle, this residual would be equal to sediment burial of N and P plus other sinks and sources of N from denitrification or N fixation (Boynton et al. 1995).

N and P loading for each budget term was calculated as the concentration multiplied by volume discharge. Error in TN and TP nutrient flux in surface water outflow was 9% and 16% respectively (Sutula 1999). For the remaining terms, error for each nutrient loading term was calculated from the product of the nutrient concentration and the error associated with its corresponding transport mechanism in the water budget. Error in the N_{Res} and P_{Res} term was propagated from the errors in the other terms as in Eq. 2.

Nutrient concentration in canal inflows (SW_i) was determined from monitoring data collected monthly by the South Florida Water Management District (SFWMD). Nutrient loading from each water management structure was calculated as the product of the monthly mean nutrient concentration and the daily cumulative water discharge. Nutrient loading in surface water outflow (SW_o) from the five creeks was estimated by Sutula (1999). For the freshwater samples, nitrate, nitrate, ammonium, and soluble reactive phosphorus were measured using a Technicon autoanalyzer. Organic N + ammonium analyzed using the micro-kjeldahl method and organic P was digested by wet oxidation with persulfate (Clesceri et al. 1989). Dissolved inorganic and organic nutrient concentrations were summed to yield TN or TP. Estuarine samples were analyzed for TN using an ANTEK nitrogen analyzer (Frankovitch & Jones 1998); TP was digested as in Solorzano and Sharp (1980).

We chose rates of atmospheric TN and TP deposition based on data available from the National Atmospheric Deposition Program (NADP) and published values for the ENP and the Florida Keys. The NADP 1996 estimate of DIN at the Everglades National Park site (F-11) is 0.32 g N m^{-2} y^{-1}, which is close to that reported for the same site in 1990 (0.31 g N m^{-2} y^{-1}, Prospero et al. 1996). Hendry et al. (1981) reported that bulk TN deposition (including ON) was 1.45 times that of DIN for a site near Key West in 1978 and 1979. Based on this assessment, we multiplied the DIN deposition rate measured at the NADP-F11 site by a factor of 1.45 to derive a bulk TN deposition rate of 0.46 g N m^{-2} y^{-1}. Atmospheric deposition of P is particularly difficult to quantify due to persistent sample contamination and limitations in sampling methods (Redfield 1998). The measured rates of bulk atmospheric P deposition in the Everglades have ranged from 0.017 to 0.07 g P m^{-2} y^{-1}, with an average of 0.03 P m^{-2} y^{-1} (Redfield 1998). A low estimate of 0.006 g P m^{-2} y^{-1} was found for the Bahamas (Graham & Duce 1982). Based on this review, we cautiously chose an intermediate bulk TP deposition rate of 0.03 g P m^{-2} y^{-1}.

Ground water nutrient concentration and the nutrient flux associated with change in storage were the two unknown quantities. It is likely that direct exchange occurs between surface water and ground water derived from the highly permeable, relatively shallow Biscayne Aquifer (Randazzo & Jones 1997). Therefore nutrient concentrations in surface waters may reflect those in surficial ground waters. We assumed that daily ground water nutrient concentration is equivalent to the daily flow-weighted mean TN and TP concentration in surface water outflow. To calculate the change in nutrient loading from $\triangle S$, we assumed the change in TN and TP concentration from the beginning to the end of the time period was negligible. Therefore, the change in nutrient loading resulting from $\triangle S$ was calculated as the product of $\triangle S$ and the mean seasonal concentration of TN and TP in Taylor Slough surface water monitoring data.

Results

Hydrologic budget

Analysis of monthly precipitation, ET, and surface inflow and outflow during June 1996 to December 1997 illustrates a distinct pattern associated with wet and dry season meteorological forcing (Figure 2). Approximately 75% of the 138 cm in mean annual precipitation fell during the rainy season. ET rates peaked during the summer months and were lowest during the winter. Monthly gross precipitation patterns were well correlated to patterns of surface water inflow and outflow in the study area ($R^2 = 0.49$), indicating that regional precipitation patterns are largely responsible for surface water flow patterns seen in the Everglades. During the rainy season, precipitation was slightly higher than ET, resulting in a positive water balance for most rainy season months (Figure 2). Net atmospheric water balance during the dry season was negative (–78 cm), when ET exceeded precipitation by a factor of two. On an annual basis, the atmospheric water balance was slightly negative (-16 ± 15 cm yr^{-1}; Figure 4).

Precipitation was more important than surface water inflow to the seasonal and annual water budgets of the Taylor Slough/C-111 basin. Precipitation exceeded canal inputs by a factor of 1.5 during the rainy season, and by a factor of 5 during the dry season (Figure 2). Annually and during both rainy seasons, surface water inflow roughly balanced outflow (Figure 3). During the dry season, surface water inflow was small, and a net flow from Florida Bay to the wetlands occurred (Figure 4).

Storage changes were negligible relative to other water budget terms both annually and during the rainy season. In the dry season, $\triangle S$ was comparable to surface water inflow and outflow, but smaller than precipitation, ET, and the residual ground water term. The high error estimate relative to average $\triangle S$ indicates high variability in water level changes among the eight stations.

The 1996 rainy season and mean annual water budgets indicate a balance among ET, precipitation, storage change, and surface water inflow and

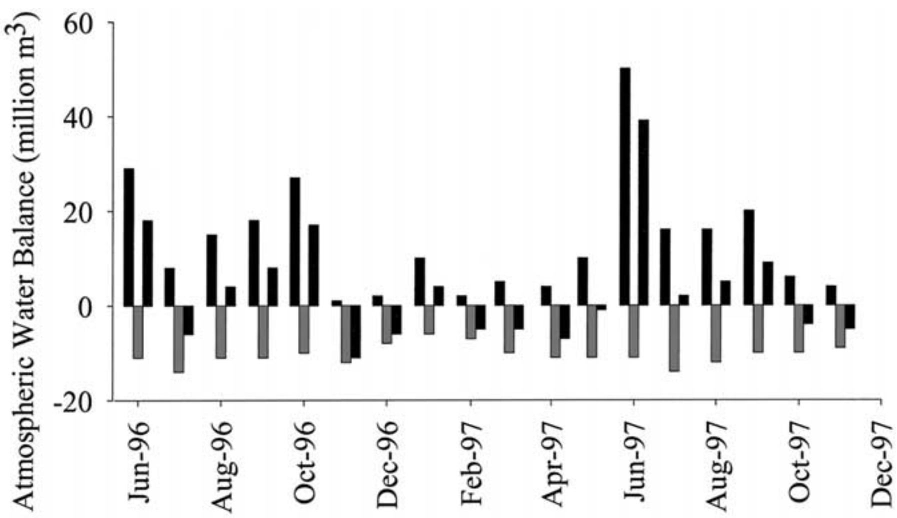

Figure 2. Taylor Slough/C-111 basin monthly atmospheric water balance for period of June 1, 1996–November 30, 1997. ET (■) and precipitation (▩) are as shown positive and negative values, respectively, indicating water input and loss from system. Net atmospheric water balance (■) is the difference of precipitation and ET.

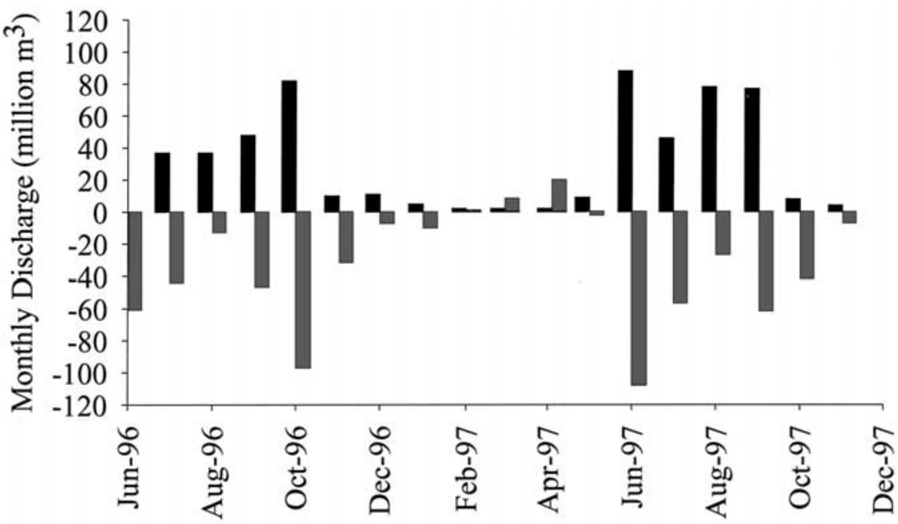

Figure 3. Taylor Slough/C-111 basin surface water inflow and outflow during June 1, 1996–November 30, 1997. Surface water inflow (■) and outflow (▩) are as shown positive and negative values, respectively, indicating water input and loss from system.

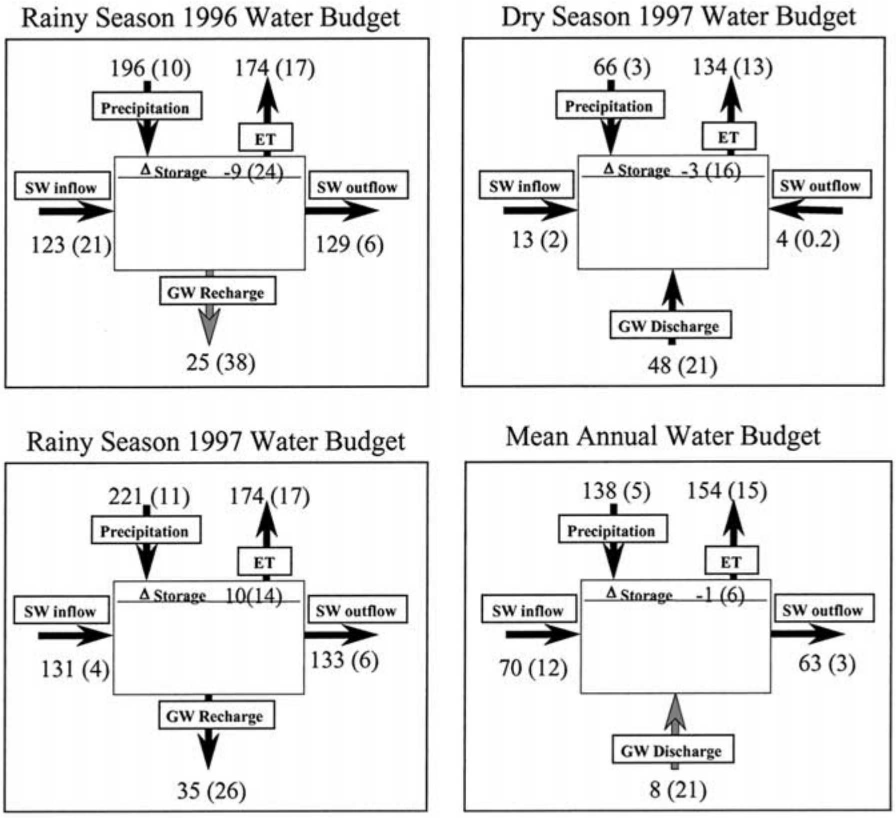

Figure 4. Taylor Slough/C-111 basin seasonal and mean annual water budgets. All values are in cm yr^{-1}. Direction of arrow indicates flow direction. Values in parentheses indicate absolute error. Black arrows represent significant flow (term > error); grey arrows represent insignificant flow (term < error). A positive change in storage is a loss from the system. Mean annual budget represents the average of values for June 1, 1996–May 31, 1997 and December 1, 1996–November 30, 1997.

outflow (Figure 4). Thus, the residual ground water terms during these periods were insignificant. The 1997 dry season budget indicated a significant ground water residual of 48 ± 21 cm yr^{-1} respectively was required along with surface water inputs and precipitation to balance high evaporative losses. A groundwater recharge term of 35 ± 26 cm yr^{-1} was required to balance the other hydrologic source and loss terms in the 1997 rainy season. However, the magnitude of this term was small in comparison with the other source and loss terms.

Nutrient budget

Atmospheric deposition was the most important input term for the P budget regardless of season, and an important input of N to the Talyor Slough/C-111 basin wetlands during the dry season (Figures 5 and 6). Atmospheric deposition exceeded P loading from surface water inputs by a factor of 3 to 6 during the wet season, and by a factor of 13 during dry season. Annually, the contribution of N from surface water inflow was roughly equal to that of atmospheric deposition. However, on a seasonal basis, the relative importance of these two terms changed. Surface water input of TN was 50% greater than atmospheric deposition during the rainy season, but one half the input of atmospheric deposition during the dry season.

On an annual basis, net ground water flux was an insignificant source of N and P to the budget of Southern Everglades wetlands. However, during the dry season the net ground water discharge into the study area was the most important hydrologic input of N into the basin (Figure 5). Ground water discharge was also an important source of P during this season, contributing 28% of the total P inputs to the wetland (Figure 6). The sum of the nutrient source and loss terms yielded a positive residual for each season, indicating a net import of N and P into the wetland from allochthonous sources (Figures 5 and 6). Surface water export of N and P generally balanced that of canal inputs, and the contribution of the change in storage term to the N and P budgets was negligible. The high input of atmospheric P was largely responsible for the significant net import of P during both the rainy and dry seasons, with rainy season import 50% higher than during the dry season. Over an annual cycle, net P import was 31.3 +/– 3.5 mg m^{-2} y^{-1}.

Significant net import of N occurred during both the rainy season and dry seasons. During the dry season, atmospheric deposition, ground water discharge, and surface water inflow were the major source terms contributing to the large positive N residual. Annually, N inputs from ground water discharge was insignificant, and the positive N residual of 649 +/– 264 mg m^{-2} y^{-1} was driven by large terms for atmospheric deposition and surface water flow.

Discussion

Relative importance of budget inputs

Atmospheric deposition was the dominant source of water and P to the Taylor Slough/C-111 basin, and as important as surface water input as a source of N. The importance of atmospheric P on the budget of these wetlands differed

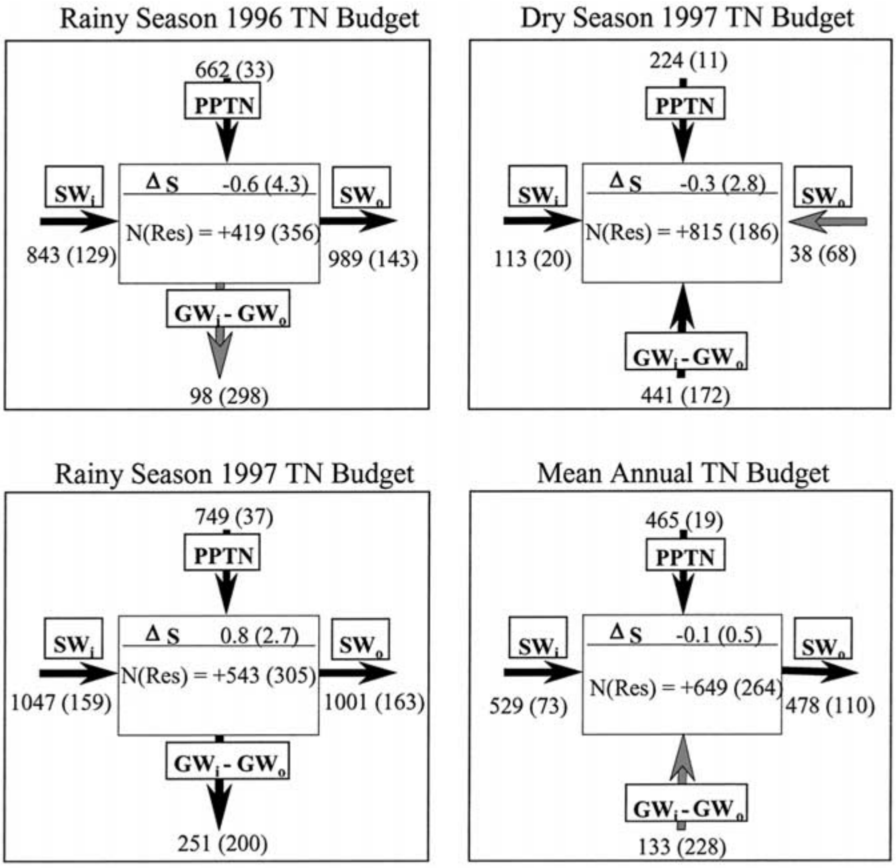

Figure 5. Taylor Slough/C-111 basin seasonal and mean annual N budgets. All values are in mg N m^{-2} yr^{-1}. N(Res) represents the sum of N inputs minus losses. Direction of arrow indicates mass flow direction. Values in parentheses indicate absolute error. Black arrows represent significant mass flow (term > error); grey arrows represent insignificant mass flow (term < error). A positive change in storage is a loss from the system. Mean annual budget represents the average of values for June 1, 1996–May 31, 1997 and December 1, 1996–November 30, 1997.

from a site in northern Everglades impacted by agricultural run off, where surface water input was the major source of P, and atmospheric sources accounted for 7% of TN and 3% of TP inputs (Moustafa et al. 1995). Over 90% of N and 60% of P measured in the surface water draining from the Everglades agricultural area is generally removed before reaching the canals that discharge into the Taylor Slough/C-111 basin wetlands (Rudnick et al. 1999). Thus, surface freshwater input is relatively low in P, and atmospheric P deposition assumes a larger role in the wetland budget.

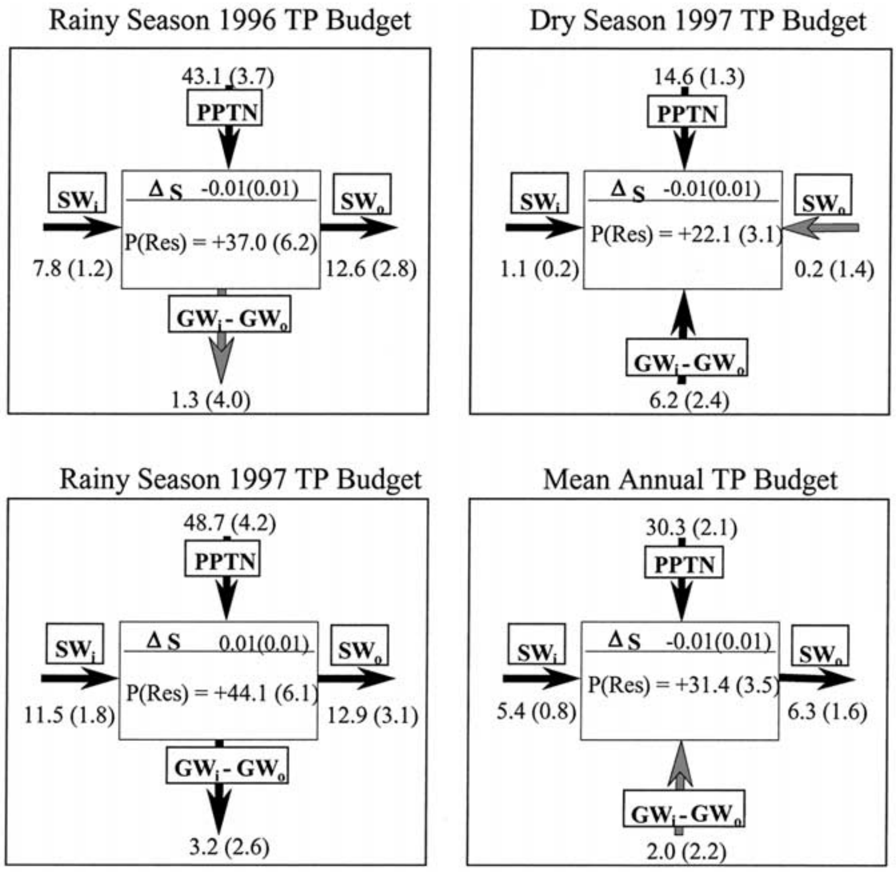

Figure 6. Taylor Slough/C-111 basin seasonal and mean annual P budgets. All values are in mg N m^{-2} yr^{-1}. P(Res) represents the sum of P inputs minus losses. Direction of arrow indicates mass flow direction. Values in parentheses indicate absolute error. Black arrows represent significant mass flow (term > error); grey arrows represent insignificant mass flow (term < error). A positive change in storage is a loss to system. Mean annual budget represents the average of values for June 1, 1996–May 31, 1997 and December 1, 1996–November 30, 1997.

Atmospheric deposition of nutrients in the Everglades is enhanced by meteorological conditions typical of South Florida, and should be considered in the management of these wetlands. Dry deposition of aerosol P, which is derived from resuspended agricultural soils, phosphogypsum mining activities, urban emissions, and long-range transport of dust, has been estimated to comprise as much as 30–50% of bulk P deposition in Florida (Landing 1997; Meyers & Lindberg 1997). Rainfall can also scavenge aerosol P and N. During the summertime, high evaporative rates from the Everglades in combination with the convergence of seabreezes and prevailing winds produce daily convective thunderstorms with heavy rainfall. These thunderstorms can reach into the troposphere, scavenging dust and solublizing constituents such as gaseous mercury or ammonia. This mechanism has been implicated in the high concentrations of dissolved mercury found in Florida rainfall (Polman et al. 1995). The high frequency of convection thunderstorms in South Florida enhances the importance of atmospheric N and P deposition to these wetlands.

While the magnitude of atmospheric nutrient deposition in terrestrial oligotrophic ecosystems has been recognized for some time, there is increasing awareness of the importance of this input in the budgets of coastal and oceanic waters (Duce 1986; Galloway et al. 1996; Paerl 1995). Fisher and Oppenheimer (1991) found that 39% of the 'new' N entering the Chesapeake Bay watershed was attributable to atmospheric deposition. Atmospheric deposition is the major N source in 12 northern Florida watersheds (Fu & Winchester 1994; Winchester et al. 1995). Higher rates of atmospheric N and P deposition are associated with proximity to urban or industrial areas (Paerl 1995; Redfield 1998). The Southern Everglades is located within 160 km of the Miami metropolitan area, so increased loading from anthropogenic atmospheric deposition should be considered in the management of these wetlands.

Surface water inflow was a major input of nutrients into the Taylor Slough/C-111 basin wetlands, accounting for 50% of N and 20% of P inputs into the system. The majority of the exchange with surface water occurred during the rainy season. During the dry season, loading from canal inputs is small, and a small net flow of water enters the wetlands from Florida Bay. This net inflow is caused by a combination of wind-driven forcing of bay water into study area and high evaporative losses, and results in the advection of higher salinity bay water into the lower Everglades (Sutula 1999). While nutrient loading in surface water inflow from canals generally balanced outflow to the Bay, evidence exists of wetland uptake and transformation of nutrients advected from surface freshwater input. Rudnick et al. (1999) observed a decrease from 11.6 to 6.1 $\mu g\ P\ L^{-1}$ within 3 km of canal discharge to the wetland. While no change in TN occurs over this transect, DIN fraction of TN decreased from 26% to less than 5%, while the organic fraction increased. Inorganic nutrients dominate the atmospheric deposition of TN and TP (Hendry et al. 1981), while the more biologically refractory organic pool comprises approximately 74% the canal inputs (Rudnick et al. 1999). In the Southern Everglades wetlands, the ecological effect of P and N loading from surface freshwater inflow is probably less important when compared with atmospheric sources.

Ground water interactions with surface water within the Taylor Slough/C-111 basin may be significant. Given the karst terrain (Randazzo & Jones 1997), communication between surface and ground waters is highly probable. Annual water, N and P budgets show the role of groundwater is insignificant. However, the ground water term represents an estimate of the net sum of ground water inputs and outputs in the study area (GW_i – GW_o). Both of these ground water terms may be large while their difference is insignificant. During the dry season, surface water inflow and outflow are very small, so the net ground water discharge is driven by the balance of net precipitation and ET. Intuitively this is reasonable, and literature exists to support the importance of ground water in this area. First, the Miami Oolite formation, which underlies Taylor Slough and Florida Bay is highly porous (Randazzo & Jones 1997). Ground water flow rates in this formation have been reported as high as 0.30 m hr^{-1} (LaPointe et al. 1990). Second, a significant inverse relationship exists between: (1) ground water level in northern Taylor Slough and salinity at the mouth of Taylor River (r = –89), and (2) ground water level at the Homestead Well and salinity in Trout Creek (r = –91; Tabb 1967). Third, the Natural Systems Model, a two-dimensional model of surface and ground water flow in the Everglades, showed that ground water must be a substantial source of evaporated water during the dry season or in dry years (Fennema et al. 1994). Although geophysical mapping of subsurface freshwater/salt water interface in Taylor Slough shows no evidence of regional freshwater subsurface flow to Florida Bay, Fitterman et al. 1999 show high resistivity zones in the upper 5 m of the coastal zone that may be due to localized fresh, ground-water flows. It is clear that more research is needed to understand the effect of ground water on nutrient transport throughout this region.

Uncertainty in water and nutrient budgets

The order of magnitude of water, N, and P budget estimates is representative of Southern Everglades wetlands during the time period measured. In this section, we comment on how uncertainty in the data and assumptions may affect the results.

The largest uncertainties in the water and nutrient budgets are associated with net ground water flux terms. While it is standard practice to obtain net ground water flux by solving for residuals, errors are inherent in procedure (e.g. Carter et al. 1979). The non-significant net value of ground water flux calculated for the annual water budget is deceiving, as both the ground water input and output terms may be large while their difference is insignificant. The lack of groundwater TN and TP data compounds this uncertainty. A better understanding of local and regional ground water movement through the area is necessary to clarify the true role of ground water on the nutrient budgets of this region. Future research includes the validation of these budgets by quantifying ground water interactions with the wetland and measuring ground water nutrient concentrations (this research is currently being carried out by the University of Miami, Louisiana State University, and the USGS).

We are fairly confident of the nutrient concentrations used to estimate surface water inflow and outflow. Although TN and TP concentration in canal inputs are sampled on a monthly basis, the concentrations are fairly constant over time, and we believe representative of monthly averages. Nutrient concentrations in three of the five creeks discharging to Florida Bay were measured intensively during a 2.5 year study (Sutula 1999). Some uncertainty exists in the quantification of surface water inflow and outflow terms. The estimate of surface water inflow from canals is a maximum value, since it is possible that surface flow can percolate into the ground, and re-enter the canal as ground water. Error in the estimation of surface water outflow is most likely to occur during the rainy season, when, in extreme high water conditions, significant sheetflow can also occur through low lying mangrove areas between the streams. The errors in measurement of surface inflow and outflow are most likely to be higher in the rainy season than dry season. These errors would result in an underestimation of ground water discharge into the wetland, and thus an underestimation of the N and P residual values. During dry season, errors in surface water inflow and outflow are at a minimum because flow through the wetland is highly channelized. Little net inflow or outflow occurs to the system. While error is inherent in the calculation of change in storage, the contribution of this term to the water and nutrient budgets was minimal, and error in its estimation is not likely to affect our results.

Estimates of precipitation, ET and atmospheric DIN deposition come from direct field measurements in the study area during the time period of interest. Some uncertainty exists in the estimates of atmospheric deposition of bulk P and organic N, since these values are derived from literature estimates.

Net hydrologic import of nutrients versus internal wetland sources and losses

Analysis of P sources and sinks in the study area shows that the wetland P budget is fairly well balanced. The budget demonstrates the strong capacity of the Southern Everglades wetland sediments and biota to retain and recycle this limiting macronutrient. The wetland P budget is balanced if the sediment burial rate plus any change in the storage of P from plant standing biomass or fauna is equal to the flux of P from hydrologic sources. Net annual accumulation of woody biomass in the freshwater and dwarf mangrove wetlands is negligible, and we assumed the annual change in faunal biomass was zero. Therefore net hydrologic P import (31 ± 4 mg P m^{-2} yr^{-1}) should be, and is, within the range of preliminary P burial rates estimated for Taylor Slough/C-111 basin (33–71 mg P m^{-2} yr^{-1}, Table 1). Everglades biotic communities and carbonate sediments have been shown to be highly efficient in scavenging water column P (Amador et al. 1992; Koch & Reddy 1992; Scinto 1997). Periphyton photosynthesis results in high pH, which in turn induces the precipitation of P-bound carbonate minerals and lowers water column P concentrations (Gleason 1972; Otsuki & Wetzel 1972). Thus, floating mats of periphyton commonly found in the Everglades are an excellent buffer for atmospherically deposited P. This assertion is supported by our P budget for the Taylor Slough/C-111 wetlands, which shows atmospheric deposition is major input term to the P budget, and is equal in magnitude to the sediment P burial term.

Nitrogen cycling in the Everglades has received far less attention than the P cycle (Rudnick et al. 1999). Interpretation of our N budget results is not conclusive, due to the relative scarcity of published rates of nitrogen fixation and denitrification rates in the Southern Everglades. Our calculations show a net annual import of 649 ± 263 mg N m^{-2} yr^{-1}. Assuming no net annual change in plant and faunal biomass, this residual should be equal to the sum of denitrification and burial minus nitrogen fixation. Sediment N burial, calculated from unpublished data in Taylor Slough (see Table 1), ranges 1890–4027 mg N m^{-2} yr^{-1}. Estimates of nitrogen fixation are available for the mangrove wetlands for Shark River Slough and Tampa Bay and for a freshwater cypress dome in the Everglades (Dierburg & Brezonik 1981; Dierburg & Brezonik 1983; Pelegri et al. 1997; Zuberer & Silver 1978). These estimates are highly variable (30–3000 mg N m^{-2} yr^{-1}), and are dependent on whether the measurements are made on plant litter, bare soil, or in the root zone (Table 1). No estimates of nitrogen fixation have been made in *Cladium* marshes, the dominant emergent macrophyte community in the Southern Everglades. Studies of direct and coupled denitrification using ^{15}N tracers have been conducted in mangrove wetland of Yucatan Peninsula, Mexico (Rivera-Monroy & Twilley 1996). Rivera et al. (1996) found low rates of denitrification (230–1150 mg m^{-2} yr^{-1}), and attributed these results to the low nitrate levels in mangrove wetlands and to high rates of N immobilization by sediment bacteria due to the high C:N ratio of mangrove leaf litter. It is likely that denitrification rates in the Southern Everglades will be low, due to the low nitrate levels found in these wetlands (approximately 0.03 mg L^{-1}).

The high rates of sediment N burial could be balanced by either high nitrogen fixation rates or an increase in the estimate of ground water discharge to these wetlands. The hypothesis that N fixation is driving high sediment

Table 1. Literature values for rates of sediment N and P burial, nitrogen fixation, and denitrification. Sediment burial rates were calculated assuming: (1) a mean sediment accretion rate of 0.01–0.02 g cm^{-2} yr^{-1} in mangrove wetlands, and 0.004–0.009 g m^{-2} yr^{-1} in freshwater wetlands, (2) sediment % TN and TP of 3.6 and 0.055% respectively in Taylor Slough mangrove wetlands, and 3.3 and 0.068% for Taylor Slough freshwater wetlands. Weighted range for the entire slough is based on an 1:3 ratio of mangrove to freshwater wetlands

Source or loss term	Rate (mg m^{-2} yr-1)	Source
P Burial		
Taylor Slough freshwater wetlands	26–58	C. Holmes and W. Orem (pers. comm.)
Taylor Slough mangrove wetlands	55–110	
Weighted range for freshwater and mangrove wetlands	33–71	
N Burial		
Taylor Slough freshwater wetlands	1320–2970	
Taylor Slough mangrove wetlands	3600–7200	
Weighted range for freshwater and mangrove wetlands*	1890–4027	
Denitrification		
Mangroves, Mexico	230–1150	Rivera-Monroy and Twilley (1996)
Nitrogen fixation		
Mangroves, Tampa Bay, FL	30–2600	Zuberer and Silver (1978)
Mangroves, Shark R. Slough, Fl	3000	Pelegri et al. (1997)
Cypress swamp, Everglades, FL	790–2800	Dierburg and Brezonik (1981)

burial rates is supported by the observation of increasing sediment N content south in Taylor Slough away from canal inputs (W. Orem, pers. comm.). Several studies have noted the importance of nitrogen fixation in N budgets of freshwater wetland because of the limited allochthonous N inputs (Chapman & Hemond 1982; Dierburg & Brezonik 1981; Dierburg & Brezonik 1983; Howarth et al. 1988). It is likely that N fixation studies cited in Table 1 were conducted in areas with higher soil phosphorus content. It is not clear if the P depletion of Everglades soils limits nitrogen fixation. In interpreting these numbers, we must also take into account the high uncertainty associated with our ground water discharge estimate. We suspect that the estimate is conservative. The calculation of surface water input is a maximum value, while that of surface water output is a minimum value. Error in these two estimates would result in an underestimation of ground water discharge. Underestimation of ground water discharge would drive the N and P residual higher, particularly if the ground water nutrient concentrations are higher than what is found in wetland surface waters. Clearly, more research is required to clarify the role of N fixation versus ground water flux on the nutrient budgets of these wetlands.

Comparison of hydrologic and nutrient budgets of the southern everglades wetlands with other wetland systems

The hydrologic and nutrient budgets of a wetland are a function of the 'energy signature' of its regional setting, or the specific climate, geomorphology, hydrology, and physical forcing regime of the landscape (Brinson 1993; Twilley 1995). The Southern Everglades wetlands are comprised largely of riverine (freshwater) wetlands, with fringe (mangrove) wetlands at its southernmost edge. These wetlands have different hydrologic and ecological characteristics than depressional or peatland wetlands, otherwise known such as fens and bogs (Novitzki 1978). Exchange with groundwater is a major term in the hydrologic budgets of depressional wetlands, and their nutrient budgets can vary depending on whether on the groundwater source is nutrient-rich or nutrient-poor (Brinson 1993). Groundwater has the potential to be important in certain regions of the Everglades riverine wetlands, primarily because of the highly-permeable karst geology underlying the peat and carbonate sediments found in this region. However, it does not appear to be the dominant hydrologic or biogeochemical budget term.

Natural surface water flow and precipitation are the key source terms in the Southern Everglades water budget, despite the manipulation of the hydroperiod by water management practices. The balance of high precipitation and evapotranspiration rates in this sub-tropical climate cause large inter-annual variation in water storage in the Everglades (Davis & Ogden 1994). The low-gradient, non-alluvial nature of the Everglades freshwater wetlands results in a minimized capacity of surface water to carry sediments and associated nutrient inputs; thus accretion occurs through biotic deposition of organic sediments rather than mineral accretion from sediment transport. The limestone bedrock and lack of terriginous-clastic sediment input result in an oligotrophic, phosphorus-limited environment, and the freshwater and mangrove Everglades biotic communities have evolved in specific adaptation to this geomorphic setting.

Conclusions

Atmospheric deposition was the dominant source of P to Taylor Slough/C-111 basin wetlands, and as important as surface water input as a source of N. This large atmospheric deposition term was equal in magnitude to the sediment P burial rate, indicating the high capacity of the Southern Everglades wetland carbonate sediments and biota to retain and recycle this limiting macronutrient. The importance of atmospheric deposition in the nutrient budgets of the oligotrophic Southern Everglades wetlands should be considered in the management of non-point source pollution in this region. Interpretation of our N budget results was not conclusive, due to the scarcity of published rates of nitrogen fixation and denitrification rates in the Southern Everglades. The high rate of sediment N burial can be attributable to either high nitrogen fixation rates or an underestimated ground water discharge in this area. We believe ground water interactions with surface water within the Taylor Slough/C-111 basin are significant, despite an insignificant groundwater flux term. Future research includes the validation of these budgets by quantifying the communication between wetland ground and surface waters, and the measurement of N transformation rates.

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