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ARTICLE

Hydrological Importance and Water Quality Treatment Potential of a Small Freshwater Wetland in the Humid Tropics of Costa Rica

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Abstract Rapid increases in population and growing food demand are causing widespread deterioration of tropical wetlands globally, and an increased focus on the role and function of these imperiled ecosystems is required. Objectives of this study were to investigate the hydrological dynamics and water quality treatment potential of a small freshwater wetland in the humid tropics of Costa Rica. High-resolution, spatially distributed surface water and meteorological data were combined with a detailed topographical survey to quantify the wetland water balance, hydroperiod, and seasonal variability of wetland area, volume, and residence time. The water balance was dominated by precipitation and outflow, with little contribution from runoff, except during the largest storms. Over 80% of the wetland was flooded continuously; hydroperiods in remaining areas were bi-modal. Small seasonal variations in wetland area, volume, and residence times yielded high and sustained water quality treatment potential. Potential pollutant removal efficiencies were 63.6–99.8% for biological oxygen demand; 60.0–99.8% for total suspended solids; 51.1–98.5% for total nitrogen; and 34.2–99.7% for total phosphorous. The study provides insights into the hydrological functions of this and similar small Central American wetlands and provides a template for extending in-depth hydrological monitoring to other tropical wetland sites.

Keywords Ecosystem service · Hydroperiod · Residence time · Treatment wetland · Water balance

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Introduction

Improved understanding of the socioeconomic and ecological benefits of wetlands has led to the identification and prioritization of the ecosystem services they provide, such as wastewater treatment, wildlife preservation, and ecotourism development (Keddy et al. 2009). However, this trend has occurred mostly in developed countries—located primarily in the temperate region—where political and economic frameworks have facilitated the development of wetland inventories and planning efforts aimed at sustainable wetland management (Junk 2002). Consequently, temperate wetlands are relatively well studied compared with tropical wetlands, which have received less attention from the scientific and management communities (Roggeri 1995; Junk 2002; Ellison 2004; Nahlik and Mitsch 2006).

Rapid increases in population and growing global food demand are causing widespread deterioration of tropical wetlands as more water and land are appropriated for agriculture and development (Junk 2002; Daniels and Cumming 2008). In Central America, the ubiquitous distribution of small wetlands (Junk 1993), often located far from major conservation sites (e.g., Daniels and Cumming 2008), makes them extremely vulnerable to degradation. As a result, small Central American wetlands commonly suffer from increasing pressure due to agriculture, industrial and urban development, pollution, and over-exploitation (Roggeri 1995; Junk 2002; Ellison 2004).

An increased focus on the role and function of these imperiled ecosystems is required, however studies that provide an in-depth accounting of hydrology in "natural" (i.e., non-constructed) tropical wetlands are scarce. Where inventories and hydrological studies of natural tropical wetlands have been performed, they have focused primarily on larger systems. For example, large wetland systems at La Selva Biological Station in Costa Rica (Genereux and Pringle 1997; Genereux et al. 2002; Genereux and Jordan 2006) and on Barro Colorado Island in Panama (Genereux et al. 2002; Ellison 2004) have been the subject of several studies. With the exception of a study that described the hydrology of an Indonesian peat swamp (Hooijer 2005), smaller tropical wetlands have received far less scientific attention.

Wetland hydrology is typically highly variable in space and time (Winter 1999; Mitsch and Gosselink 2000), and quantifying the wetland water balance is the foundation for understanding how individual wetlands function and how wetland systems differ (Giraldo et al. 2007). Some fundamental components and functions of tropical wetlands, such as flooding mitigation and the delivery of base flow to rivers, are likely similar to those in temperate wetlands. However, management recommendations developed in temperate wetlands may not be directly applicable in humid tropical areas because of extreme hydrological inputs (e.g., annual precipitation can exceed 4000 mm) and dissimilar processes and interactions among ecosystem components. For example, tropical wetlands are among the most productive ecosystems on the planet (Roggeri 1995) and can potentially improve water quality throughout the year due to their fairly stable water temperature (~25°C). Indeed, temperature has a strong influence on chemical and biological process such as nitrogen cycling (Kadlec and Knight 1996). The composition and structure of wetland plant communities also largely depend on the hydrologic characteristics of the water balance (e.g., Riis and Hawes 2002; Zweig and Kitchens 2009), and understanding these dynamics is essential to the sustainable management of wetlands in the tropical region.

Our hypothesis is that due to their abundance and distribution in the landscape, small Central American wetlands play a critical and multifaceted role in the environmental quality of the area (water storage, flood control, and water quality improvement). The objectives of this study were to: (1) quantify key components in the water balance; (2) identify seasonal wetland area, volume, and hydroperiod variation; and (3) assess the wetland's potential to remove incoming pollutants, including biologic oxygen demand (BOD_5), total suspended solids (TSS), total nitrogen (TN), and total phosphorous (TP). In addition to providing insights to the function of this and similar small Central American wetlands, this study provides a template for the extension of in-depth hydrological monitoring to other tropical wetland sites of hydrological and ecological interest.

Methods

Geographic Setting

The study was carried out in the humid tropics of Costa Rica, in the natural wetland "La Reserva" on the campus of EARTH University (Escuela de Agricultura de la Región Tropical Húmeda) (Fig. 1). The campus is located 60 km west of the Caribbean coast in the Guácimo canton (i.e., county) of Limón province (Guácimo de Limón; Fig 1b). The study area has elevations from 20 to 30 m above sea level (m.a.s.l) (National Geographical Institute of Central America, 1990). In Costa Rica, the volcanic central cordillera forms a geographic/climatic barrier separating the Pacific dry tropics and Caribbean humid tropics. Precipitation on the windward Caribbean coast is often >4000 mm yr^{-1} (Frankie et al. 1974; Lieberman et al. 1985), with a short-duration "dry" season of only 1 to 2 months (Powell et al. 2000). High rainfall, low evaporation (due to the dominant humid conditions), and lowland topography have resulted in poorly drained soils and wetland formation in the Caribbean region (Ellison 2004).

The EARTH university campus (Fig. 1c) is part of the 2950 km^2 Parismina watershed, which extends between the central cordillera and the Caribbean coast. The campus contains several small, natural wetlands on clayey, hydromorphic soils (Aquepts) (Mitsch et al. 2008). Average annual temperature and rainfall measured on the campus of EARTH University from 1996 to 2008 were 24.5°C and 3227 mm, respectively, placing the region in the premontane wet forest and tropical moist forest ecoregions (Holdridge 1967; Harris 1973). The watershed is not highly urbanized, but has intensive agricultural activities, dominated by banana production.

The ~10 ha wetland catchment investigated in this work is a sub-watershed of the ~400 ha "La Reserva" rainforest

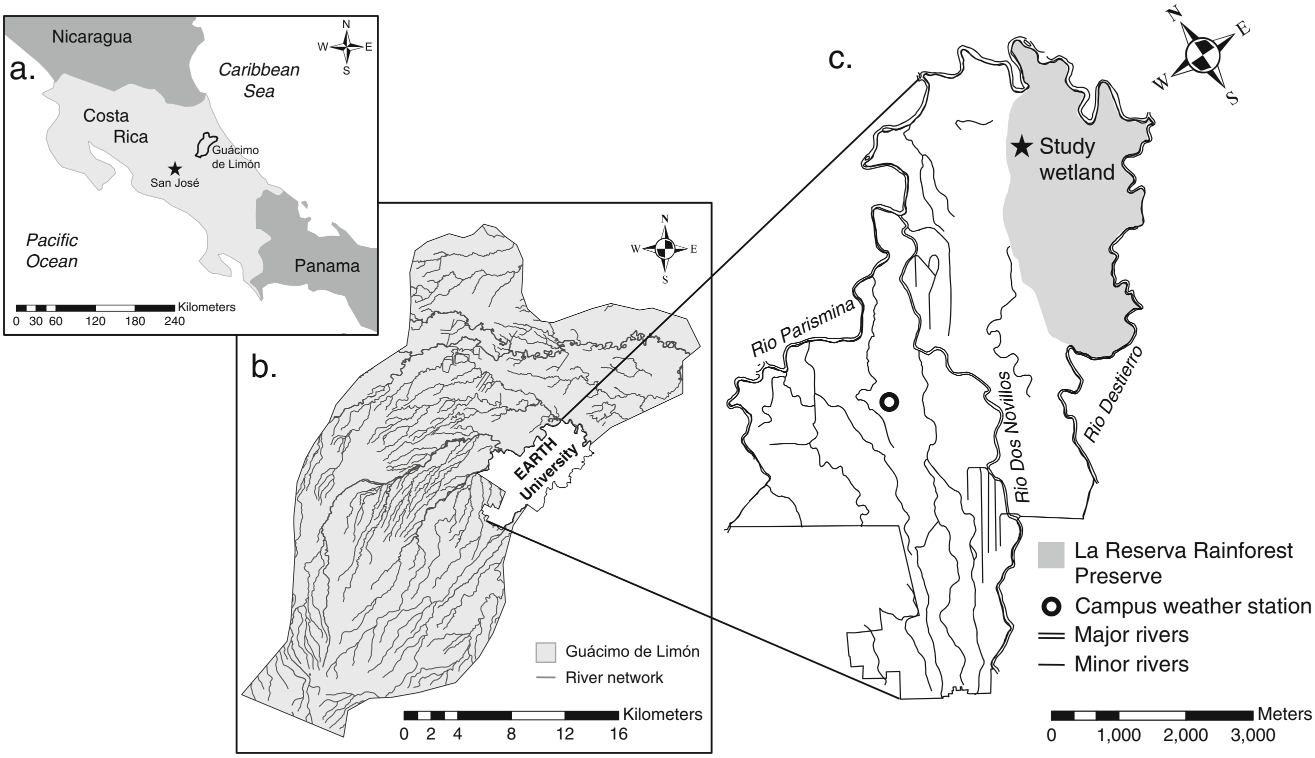


Fig. 1 Location of the study wetland within "La Reserva" rainforest preserve on the campus of EARTH University in Guácimo de Limón, Costa Rica

preserve system (Fig. 1c), where irregular lowland topography forms several waterlogged basins with three main branches that join in a central herbaceous marsh (Fig. 2). A small fourth branch (adjacent to S7 in Fig. 2a) joins the central herbaceous marsh from the west. The wetland has no specific inlet and is isolated from the larger "La Reserva" wetland system by an unpaved access road. Wetland outflow (Q in Fig. 2a) is through a culvert that connects the study area to the rest of the wetland system, which eventually drains to the Rio Dos Novillos (Fig. 1c). This wetland and others in "La Reserva" belong to a protected area and have not received human intervention in the 20 years since road construction, before which the area remained undeveloped due to difficult access (Kolln 2008).

Soils in the study wetland are highly organic and composed primarily of poorly decomposed plant material. Upland soils in the catchment are primarily oxisols, with low organic content. The central herbaceous marsh is dominated by a variety of graminoids and several species of broad-leaved plants belonging to the Araceae family (e.g., peace lily [*Spathiphyllum friedrichsthalii* Schott]) (Kolln 2008). The upper wetland branches have a canopy dominated by swamp palm (*Raphia taedigera* Mart.) and oil tree (*Pentaclethra macroloba* [Willd.] Kuntze), with a diverse herbaceous understory (Mitsch et al. 2008). Wetland water chemistry measured in May 2008 was characterized by high acidity (pH of 4.8–6.4) and low salinity (conductivity of 25–50 μS/cm). Cocha Barros and Muñoz Bogantes (2005) and Gallardo and César (2006) found BOD_5, TSS, nitrate ammonium, and phosphate to vary spatially along the direction of water flow, with lowest concentrations near the wetland exit. Nahlik and Mitsch (2006) reported relatively low dissolved oxygen, variable and low redox potential, and low inorganic nutrient concentration.

Field Instrumentation and Topographic Survey

A distributed network of automatic field devices was installed in May 2008 to measure and record precipitation, water levels, and outflow (Fig. 2a). Field instruments were selected with special attention to the local conditions to ensure simplicity, easy maintenance, high accuracy, and low cost. Simple, self-contained, low-cost (~US$130) float and pulley stage recorders (Schumann and Muñoz-Carpena 2002; Ritter and Muñoz-Carpena 2006) were constructed on site and used to record water levels at eight stations (S1 to S8 in Fig. 2a). S8 was installed in May 2009 to refine observations in the upper part of the wetland. The devices were programmed to record wetland water stages at 15-minute intervals from May 2008 through May 2009 and converted to surface water elevations (SWE) based on a detailed topographical survey (see below).

An automatic tipping bucket rain gauge (Logging Rain Gauge RG2M, Onset Computer Corp., Bourne, MA) was

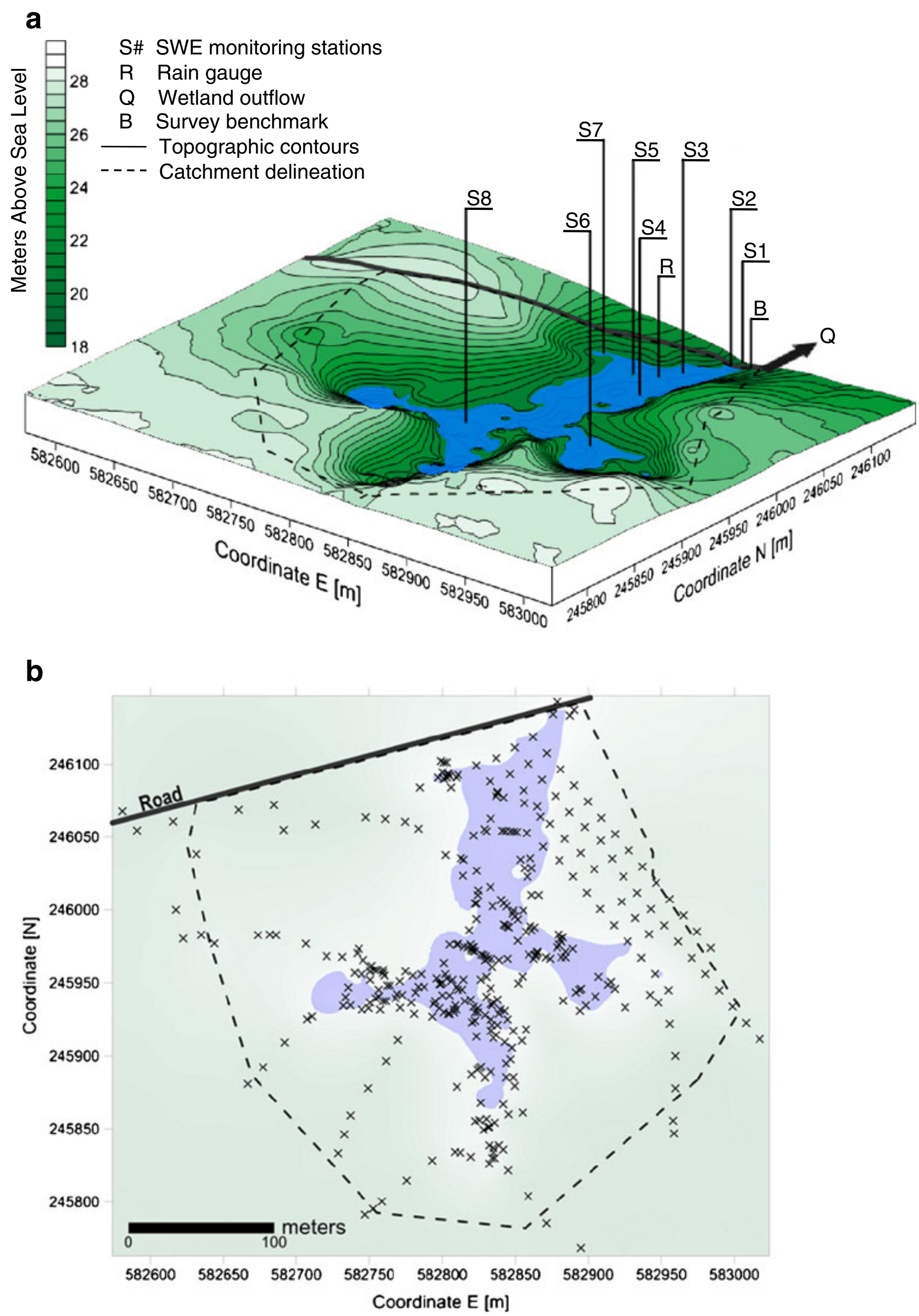


Fig. 2 **a** Experimental setup showing surface water elevation (S#), rainfall (R), and outflow (Q) measurement locations and catchment topography. **b** Location of topographic survey points

installed in the center of the wetland in an area of broad herbaceous marsh without overhanging canopy (R in Fig. 2a). Both the stage recorders and rain gauge used compact data loggers (HOBO H8, Onset Computer Corp., Bourne, MA) that were downloaded by EARTH University students at 2-week intervals. The tipping-bucket rain gauge installed in the wetland was found to consistently overestimate rainfall by ~40% compared to the EARTH campus weather station, located approximately 3 km south-west of the wetland (Fig. 1), likely due to the fact that the wetland gauge was not calibrated for high-intensity, tropical rainfall conditions. In May 2009, the gauge was recalibrated using a field calibration kit (FC-525, Texas Electronics, Inc., Dallas, TX) and the previous data were recalculated. After this correction, data from the two rain gauges were very similar (Pearson $r=0.93$), and gaps in the 5-minute rainfall data from the wetland (<1% of values) were filled with data from the campus weather station.

The wetland outlet flows through a 7-m (length), 50-cm (diameter), uncoated, cast iron culvert under the road that forms the northeast boundary of the wetland (Q in Fig. 2a). Two stage-recording stations, located just upstream and downstream of the culvert (S1 and S2; Fig. 2a), were used to compute wetland outflow based on head difference using flow equations from Bodhaine (1968) for type 3 (tranquil flow throughout) and type 4 (submerged outlet) conditions, depending on backwater elevation. Wu and Imru (2005) reported good results using this method to compute slow flow in road culverts connecting wetlands in the Everglades (FL, USA).

Discharge measurements made in May 2008 and May 2009 using the velocity-area method (Mosley and McKerchar 1993) and an acoustic Doppler velocimeter (FlowTracker, SonTek/YSI, San Diego, CA) were used to estimate culvert discharge coefficients (see Bachelin [2009] for details). When the head difference was too small to be resolved using the SWE stations, outflow was set to the minimum calculated value (0.0008 m^3 s^{-1}). Finally, when SWE at station S2 exceeded the road elevation (19.8 m.a.s.l), additional wetland outflow was calculated following Normann et al. (1985), assuming the road acted as a broad crested weir with a length of 1 m. Flow calculations were performed using 15-min SWE data and averaged to daily means.

An initial topographic survey of the wetland area and surrounding catchment was made using an optical level (model AT-G6, Topcon Positioning, Livermore, CA) following a 15-m square grid in 2008 (Kolln 2008). Approximately 200 additional measurements were taken with a rotary self-leveling laser (model LM500, CST/Berger, Watseka, IL) during the 2009 field campaign to refine the survey, with particular attention to characterizing the wetland interior. A total of 399 elevation measurements were made, resulting in an overall sampling density of ~44 points ha^{-1} (average spacing of ~15× 15 m) (Fig. 2b). Stage recording stations were topographically referenced to a local benchmark (B in Fig. 2a) in order to calculate surface water elevations (SWE) from water level data.

Water Budget

For a wetland not connected to an upstream water body and with a single downstream outlet, the change in water volume over an interval of time is the difference between the inflow and the outflow components:

$$dS = P + RO - ET - Q \quad (1)$$

where dS is the change in water volume or storage, P is precipitation, RO is runoff from the catchment in the wetland, ET is evapotranspiration, and Q is outflow. Equation 1 assumes that the net contribution of groundwater to the water budget is negligible due to low permeability, clayey alluvial soils that generally underlie the wetland basin (Nahlik and Mitsch 2006). The wetland water budget was calculated based on average daily values of hydrologic and ET data and daily P sums. All terms in Eq. 1 were expressed in units of volume [m^3]. To convert P, ET, and RO values from length [mm] to volume [m^3], P and ET were multiplied by the daily wetland surface area, and RO was multiplied by the daily catchment area (see below for area calculations).

Precipitation and Q were taken from field rainfall and outflow measurements (see preceding sections). Daily ET was calculated based on the Penman-Monteith equation (Allen et al. 2004) using climate data from the campus weather station (Fig. 1). Runoff was calculated using the Natural Resources Conservation Service (NRCS) curve number (CN) method (NRCS 2003). Little information is available on appropriate CNs for tropical soils—or indeed whether the CN method is sufficient to describe rainfall-runoff relationships in the tropics. To address this deficiency, Cordero Rodriguez and Solano Valverde (2010) developed rainfall-runoff relationships for this study site to improve runoff estimation and, more generally, to test the efficacy of the CN method in the Costa Rican humid tropics. They found the CN method to adequately describe the rainfall-runoff relationship for the oxisols in the wetland catchment, with CNs ranging between 36 and 43. We used their average value (CN=40), which is in the range estimated for other tropical oxisols under full vegetative cover (e.g., Cooley and Lane [1982] estimated CNs from 38 to 48 for oxisols in watersheds with pineapple production in Hawaii).

Calculation of Wetland Area, Volume, and Hydroperiod

Data from the topographic survey were processed using Surfer (version 9.1, Golden Software, Golden, CO). A 3-dimensional (3-D) model of the wetland and catchment area was generated using the kriging geostatistical gridding method with a linear variogram. This method estimates the values of the points at the grid nodes and produces maps from irregularly spaced data. From the topography grid, a topographic map was constructed, and the catchment area was delineated and calculated (Fig. 2a). Time series of water surface extent (i.e., wetland area) and volume were computed using the same kriging method using daily average SWE from each of the stage-recording stations. Changes in daily wetland storage volumes estimated with this 3-D model were compared to those calculated using Eq. 1. Water depth grids and contour maps were generated by subtracting the topographical grid from the SWE grid and used to calculate hydroperiod frequency distribution.

Residence Time and Potential Water Quality Treatment Function

The wetland residence time (τ) distribution was estimated by dividing daily values of wetland volume (V) by average daily outflow (Q). Theoretically, this calculation assumes a well-mixed system and may overestimate τ. Concurrent tracer work (Bachelin 2009) refined the τ distribution calculated here to account for areas of differential mixing. Potential pollutant removal efficiency was calculated as a function of hydraulic loading rate (q) by coupling dynamic wetland characteristics (daily area and flow rate) with specific pollutant characteristics (k and C^*) using (Kadlec and Knight 1996):

$$C_2 = C^* + \left(C_1 - C^*\right)e^{(-k/q)} \tag{2}$$

where C_1 is incoming pollutant concentration [mg L^{-1}], C_2 is pollutant concentration at the outlet [mg L^{-1}], C^* is the background, irreducible pollutant concentration [mg L^{-1}], k is the rate constant [m yr^{-1}], and q is the hydraulic loading rate (m yr^{-1}; q=Q/A). Removal efficiencies for BOD_5, TSS, TN, and TP were calculated for different classes of q corresponding to the observed range of flow and surface water area conditions. Average values of each class were used to calculate the percentage of pollutant removal according to Eq. 2 for a range of pollutant input concentrations.

Removal rate constants for each pollutant were calculated based on a local average annual temperature of 25°C using k values estimated for 20°C corrected by the modified Arrhenius equation, after Kadlec and Knight (1996). Little data are available on pollutant concentrations entering natural wetlands in the tropics, however previous monitoring suggests low pollutant loading to the study wetland (Cocha Barros and Muñoz Bogantes 2005; Gallardo 2006). On the other hand, constructed tropical treatment wetlands often have extremely high pollutant influent concentrations (e.g., Katsenovich et al. 2009; Nahlik and Mitsch 2006). In this analysis, we therefore calculated the potential ability of the wetland to improve water quality under a wide range of possible influent concentrations and existing hydrologic conditions.

Results and Discussion

Precipitation, Evapotranspiration, and Surface Water Elevation Time Series

A total of 4283 mm of rainfall was measured in the wetland over the study period (Table 1), with the greatest rainfall occurring in November, December, and February (Fig 3a). Evapotranspiration measured at the campus weather station (Fig. 3a) was relatively low and consistent over the monitoring period. Mean daily ET was 3.14 mm d^{-1}

Table 1 Hydrological monitoring station locations and descriptive statistics over study period from 5/12/08 to 5/26/09

Station[a]	N-Coord.[b]	E-Coord.[b]	Dist. to outlet (m)	Elevation (m.a.s.l)	n[c]	Units	Min	Max	Mean	CV[d] (%)	Avg. SW slope[e] (%)
S1	1131113	546548	–	19.38	36535	m	19.49	20.02	19.58	15.3	−0.2
S2	1131108	546554	7.8	19.24	36742	m	19.50	20.09	19.60	19.5	–
S3	1131078	546533	38.1	19.89	36450	m	20.05	20.42	20.20	6.8	1.7
S4	1131032	546534	82.2	20.10	35541	m	20.26	20.58	20.41	4.9	1.0
S5	1131054	546519	65.7	20.05	36661	m	20.21	20.52	20.35	5.0	1.2
S6	1130945	546568	169.2	20.63	36404	m	20.89	21.10	20.99	1.9	0.9
S7	1131066	546478	84.3	20.71	36449	m	20.71	20.81	20.76	1.7	1.3
Q	1131108	546554	–	19.38	36396	m^3 d^{-1}	68.9	3470.7	149.9	53.5	–
										Sum[f]	
P	1131064	546524	54.56	22.987	107423	mm d^{-1}	0	172	11.33	4283	
WS-P	1128959	544425	3024	~30	131540	mm d^{-1}	0	172	12.95	4222	
WS-ET	1128959	544425	3024	~30	391	mm d^{-1}	0.44	4.61	3.31	1085	

[a] *S#* stage recorders; Q outflow; P rain gauge in wetland; WS-P/WS-ET rain gauge and ET measurements from campus weather station (see Figs. 1 and 2)

[b] Costa Rica Transverse Mercator 90 (CRTM 90) coordinate system (m)

[c] Represents 15-min data from stage recorders, 5-min sums from rain gauges, and ET calculated from daily averages of meteorological data

[d] Coefficient of variation

[e] Average surface water slope from station to wetland outlet (culvert headwater) over period of record.

[f] Sum over period of record (mm)

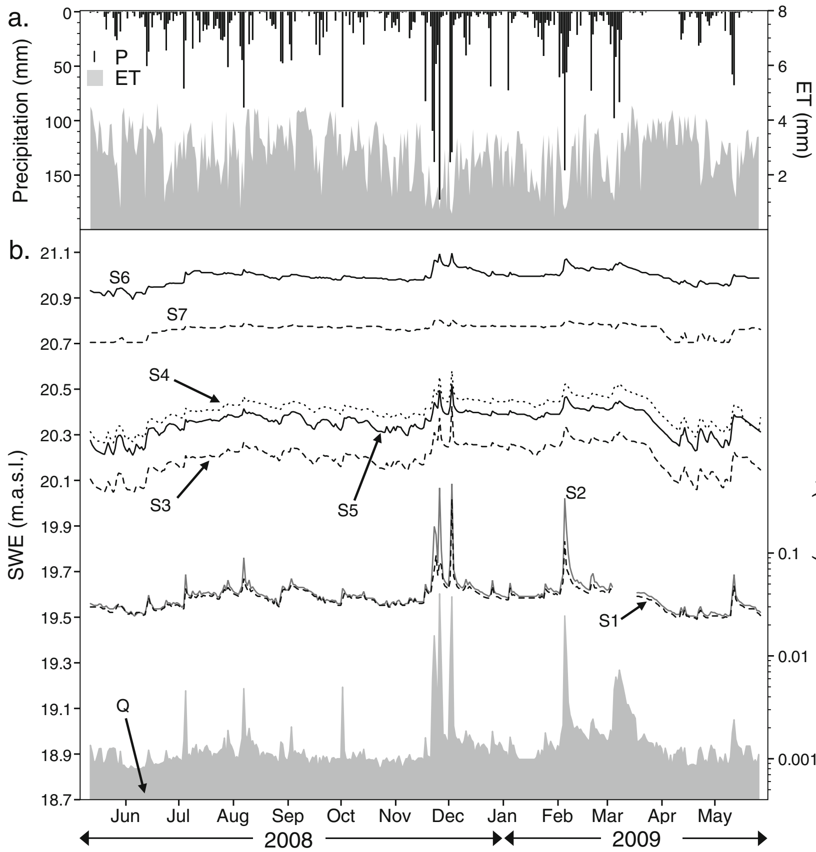


Fig. 3 Experimental time series of: **a** precipitation (P) and evapotranspiration (ET); **b** surface water elevation (SWE) at stations 1 through 7 (S1 to S7) and wetland outflow (Q). Gaps in panel b represent missing data. Water level variation was highest close to the outlet (S1 and S2), but was relatively stable across the wetland over the monitoring period

($0.58 \leq ET \leq 4.72$ mm d^{-1}; coefficient of variation, CV= 5.3%), and yearly total ET was 1085 mm. This is similar to estimated ET rates in other humid tropical forests (948–1150 mm yr^{-1} [Bonell and Balek 1993]; 1200–1500 mm yr^{-1} [Penman 1970]), but lower than ET estimates from modeling studies in La Selva biological station in the northern part of Limón province (1318–1509 mm [Bigelow 2001]; 1892–2292 mm [Loescher et al. 2005]), likely due to physiogeographic differences between the sites (e.g., La Selva's higher elevation and solar radiation [Loescher et al. 2005]).

Approximately 36,000 SWE data points were collected at each station (Table 1), and overall data completeness was 99%. A number of prolonged, high-intensity rainfall events caused rapid responses in water level (for example, in November and December 2008 and February 2009), but these peaks only lasted for several days (Fig. 3b). In general, there was a 2-day time lag between peak P from storm events (Fig. 3a) and peak Q (Fig. 3b). SWE decreased across all stations in March and April of 2009 when the wetland experienced 33 days with little or no rainfall (25 days with no rainfall; total rainfall=14 mm over this period). Flow through the outlet culvert (Fig. 3b) resulted in the accumulation of water in the downstream portion of the wetland during some large rainfall events, but backwater effects generally lasted only 1–2 days.

Coefficients of variation (CV) for the seven SWE series were generally low (1.7 to 19.5%; Table 1) indicating an overall stability in water levels throughout the year. SWE was generally most dynamic at low-elevation stations close to the wetland outlet (S1 and S2 in Fig. 3b) and became more stable with increasing elevation/distance from the outlet (S3–S7 in Fig 3b). The highest elevation areas of the wetland are likely more stable in time due to less preferential flowpath connectivity with the rest of the wetland, while lower-elevation sites are better connected and more affected by the outlet condition.

Interestingly, the magnitude of wetland water level variation is well fitted (R^2=0.99) by a power function between the CV of each SWE time series and station elevation (Fig. 4). While this phenomenon is expressed over a relatively small elevation range (i.e., ~20 to 22 m.a.s.l), it extends the findings of other authors, who have reported similar relationships in river basins. For example, Leopold et al. (1995) showed that the slope of a power relationship between water level and contributing area (for which elevation can be considered a proxy) was close to zero or slightly negative in arid river basins and moderately negative in temperate regions. Here, the slope is highly negative. This effect is presumably driven by the magnitude and spatio-temporal distribution of rainfall (i.e., low and

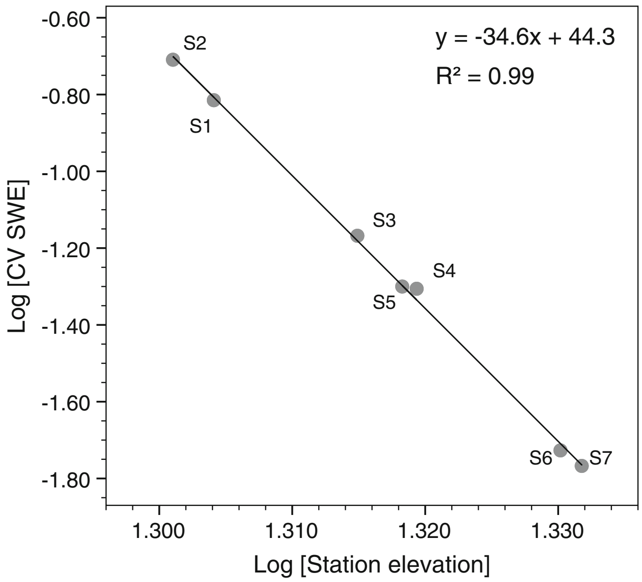


Fig. 4 Relationship between station elevation and the coefficients of variation (CV) of measured surface water elevation (SWE) at stations S1–S7

flashy in arid regions; moderate and distributed in temperate regions; high and nearly constant in tropical regions). While these results are from a single site, further investigation in other locations would help clarify whether this relationship is characteristic of tropical wetlands (and/or river basins) in general, or is unique to this wetland.

While water surface slope is generally assumed to be negligible or minor in wetlands (e.g., Healey et al. 1981; Carleton 2002), spatial SWE patterns in the study wetland showed marked hydraulic gradients from wetland edges towards the outlet that generally mirrored the underlying bed slope. For example, the average SWE difference between S6 (located on an upstream branch) and S1 (located at the wetland outlet) was 1.41 m over 170 m, equivalent to a water surface slope of 0.8% (compare, for example, with the 0.2% water surface slope threshold between gradual and steep-gradient mountain streams [Wohl 2000]). Average downgradient surface water slopes stations ranged from 0.2 to 1.6%. Despite these relatively high slopes, the high density of emergent wetland vegetation, and ensuing hydraulic roughness, resulted in low flow velocities in most vegetated areas of the wetland, although some small, channelized sections carried faster flows. Specific flow paths, velocities, and travel times were explored in a parallel tracer study (Bachelin 2009).

Water Budget

Figure 5 shows the accumulated volumes of P, RO, ET, and Q in the wetland over the study period. Precipitation and ET volumes were calculated based on daily water surface area (calculated using SWE and topographic data), while RO was calculated over the catchment area, excluding wetland area. The topographical survey and analysis yielded a total catchment area of ~9.14 ha, including the surface area of the wetland; variation in wetland area is discussed below.

Precipitation (dashed line in Fig. 5) was the largest positive element in the water budget, with a total of 67600 m^3 of rain falling directly into the wetland over the monitoring period. Rain fell on 280 of the 380 days in the study period, but P rates were highly dynamic, varying over three orders of magnitude ($0 \leq P \leq 2884\ m^3\ d^{-1}$; i.e., rainfall of 0 to 172.5 mm d^{-1}). The largest P contributions were during the heavy rains of November 2008 and early February 2009 (7 and 8 days of continuous rain, respectively). Runoff (dotted line in Fig. 5) was also a variable positive input to the water budget, although of much smaller magnitude than P (4380 m^3). The permeability of

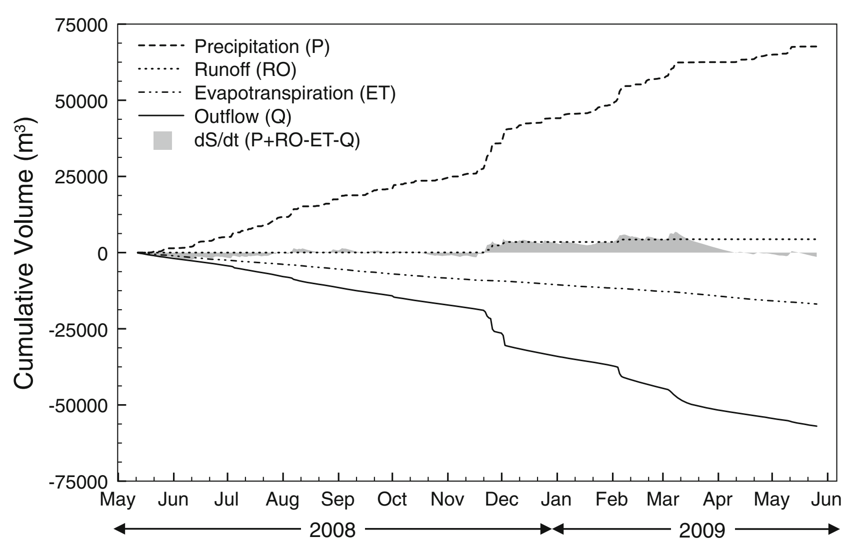


Fig. 5 Wetland water budget showing cumulative inflows (precipitation and runoff), outflows (evapotranspiration and outflow), and change in storage (dS/dt)

the oxisols and the dense vegetation in the upland watershed area resulted in a lag between precipitation and the contribution of RO to the surface water budget. Accordingly, large P rates were needed to produce RO (>33, 76, and 181 mm d^{-1} to satisfy initial abstraction for wet, average, and dry antecedent conditions, respectively). Runoff was therefore an additional important input during periods of heavy rain, but only occurred on only 11 days of the study period ($0 \leq RO \leq 1449$ m^3 d^{-1}), and did not contribute significantly to the water balance during other periods.

Outflow (solid line in Fig. 5) was the largest negative component of the water budget, with a total outflow of 57000 m^3 over the study period. Missing Q data (2-week gap in March) were filled using a third-order polynomial regression between SWE at S3 and measured Q (R^2=0.78). Daily Q volume varied over two orders of magnitude ($68.9 \leq Q \leq 3470$ m^3 d^{-1}) but was relatively low and stable for much of the period of record, as indicated by areas of linearity on the cumulative Q curve. During periods of heavy rain, however, stage increased at the wetland outflow and led to road overtopping and rapid outflow. Despite occurring only 1.2% of the time, these over-road flows accounted for 20.4% of the total wetland outflow. Evapotranspiration losses (16900 m^3) were substantially smaller than Q, and were fairly constant over the study period (as also indicated by linearity of the cumulative ET curve). ET losses accounted for 24.4% of direct P.

Wetland Area, Volume, and Hydroperiod

Wetland topography was linked with SWE time series to evaluate the spatial and temporal evolution of flooded area, water storage, water depth, and hydroperiod. The spatial extent and depth of flooding in shallow, isolated wetlands can change rapidly when water levels change (e.g., Mitsch et al. 2009), affecting nutrient fluxes, biogeochemical cycling, and habitat suitability. For example, the frequency and duration of flooding extent are a decisive factor for the type of vegetation present in transitional areas (e.g., van der Valk 1981; Lee et al. 2009). However, the data presented in this work point to remarkably stable hydrologic behavior in the study wetland, where wetland area and storage volume changed only slightly over the monitoring period (Fig. 6). This contrasts with pulsed wetland systems (e.g., river floodplains, deltas, ephemeral ponds, etc.) and has important hydrological, ecological, and biogeochemical implications. Frequency distributions of wetland area and volume (Fig. 7a–b) generally approached normal distributions with small range of variability that highlight the wetland's stable behavior. Data outside of the 95% confidence interval (CI) occurred during large rainfall events (November to December 2008; February 2009) and extended dry periods (May to June 2008; March to April 2009). Wetland area was less variable than wetland volume (CVs of 3.6 and 7.0%, respectively; Table 1) due to relatively steep wetland edges, which allowed only small fluctuations in wetland areal extent. This is illustrated in Online Resource 1, which shows an overlay of the most frequent water surface area with the lower and upper boundaries of the 95% CI of the frequency distribution; the difference in flooded area is minimal.

Water depths were calculated as the difference between SWE and topography grids (1000×800 cells each) to investigate the spatial distribution of wetland hydroperiod. The majority of wetland area (1.36 ha) was inundated 100% of the 380-day study period (Fig. 8), which has important implications for carbon storage and nutrient biogeochemis-

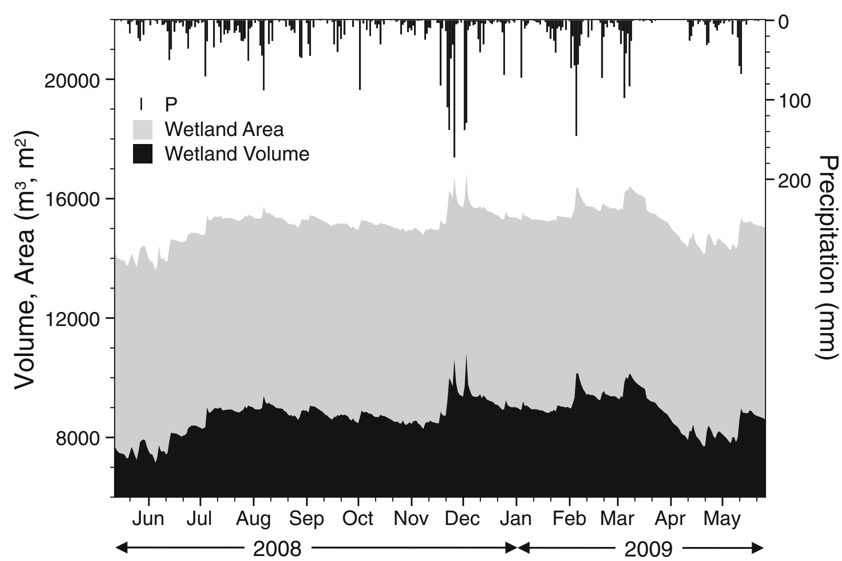


Fig. 6 Evolution of daily wetland area and volume with precipitation during the experimental period

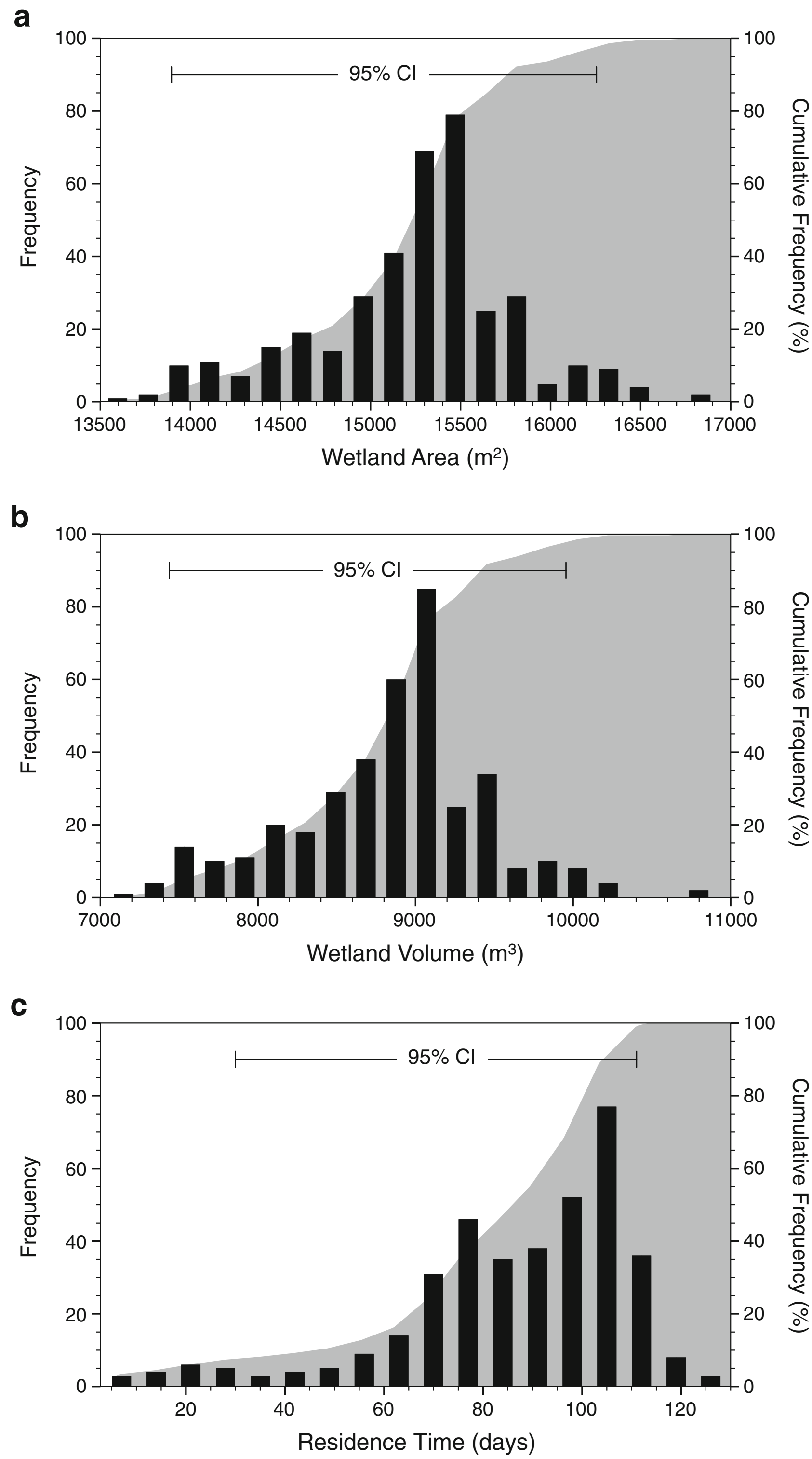
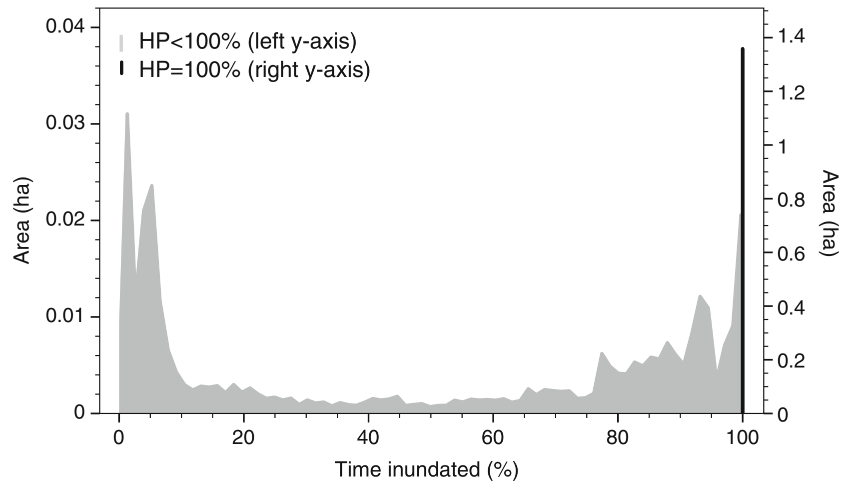


Fig. 7 Histograms showing distribution of (**a**) wetland area; (**b**) wetland volume; and (**c**) wetland residence time

try (e.g., high potential for carbon storage; dominant reducing conditions for denitrification; etc.). An additional 0.33 ha of wetland edge was inundated between 1 and 380 days with generally a bimodal distribution (Fig. 8). These edge areas (located both on the wetland perimeter and on the edges of raised "islands" within the wetland) were inundated either very often (i.e., >75% of the time) or very rarely (i.e., <10% of the time), and thus represent either "wet" or "dry" average annual soil moisture conditions. This is consistent with the results of stochastic

Fig. 8 Distribution of wetland hydroperiod. Areas inundated 100% of the time are shown in black on the right y-axis and account for nearly 80% of the total wetland area. The distribution of hydroperiods in the remaining 20% of the area is bimodal



modeling of soil moisture by D'Odorico et al. (2000), who found bimodal soil moisture distributions to occur under highly variable climate conditions. Despite the relatively stable climate conditions observed here—as also evidenced in the stability of wetland area, volume, and depth—the distinct (albeit short) dry period may provide sufficient variation to reinforce this phenomenon. Moreover, Daly et al. (2009) argue that soil moisture bimodality is driven by interaction between saturated and unsaturated zones in soils with shallow water tables, such as those at the wetland edges observed here. These results indicate that wetland hydrology favors plant species that tolerate consistently inundated conditions and provides appropriate hydrological conditions for short-hydroperiod species in small areas, but may not support plants that favor intermediate inundation.

Residence Time and Water Quality Treatment Potential

Estimated wetland residence times (τ) varied from 7 to 126 days over the monitoring period, with a distribution skewed towards higher values (Fig. 7c). The 95% CI for τ was 30–111 days, with a mean value of 89 days. Given the relatively stable wetland volume, this variability was driven primarily by dynamic outflow, with short residence times corresponding to less common high-flow events and long residence times associated with more common low flow events. These first-order estimates of τ represent an integrated wetland response and assume a well-mixed system. As noted by Mitsch and Gosselink (2000, p. 123), "[t]he theoretical residence time…is often much longer than the actual residence time…because of non-uniform mixing." Indeed, these results are higher than those reported by Bachelin (2009) in a parallel study that observed tracer transport in two specific wetland flowpaths. In that study, estimated values of τ ranged from 36 to 75 days in areas of slower, sheetflow-like transport (primarily through areas of herbaceous marsh) and 8–18 days in areas of faster, channelized flow (primarily through areas of forested wetland).

Coupling calculated values of hydraulic loading rate (q) with specific pollutant characteristics (Kadlec and Knight 1996) and Eq. 2 allowed us to estimate the wetland's water quality treatment potential under a range of pollutant input concentrations (Table 2). Values of q are listed with their cumulative frequency of occurrence and corresponding range of τ. Higher q values correspond to lower τ, although some overlap in τ ranges exist since wetland area (used to calculate q) and wetland volume (used to calculate τ) were determined independently. The majority of calculated q values were extremely low, yielding high estimates of potential pollutant removal across a broad range of observed wetland hydrology and input concentrations: 63.6–99.8% for BOD_5; 60.0–99.8% for TSS; 51.1–98.5% for TN; and 34.2–99.7% for TP. These results are in the range reported for artificial wetlands in Costa Rica and other humid tropical locations (Nahlik and Mitsch 2006; Katsenovich et al. 2009; Tejada and Breve 2010; Tejada et al. 2010). Under the current hydrological regime, the wetland's natural water quality enhancement potential is high even at higher q values (including those corresponding to the range of τ values reported in Bachelin [2009]; see Table 2). Although little data are available on influent pollutant concentrations into natural wetlands in the tropics, these results suggest that small tropical wetlands, like that in this study, have the potential to naturally improve water quality over a wide range of influent concentrations under existing hydrologic conditions.

Comparison of Wetland Water Budgets

Wetland storage volumes calculated with the water balance (Eq. 1) and with the 3-D surface model and

Table 2 Average pollutant removal efficiencies for different classes of observed hydraulic loading rates (q) and a range of influent concentrations (C_1; given in mg L^{-1})

q (m yr^{-1})	Cumul. Freq. of q (%)	τ (days)	% Pollutant Removal[a] BOD5 (k=34 m yr^{-1})[b]			TSS (k=1000 m yr^{-1})			TN (k=28.1 m yr^{-1})			TP (k=12 m yr^{-1})		
			C_1=10	C_1=500	C_1=1000	C_1=5	C_1=100	C_1=1000	C_1=5	C_1=50	C_1=100	C_1=0.1	C_1=5	C_1=10
<1.85	5	138-153	80.0	99.6	99.8	60.0	98.0	99.8	70.0	97.0	98.5	79.9	99.5	99.7
1.85-2.06	25	107-129	80.0	99.6	99.8	60.0	98.0	99.8	70.0	97.0	98.5	79.8	99.4	99.6
2.06-2.38	50	80-115	80.0	99.6	99.8	60.0	98.0	99.8	70.0	97.0	98.5	79.7	99.2	99.4
2.38-2.95	75	66-91	80.0	99.6	99.8	60.0	98.0	99.8	70.0	97.0	98.5	79.1	98.5	98.7
2.95-8.00	95	29-63	80.0	99.6	99.8	60.0	98.0	99.8	70.0	96.9	98.4	76.7	95.5	95.7
>8.00	100	2.5-21	63.6	79.1	79.3	60.0	98.0	99.8	51.1	70.8	71.8	34.2	42.6	42.7

[a] *BOD5* 5-day biochemical oxygen demand, *TSS* total suspended solids, *TN* total nitrogen, *TP* total phosphorous

[b] Rate constants calculated for annual average temperature of 25°C, see text.

Shown with corresponding range of calculated residence times (τ). Shaded region represents the range of τ estimated from a tracer study by Bachelin (2009)

SWE data followed similar patterns (Pearson r=0.75) and showed good agreement in the timing of volume peaks and declines, but often had different magnitudes (see Online Resource 2). The water budget model was generally "flashier," yielding larger storage increases than the 3-D/SWE model for most rainfall/runoff events, but also had had more consistently negative storage values. During days with little or no P, dS/dt calculated with Eq. 1 was negative, principally because Q continued at a low, but steady rate (see Fig. 3b). Conversely, during high-intensity, long-duration P events, dS/dt was positive. In general, dS/dt time series calculated with the two methods were in agreement, with a root mean square difference of 205.5 m^3 d^{-1}(approximately 2% of the median wetland volume as calculated with the 3-D/SWE model).

There are several possible explanations for the differences between the results from the two methods. While Q calculations were based on high-resolution SWE data, discharge coefficients for the flow equations were calculated with field measurements under a relatively narrow range of field conditions (lower flows) which may be insufficient to fully describe dynamic Q conditions. It is also possible that unidentified wetland surface water inflows and/or outflows and groundwater seepage may also exist, particularly under extremely wet (high SWE) conditions. Any errors in calculation of Q would cascade into calculations of τ, q, and pollutant removal potential, making accurate estimation of wetland inflows and outflows a vital, if difficult, element of wetland monitoring. Errors may also exist in the volume calculations made using the 3-D/SWE model due to assumptions about the spatial interpolation of topography and SWE. In particular, the 3-D/SWE model presented here may underestimate wetland volume and the magnitude of dS/dt. This error could be reduced by installing additional monitoring stations, particularly at the ends of wetland branches, to more accurately depict SWE. Despite these limitations, the overall agreement in water budgets suggests that the results presented here provide a thorough accounting of hydrology in this small tropical wetland.

Conclusions

This case study described the hydrological variability and potential water quality treatment function of a small, natural, tropical freshwater wetland in the humid tropics of Costa Rica. Wetland water volumes calculated with the water budget approach and those made using surface water elevation (SWE) and topography data both showed the wetland's hydrology to be remarkably stable, although differences in hydrological dynamics calculated with the two methods existed. Given inherent uncertainties in the measurement and calculation of water budget components, we suggest that SWE and topographic data, like those presented here, can help lend credence to hydrological studies, particularly in remote or less-studied field sites where incomplete information (e.g., about seasonal surface water or groundwater connections) can lead to errors in water budget calculations.

The quantification of key components in the water balance and analysis of daily variation in wetland area, volume, and hydroperiod highlighted the wetland's hydrologic stability and water quality treatment potential. In general, water level variations were small and showed a strong power relationship (R^2=0.99) between the CV of SWE and wetland elevation. Hydraulic loading rates were sufficiently low to potentially remove the majority of incoming pollutants most of the year, though removal rates were reduced during some very high flow events. Estimated pollutant removal efficiencies over a range of influent concentrations were 63.6–99.8% for BOD_5; 60.0–99.8% for TSS; 51.1–98.5% for TN; and 34.2–99.7% for TP.

While these potential removal efficiencies are high, additional loading from agricultural runoff or other sources could reduce these efficiencies by increasing the hydraulic loading rate. The high hydrological buffering capacity of this small tropical wetland, both in terms of water quality and quantity, confirms the important ecosystem services these areas provide and strongly supports the conservation of these vital and threatened resources.

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