Hydrologic Budget Analysis of a Small Natural Wetland in Southeast USA

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ABSTRACT. Temporal variability and linkages among hydrologic components of a natural riparian wetland in the southeast USA were examined using two years of measured data. Rainfall was the dominant inflow and evapotranspiration (ET) the dominant outflow for the wetland. The wetland response factor, defined as the ratio of runoff to rainfall volume, was small and surface runoff accounted for only 9% of the total rainfall. ET was significantly different for wetland vegetation types and was significantly less than Class A Pan evaporation for most part of the year. Water losses through groundwater discharge accounted for 20% of the annual water budget. On an annual scale, very little water was added to storage within the wetland. Because of its shallow nature the wetland did not have a large capacity for flood storage and did not always attenuate floods. The results obtained from this research should be applicable to other natural riparian wetlands in temperate/subtropical climates. Also, the data should be useful to developing and validating hydrologic models of natural and constructed wetlands.

Keywords: Evapotranspiration, hydrologic budget, wetlands

1. Introduction

Of all the factors that influence wetland characteristics, hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes (Mitsch and Gosselink, 1993). Species composition and richness, primary productivity, organic matter accumulation, and nutrient cycling in wetlands are all affected by general hydrologic factors such as kinetic energy of flow, predominant direction of water flow, and hydroperiod which includes both duration and frequency of flow (Lugo et al., 1988). Hydrologic conditions of a wetland can directly modify or change chemical and physical properties such as nutrient cycling and availability, degree of substrate anoxia, soil salinity, sediment properties, and pH levels (Mitsch and Gosselink, 1993; McBean et al., 1996). Nestler and Long (1994) noted that most significant wetland functions could be described completely or in part by hydrologic factors.

Several studies have stressed a need for an improved understanding of wetland hydrology as a critical component for supporting a variety of wetland research and management objectives (Kusler and Kentula, 1990; NRC, 1995; Hughes et al., 1998) and for developing wetland hydrologic models for vulnerability assessment (Gilvear et al., 1993). Despite of the importance placed on the influence of hydrology on wetland processes, the wetland hydrology is still not fully understood (Zmolek et al., 1997), and consequently, many of the mechanisms by which wetlands retain and process waterborne inputs are also poorly understood (Johnson, 1991). This need for fur-

ther hydrologic understanding would seem particularly acute in the Southeast US where very few studies have focused on natural riparian wetlands, despite numerous such studies elsewhere (e.g., Winter and Carr, 1980; Siegel, 1983; LaBaugh, 1986; Hollands, 1987; Siegel and Glaser, 1987; Siegel, 1988; Lide et al., 1995; Koreny et al., 1999).

Another component of wetland hydrology that clearly requires additional study is the temporal and spatial variability of evapotranspiration (ET) and its role in regulating wetland water budget. In shallow wetlands, typical of many found in southeast USA, ET is considered to be one of the principal forces regulating the wetland hydroperiodicity on a daily time scale (Ward, 1998). Even though for most wetlands ET is the major component of water loss (Souch et al., 1996), study of wetland ET has received considerably less attention than for other surfaces. There have been conflicting reports about the role of vegetation on wetland ET. While some studies have suggested that the ET from a vegetated wetland is always less than the open water evaporation (e.g., Cooley and Idso, 1980; Anderson and Idso, 1987), other studies have resulted in the opposite conclusions (Rao, 1988; Allen et al., 1992). Very few studies have considered vegetation specific ET in wetlands. One of the reasons for the lack of wetland ET quantification is the large data requirement for most of the currently available models. Although Class A pan evaporation data are widely available to estimate ET, the accuracy of this method is quite problematical (Koerselman and Beltman, 1988), particularly in a wetland environment because of the critical need for a spatially integrated correction coefficient (Kpan) (Kadlec, 1993; Zmolek et al., 1997). Therefore, there is an urgent need to quantify wetland ET related to different habitat types and to combine this information with Class A pan evaporation data to

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derive a vegetation specific evaporation pan coefficient. This information will be extremely useful in wetland restoration activities and for using natural wetlands for pollution mitigation purposes.

Consequently, the objectives of this study were to: (1) examine the temporal variability and linkages between components and processes, such as rainfall, stream inflow and outflow, groundwater flow, and ET, of a natural riparian wetland in southeast USA.; and (2) estimate vegetation specific ET for various habitats in this wetland. This study contributes to the knowledge of wetland hydrology by measuring/estimating components of a hydrologic budget and elucidating relations among the components of the hydrologic budget. The results obtained here may be broadly similar over wide scales of different wetland/littoral ecosystem components, particularly in a south temperate/subtropical region. The hydrologic budget analysis from this wetland will hopefully be of interest to the scientists working in the area of environmental and ecological modeling and assessment in wetland environments, and monitoring and analytical techniques of wetland data, especially in developing wetland hydrologic models and validating wetland models for hydrologic conditions typical of southeast USA.

2. Site Description

This study was conducted within the Talladega Wetland Ecosystem (TWE), a 15.1 ha. wetland located in Hale County, West Central Alabama, USA (Figure 1). The study site and its surrounding catchment (386 hactares) lie within the Talladega National Forest, an area dominated by mixed hardwoods and pine. The wetland was created in the late 1940s by beaver impoundments on a second-order stream, resulting in a series of ponds, anastomosing stream channels and spatially complex arrays of aquatic and semi-aquatic habitats.

The TWE lies in the Fall Line Hills of the Eastern Gulf Coastal Plain, a dissected upland with broad flat ridges separated by the occasionally deep valleys. Geologically, the study site is underlain by the Gordo Formation of the Tuscaloosa Group (Davis et al., 1975). The Gordo Formation ranges in a thickness from 90 to 110 m and includes light-gray to mottled red and gray thin-bedded to massive clay and light tan to brown sand and chert gravel. Prevalent in the lower portion of the Formation are poorly sorted coarse-grained sand and chert gravel beds. The lower 30 to 45 m of the Gordo Formation is a major aquifer for Hale County. The upper part of the Formation which underlies the Talladega Wetland consists of laminated to massive clay and lenticular beds of sands which are relatively thin and generally yield only small to moderate quantities of water (Davis et al., 1975). Therefore, whereas substantial quantities of groundwater lie at greater depths (60 to 65 m), the wetland is separated by layers with little water storage capability.

Sediments immediately below the TWE are characterized by a shallow (ca. 20 cm) upper layer of permeable organic and inorganic materials that overlie a much less permeable clay and sand (Dobson, 1995). This structure greatly reduces

connectivity between porous saturated surface sediments and the regional water table. Thus, the TWE lacks the water level damping effect of direct connection with a regional intergranular flow aquifer.
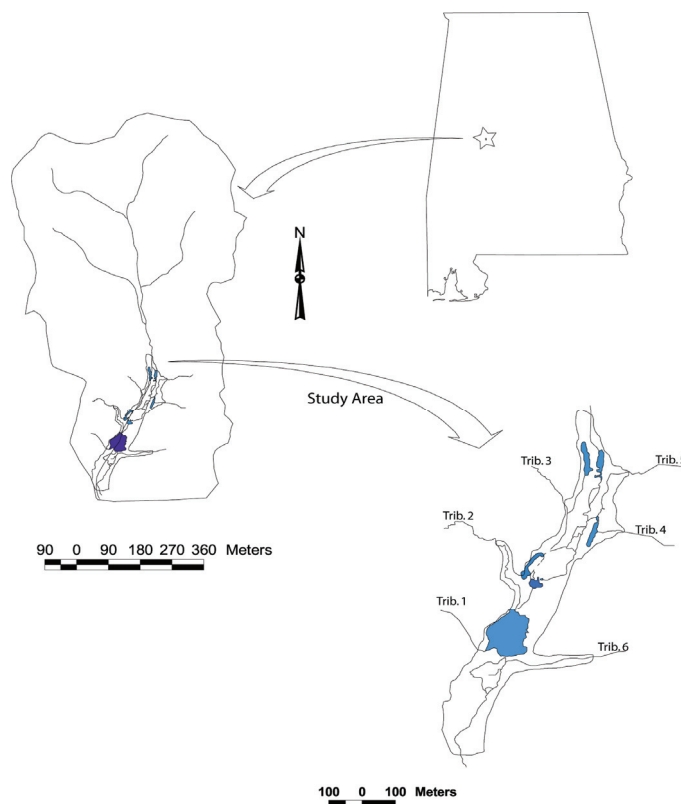

Figure 1. Location of the Talladega wetland ecosystem in Alabama.

Vegetation in the TWE has been mapped using the aerial photographs and ground surveys. The spatial distribution of the vegetation pattern within the TWE appears to be related to the inundation patterns. The TWE and its surrounding catchment have five areas that differ in dominant vegetation. In sequence from un-inundated to complete inundation these vegetation types are: upland forests with large, mature deciduous trees; upland forests with mixed coniferous-deciduous trees; within the wetland mixed alder (*Alnus serrulata*) and willow (*Salix* ssp.), inundated mostly in winter and spring, but with moist soils into mid summer; meadows of the common rush (*Juncus effusus*) which are inundated much of the year; six permanent open water ponds of variable sizes imbedded within alder/*Juncus* stands. The largest of these was a shallow ($z = 0.2$ m) 1.4 ha. pond dominated by the lily *Nymphaea odorata* and the *J. effusus*, in which small changes in water elevation resulted in relatively large changes in inundated area (Ward, 1998).

Since 1992 the TWE has been the site of an interdisciplinary research effort to evaluate wetlands as land-water interfaces with emphasis on carbon flux patterns, quantification of

the material flow through the system, and quantification of the mechanisms important to the material retention and biological productivity (e.g., Stanley and Ward, 1997; Benke et al., 1999; Wetzel and Howe, 1999; Kuehn et al., 2000; Mann and Wetzel, 2000a,b; Stanley et al., 2003).

3. Methods

Collections of meteorological data and discharge into the TWE have been continuous since 1993. The results presented here are based on data collected in 1994 and 1995. Figure 2 shows the instrumentation sites used to measure/estimate the components of the wetland hydrologic budget. The wetland water budget was quantified as follows:

$$\frac{dV}{dt} = P_n + S_i + G_i - S_o - G_o - ET \qquad (1)$$

where V = volume of water storage in wetland, t = time; P_n = net rainfall (defined as total rainfall – interception losses); S_i = surface inflow including flooding streams; G_i = groundwater inflow; S_o = surface outflow; G_o = groundwater outflow; ET = evapotranspiration.
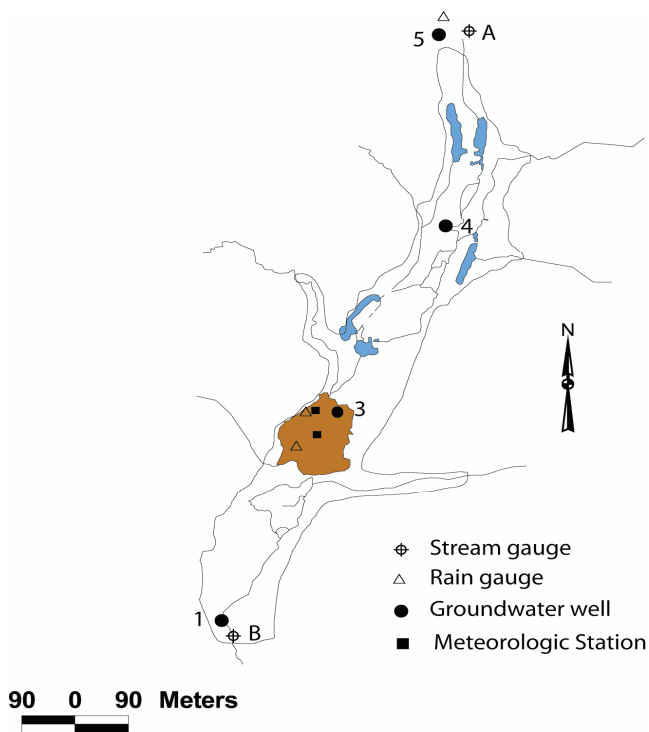

Figure 2. Location of hydrologic and meteorological instrumentation sites within the Talladega Wetland Ecosystem (gold and blue areas represent permanent water ponds).

Rainfall was measured at 5-minute intervals by using six tipping bucket rain gauges. Two gauges were installed in open areas to obtain the total rainfall, while four rain gauges were installed beneath vegetation canopy to measure throughfall. Total rainfall and throughfall were estimated by calculating the arithmetic means of the rainfall values at these sites. Interception was estimated as a difference between total rainfall and throughfall.

Continuous measures of stage through the channel network were obtained using pressure transducers (PS-9104, 0-5 psi, Instrumentation Northwest, Inc.) and dataloggers (CR10X, Campbell Scientific, Inc.) recording data at 5-minute intervals. At each gauge a stage-discharge relation was developed using measured stage, stream cross sectional area, and stream velocity. Continuous estimates of the inflow and outflow of water through the channel network were estimated using the stage-discharge relationships. To maintain accurate stage-discharge relationships, an instantaneous flow was measured weekly (or biweekly) and the relations were updated as necessary. While only two of the seven tributaries to TWE were continuously gauged, we also estimated continuous discharges at the five ungauged sites. To do so, we developed a statistical relation between instantaneous discharge at each of the remaining five sites and that at the continuously gauged main channel site. Data from this relation was obtained through approximately weekly to biweekly measurements of instantaneous discharge at all sites from 1993-1995. A significant correlation ($p < 0.05$) was found between the seasonally averaged flow values in small tributaries and those in the main channel. Total stream inflow was calculated as the sum of all tributary and main channel flows, as measured at stream gauge A (Figure 2).

Base flow was separated from total flow by using the approach outlined by Kim and Hawkins (1993) to get storm runoff. This methodology separated base flow using a gradient technique to determine storm runoff from storm hydrographs. In this technique, a straight line departed the rising limb of the hydrograph and divided the flow into its base flow and storm runoff components.

Groundwater flow was estimated using the data obtained from a network of wells at four sites (Sites 1, 3, 4, and 5 in Figure 2). At each site, water elevation data from two depths were available, 1.5 m and 6.1 m. Water levels were monitored at weekly or more frequent intervals. In a separate study designed to quantify subsurface hydrology and sediment characteristics of the TWE, Mann and Wetzel (2000a,b) measured the hydraulic conductivity, the sediment organic matter, and the bulk density from 56 sediment cores. They also measured groundwater flow using data from 22 nested piezometers and their measured sediment hydraulic properties. We used these data in conjunction with the groundwater well elevation data to estimate groundwater flow rates using Darcy's Law.

Meteorological data were collected through using two instrumentated stations shown in Table 1. The air temperature, relative humidity (Vaisala HMP45AC relative humidity and temperature probe, CSI), wind speed and direction (03001 RM Young wind sentry wind set, CSI), and water/sediment temperatures were measured at a one-minute interval and the average values were recorded at a five-minute interval. Evaporation data were collected using a Class A evaporation pan.

Table 1. Mean Monthly Meteorologic Data for the Talladega Wetland Ecosystem

	Tmax[1] (°C)	Tmin (°C)	Tavg (°C)	RH(avg) (%)	RS (WM^{-2}d^{-1})	Wind Speed (m·s^{-1})	Rainfall (mm)
1994							
January	21.0	-11.3	4.3	77.1	8.02	0.69	158
February	24.6	- 9.4	9.1	79.3	10.42	0.66	113
March	27.3	- 2.3	11.9	77.4	14.16	0.76	194
April	30.3	- 1.7	17.5	79.3	18.71	0.66	60
May	29.6	7.3	19.0	81.7	20.41	0.50	61
June	32.9	15.8	24.0	89.1	17.40	0.47	124
July	32.3	14.3	23.9	91.1	16.87	0.37	89
August	33.0	15.6	23.7	90.2	17.40	0.33	147
September	30.6	7.4	20.7	90.1	16.66	0.37	143
October	28.9	1.8	16.7	91.7	9.81	0.49	120
November	25.1	- 2.2	13.3	84.7	9.84	0.53	56
December	20.7	- 3.3	9.0	89.6	7.62	0.48	102
1995							
January	22.9	-6.5	6.6	82.1	7.89	0.65	81
February	24.7	-9.6	8.2	78.9	11.02	0.69	189
March	31.4	-2.3	13.6	77.3	11.55	0.72	89
April	28.9	0.4	16.4	79.4	17.56	0.62	191
May	31.4	5.7	21.2	86.0	19.62	0.59	118
June	33.6	8.7	22.5	85.6	20.44	0.41	35
July	35.0	17.4	25.3	87.3	20.18	0.42	70
August	36.3	19.5	26.5	87.4	18.68	0.56	135
September	33.9	11.2	21.5	84.5	15.04	0.43	53
October	29.3	0.1	15.7	88.5	12.23	0.47	226
November	23.1	-3.6	8.6	87.4	8.29	0.54	148
December	21.4	-9.0	7.5	81.9	8.35	0.69	98

[1] Tmax = maximum air temperature, Tmin = minimum air temperature, Tavg = average air temperature, RH = relative humidity, RS = solar radiation.

The aerodynamic and the energy balance based Penman-Monteith (PM) method was used to quantify the wetland ET. This method is most accurate when used to estimate hourly and daily wetland ET (Hughes et al., 2001). Results reported by Jensen et al. (1990) demonstrate that even when monthly-averaged weather data are used, the Penman-Monteith model is the most accurate of the 20 different ET models evaluated. It is a widely used physically-based model that incorporates the effects of vegetation on the ET regime (Jensen et al., 1990; Sala et al., 1996; Souch et al., 1996). The ET equation is represented as

$$\lambda E_t = \frac{\{\Delta[R_n - G] + \rho C_p [e_s - e_a]/r_a\}}{\{\Delta + \gamma[r_c + r_a]/r_a\}} \quad (2)$$

where λ = latent heat of vaporization, E_t = the ET by the PM method, Δ = slope of the saturation vapor pressure-temperature function, R_n = net radiation, G = vertical heat exchange with the soil, ρ = air density, C_p = specific heat of air at a constant pressure, e_s = saturated vapor pressure of air measured at height z, and e_a = actual vapor pressure of air measured at height z, r_a = aerodynamic resistance to water vapor diffusion into the atmospheric boundary layer, r_c = vegetation's canopy resistance to water vapor transfer, and γ = psychrometric constant.

The key parameters in determining ET are air temperature (°C), relative humidity (%), net radiation ($MJ·m^{-2}·d^{-1}$), canopy resistance ($s·m^{-1}$), and aerodynamic resistance ($s·m^{-1}$). Neglecting energy storage, the net radiation, R_n, can be represented as (Jensen et al., 1990)

$$R_n = (1-\alpha)R_s \downarrow - R_b \uparrow \quad (3)$$

where α = vegetation albedo, defined as the fraction of short wave radiation reflected at the surface, $R_s\downarrow$ = incoming short wave radiation, and $R_b\uparrow$ = net outgoing long wave radiation.

Albedos for open water, meadow/*Juncus*, brush, deciduous forest, and mixed coniferous forest used were 0.05, 0.23, 0.23, 0.13, and 0.13, respectively. Incoming short wave radiation measured at a nearby site located less than 100 km from the TWE was used. Net outgoing long wave radiation was estimated using the method outlined by Jensen et al. (1990).

The aerodynamic resistance, r_a, is estimated by using (Jensen et al., 1990)

$$r_a = \frac{\left\{\ln\left[(z_p - d)/z_{ov}\right]\ln\left[(z_w - d)/z_{om}\right]\right\}}{(0.41)^2 u_z} \tag{4}$$

where z_w = height of the wind speed measurement, z_p = height of the humidity and temperature measurements, d = displacement height, u_z = wind speed at height z_w, z_{ov} = roughness length for vapor transfer, z_{om} = roughness length for the momentum transfer. Typical values reported for r_a are 5 to 10 s·m^{-1} for mixed forest (Munro, 1986), 5 to 8 s·m^{-1} for Douglas fir (McNaughton and Black, 1973), 5 to 40 s·m^{-1} for pine in the southeastern U.S. (Murphy et al., 1981), 50 to 60 s·m^{-1} for deciduous forest (Verma et al., 1986), and 10 to 45 s·m^{-1} for oak-hickory (Baldocchi et al., 1985).

The vegetation specific parameter required to estimate ET is the canopy resistance, r_c. This parameter is fundamentally unique to the vegetation type and, in the absence of a measured value, can be estimated as (Jensen et al., 1990):

$$r_c = \frac{100}{0.5 LAI} \tag{5}$$

where LAI = leaf area index. The leaf area index can be estimated by

$$LAI = 1.5\ln(h_c) - 1.4 \tag{6}$$

where h_c = height of canopy. The values of r_c used were 5, 33, 125 and 200 $s·m^{-1}$ for meadow/*Juncus*, brush, deciduous forest, and mixed coniferous forest, respectively. The values of r_c reported in the literatures range from 20 to 50 $s·m^{-1}$ in morning hours and 100 to 150 $s·m^{-1}$ in afternoon hours (Murphy et al., 1981; Baldocchi et al., 1985; Verma et al., 1986). Hughes et al. (2001) recommended the r_c value of 5 $s·m^{-1}$ for estimating ET from the salt marshes. The wetland vegetation r_c used in this study were the same as the values recommended by Hughes et al. (2001).

In this study, the roughness lengths for vapor and momentum transfer and the displacement length were determined as a function of the height of vegetation using the following approximations (Brusaert, 1982; Stull, 1988)

$$z_{om} = 0.123 h_c$$

$$z_{ov} = 0.0123 h_c \tag{7}$$

$$d = 0.667 h_c$$

The vapor pressure deficit ($e_s - e_a$) was determined from the measured air temperature and relative humidity and the method described by Jensen et al. (1990).

The ET calculated using the Penman-Monteith equation typically does not account for evaporation of the intercepted rainfall. The interception values were combined with the Penman-Monteith ET to calculate the total ET for the wetland.

4. Results and Discussions

4.1. Temperature and Precipitation

The temperature patterns derived from an on-site meteorological station are typical for those of a southeastern US wetland ecosystem (Table 1). Summers are warm and humid while winters are short and mild. The mean monthly air temperatures are maximal from June to August (22 to 26 °C) and lowest in January (4 to 6 °C). The maximum air temperature occurs in August (33 to 36 °C) with the winter minimum near -10 °C. The mean annual air temperature for the 2-year study period was 16.1 °C.

Annual rainfall at the study site for 1994 and 1995 was 1367 and 1433 mm, respectively (Table 2), which was slightly above the long-term mean of 1320 mm (Moore and Richter, 1986). Rainfall pattern for the TWE for the two years of study period is shown in Figure 3. Rainfall values, observed at two sites within the basin anually, were not significantly different. As is typical for this geographic location, there were no strong seasonal patterns in precipitation. When strong seasonal differences do occur they are largely due to the interannual variability during summer months. In some years summer precipitation can be rather high as in 1994, but summer droughts are not uncommon. Summer precipitation is largely convectional, while winter precipitation is frontal.

4.2. Surface Flow

The total inflows to the wetland were 312 and 418 mm for 1994 and 1995. Surface water input to TWE was primarily through the seven inflowing streams (Figure 1). Three streams were intermittent (tributaries 2, 4, and 5 in Figure 1 were dry during summer) while four tributaries were permanent. Of these, one stream carried from 67 to 77% of the combined tributary inflow to the wetland (stream gauge A in Figure 2). Downstream of the largest wetland pond, the surface water outflow was concentrated in a single channel.

Despite the lack of strong seasonal variations in precipitation, there was a strong seasonal signal to both wetland inflow and outflow. A hydrograph of wetland outflow, measured at the stream gauge B (Figure 2), for the two years of study is shown in Figure 3. Inflow and outflow hydrographs were very similar, thus only the outflow is illustrated. Winter base flow from the primary inflowing stream (0.03 $m^3·s^{-1}$; late October to March) was always higher than in summer (0.008 $m^3·s^{-1}$). A similar, but more exaggerated range was seen at the outflow stream. The mean daily wetland outflow was 0.046 $m^3·s^{-1}$ and ranged from 0 to 1.35 $m^3·s^{-1}$. During both years of study, there
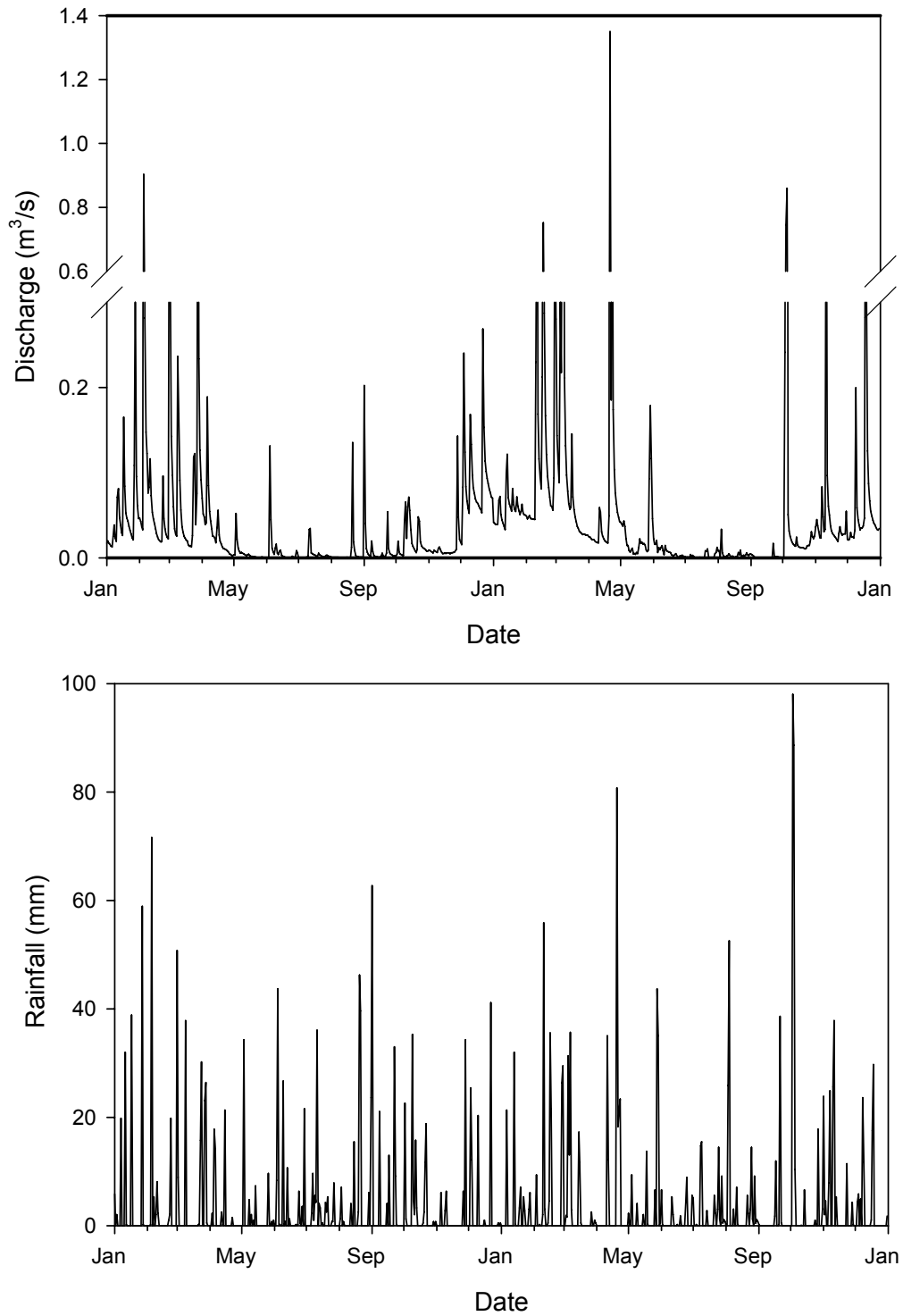
Figure 3. Wetland surface discharge and rainfall pattern for the Talladega Wetland Ecosystem for 1994 and 1995.

Table 2. Monthly Water Budget for the Wetland

Month	Rainfall (mm)	Throughfall (mm)	Inflow (mm)	Outflow (mm)	PM ET[1] (mm)	Total ET[2] (mm)	Groundwater (mm)	Storage (mm)
1994								
Jan.	158	139	33.9	37.3	27.1	46.4	25.5	63.4
Feb.	113	91	45.1	56	36.6	58.8	21.6	-0.5
March	194	164	56.9	73.1	51.5	81.1	23.0	44.1
April	60	53	26.1	21.8	72.6	80.1	21.7	-45.0
May	61	52	11.6	3.5	81.6	90.9	23.3	-54.4
June	124	98	18.1	6.3	75.4	101.2	25.0	-16.2
July	89	73	9.7	2.8	75.8	92.2	25.9	-38.6
Aug.	147	111	9.9	4.4	80.4	116.7	24.8	-25.3
Sept.	143	125	14.8	9.1	67.3	85.2	23.8	21.8
Oct.	120	101	19.7	14.4	38.3	56.9	25.1	24.7
Nov.	56	49	15.3	9	40.0	46.6	23.1	-14.0
Dec.	102	95	50.9	63.2	24.6	31.6	22.9	28.2
Total	1367	1150	312	301	671	888	286	-11.8
1995								
Jan.	81	75	32.7	39.5	27.9	33.9	28.0	6.3
Feb.	189	165	74.1	97.1	31.6	55.6	25.3	61.1
March	89	76	68.6	80.6	53.2	66.2	28.3	-30.5
April	191	167	55.9	69.7	65.9	89.9	27.2	36.1
May	118	105	22.7	19.8	80.0	93.0	27.8	-12.9
June	35	28	13.1	5	87.3	94.3	30.1	-88.3
July	70	55	7.4	1.6	99.1	114.1	31.8	-85.1
Aug.	135	113	9	2.9	94.7	116.7	30.1	-27.7
Sept.	53	46	7.6	0.9	74.1	81.1	29.3	-57.7
Oct.	226	195	39.9	52	48.1	79.1	30.8	73.0
Nov.	148	125	42.7	36.2	27.4	50.4	28.4	52.7
Dec.	98	91	44.7	47.2	12.3	19.3	28.1	41.1
Total	1433	1241	418	453	702	894	345	-32.0

[1]ET estimated using measured meteorologic data and Penman-Monteith equation
[2]Total ET = PM ET + Interception Losses

was intermittent loss of all wetland surface outflows from June through October. Periods of zero surface outflows were broken by runoff after storm events, but would reappear unless sustained precipitation occurred.

Base flow was separated from stream flow to calculate surface runoff volume. For most rainfall events, runoff occurred for a less than one day. The response factor, defined as the ratio of monthly runoff volume to rainfall, can be used as an indicator of hydrologic response characteristics of a watershed. An alteration in watershed hydrologic condition results in an altered response factor. For example, a change in land use conditions usually results in a change in the total volume of runoff generated from a given rainfall event. The response factor for the TWE is shown in Figure 4. For the two years of results presented here, it ranged from 0.02 to 0.31 in 1994 and from 0.01 to 0.21 in 1995. Smaller response factors were ob-

served for the summer months when the propensity for infiltration losses was higher. Thus, during periods when the wetland outflow was very low, it was not unusual to observe that runoff from modest storm events did not increase surface water output. On a yearly basis, the runoff volume was only 9% of the rainfall volume. This was similar to the only other response factor reported in literature by Fujieda et al. (1997) for a riparian wetland in Brazil. In a three-year monitoring study, the response factor was found to range from 0.11 to 0.18. Fujieda et al. (1997) also reported the mean runoff volume to range from 4.8% of rainfall in the dry season to 9.7% of rainfall in the wet season.

4.3. Groundwater Flow

The position of the water table during the study period as

indicated by weekly measurements from four groundwater wells to 1.5 m depth is shown in Figure 5. Well 1 was located near the outlet and Well 5 was located at the upstream end of the wetland. The wetland ground surface was always higher than the water level indicated by the groundwater wells. The piezometric surface was highest in well 5 (upstream) and lowest in well 1 (downstream) indicating that flow of groundwater was in the general direction of surface water flow in the wetland. Maximum variability in the groundwater elevation occurred near the outlet of the wetland as indicated by Well 1. The groundwater levels at all other wells were fairly stable. Groundwater elevation in these wells was consistently higher than groundwater elevations in the four 6.1 m wells, indicating the general direction of water movement in the ground was downward.

Figure 5. Groundwater table position for 1.5 m wells during TWE in 1994 and 1995 (see Figure 2 for specific locations of wells).

4.4. Evapotranspiration

The evapotranspiration (ET) for each vegetation type was estimated separately and the values were spatially-averaged to calculate overall wetland ET. Canopy-intercepted rainfall that does not reach the ground as stem-flow evaporates back to the atmosphere was calculated and included in total ET estimates. The interception losses were added to the ET estimated by the PM method to obtain total wetland ET. Figure 6 shows the averages for the vegetation-specific ET and pan evaporation data for the TWE. Differences in the vegetation structures resulted in significantly different ET. The wetland ET was calculated as the area-weighted mean of the vegetation-specific ET.

The temporal trends of ET estimated by the PM model and Class A pan evaporation data are shown in Figure 7. Both pan evaporation and ET were highest between May and August when the altitude of the sun is high, and were lowest between November and January when days are shorter. ET in the wetland follows the same pattern as the pan evaporation, but is less than for all months except January 1994, February 1994, and November 1995. Pan data and wetland ET are highly correlated ($r = 0.87$, $p < 0.05$) for the two years of data analyzed here. For the two years of study, the area-weighted average ET in the TWE ranged from 0.61 (December, 1995) to 3.7 $mm \cdot d^{-1}$ (August, 1994, 1995). The ET for freshwater wetlands in southeastern U.S.A. has been reported to range from 0.5 to 10.1 $mm \cdot d^{-1}$ (Dolan et al., 1984; Abtew, 1996). The ET for the TWE was within the range reported by these studies.

In many wetland hydrologic studies, pan data have been used to estimate wetland ET, in the absence of detailed micro-meteorologic data. Under such a condition, pan data could

Figure 4. Hydrologic response factor for TWE (Solid line represents 1:1 response factor).

The monthly groundwater flow from the wetland ranged from 21 to 32 mm for two years of study (Table 2), with the annual groundwater flow accounting for 20% of total wetland outflow. The monthly losses were fairly constant throughout the year, with no apparent relationship with either rainfall or stream flow. This was likely due to the presence of a thick clay layer beneath the wetland sediments that restricted movement of groundwater, acting as an effective aquiclude. Such a structure is evident from the descriptions of the subsurface environment by Dobson (1995). Thus, groundwater exchange in TWE must be primarily lateral rather than vertical. However, in a study of groundwater movement in one area of TWE (the large pond, see Figure 2), Mann and Wetzel (2000b) indicated that shallow groundwater movement was very slow and very transient. Carey et al. (1997), using the measured sediment characteristics at TWE and a groundwater model, reached a similar prediction result in terms of the groundwater recharge. They predicted groundwater flow to account for 26% of total flow budget of the wetland. Further measurement of groundwater movement and exchange in the TWE is a high priority for future research.
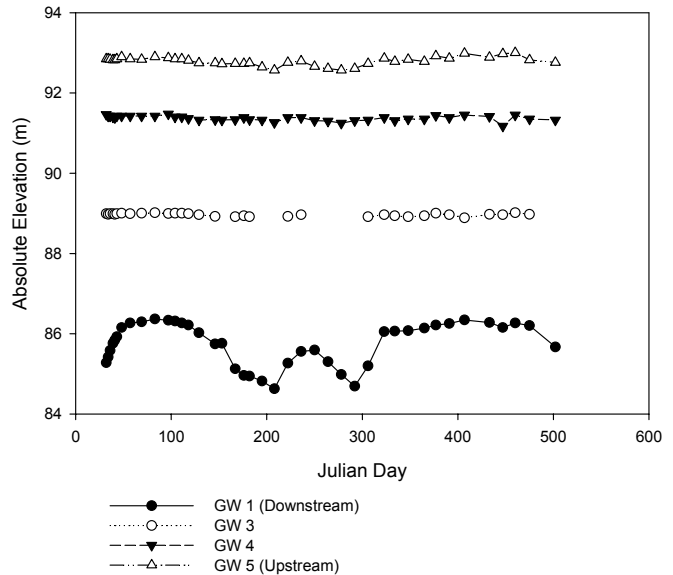
be multiplied by a coefficient, known as wetland coefficient or pan coefficient to obtain the wetland ET as follows (Ruston, 1996):

$$ET_{wetland} = K_{pan} \times \text{Pan Evaporation} \tag{8}$$

where K_{pan} is the Pan coefficient. A wide range of K_{pan} values has been suggested. Kadlec (1993) recommends a K_{pan} value of 0.80 for the wetlands in spring, summer, and fall, whereas the others have suggested different values ranging from 0.67 (Dolan et al., 1984) to 1.7 (Koerselman and Beltman, 1988). On a monthly scale, the coefficient for TWE ranged from 0.4 (July, 1995) to 2.3 (January, 1995). The unusually high value of K_{pan} in January 1995 may due to formation of an ice-sheet on the upper portion of the pan water. This may have prevented any significant evaporation from the pan. If we reject this single data point as an outlier, the maximum K_{pan} for the two year data set is 1.4 (November, 1995), a value well within range suggested by other researchers. However, a coefficient larger than 1 occurred during only 3 months in the two-year study period, all in winter months. In general, it is recognized that this average coefficient does not accurately estimate the wetland ET during winter months due to dormant vegetation (Ruston, 1996). The average K_{pan} for the two years of study was 0.70, indicating that on an annual-scale ET from the TWE was less than the open water evaporation. The average K_{pan} should only be used to quantify wetland ET in the absence of any other better estimate.
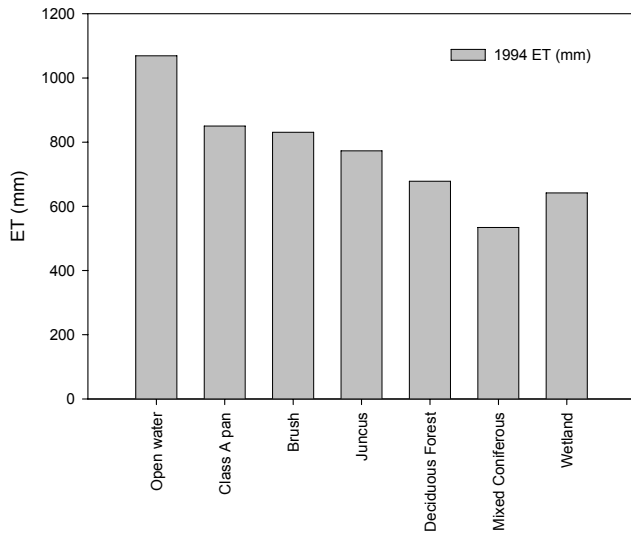

Figure 6. Vegetation specific ET in TWE in 1994 as estimated using Penman-Monteith equation.

4.5. Wetland Water Budget

Calculations of wetland water budgets have historically been problematic because often ground water flow and evapotranspiration are estimated rather than directly measured, resulting in budgets with unknown uncertainties associated with

these components. In this regard, the present study has benefited from available data at four sets of groundwater wells, in which each set had wells drilled to 1.5 and 6.1 m. Thus, we could produce direct calculations of the direction and potential magnitude of groundwater flux. Budget calculations were also made easier because the aquiclude at TWE simplified the groundwater flux issue. In addition, we have developed estimates for evapotransiration based on empirical calculations and direct measurements of vegetative and micrometeorological variables. While not as desirable as direct measurements, such calculations do provide an objective measure of ET and provide information on spatial variability. Therefore, we did not rely on the residuals of the budget calculations to predict either evapotranspiration or groundwater flux. This budget did, however, use budget residuals to obtain values for hydrologic storage.
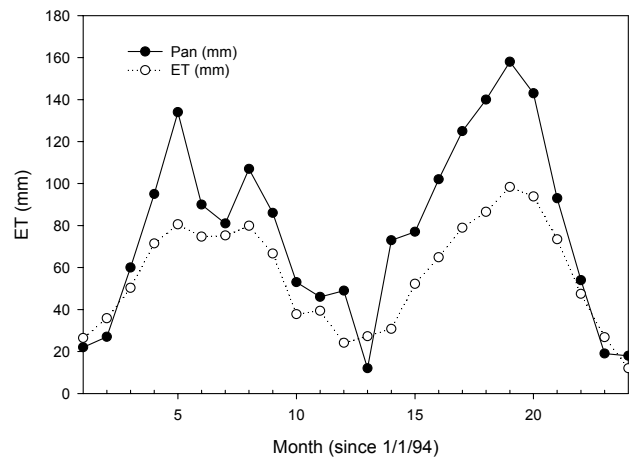

Figure 7. Temporal trend of ET and Class A Pan Evaporation data in TWE, 1994-1995.

The water budget for the TWE is shown in Table 2. Rainfall, in the form of throughfall, was the dominant inflow to the wetland, accounting for 79% and 95% of total inflow for 1994 and 1995, respectively. On average, 15% of total rainfall was intercepted by vegetation canopy and contributed to total ET losses from the wetland. ET was the principal outflow pathway from the wetland representing 60%, and 53%, of total outflows for 1994 and 1995, respectively.

Direct stream discharge occurred throughout the year from the wetland and was very similar to stream inflow into wetland on an annual scale. During the drier of the two study years (1994) outflow was only very slightly less than inflow (301 mm vs 312 mm). However, in the wetter of the two study years (1995) outflow was approximately 8% greater than inflow. Seasonally, however, there were substantial differences between total inflow and outflow. During April to September, the combination of high evaporative demand, infiltration into soil, and refilling of surface water storage areas led to a consistent pattern in which surface water outflow from the wetland was less than inflow for the period April through September (Table 2).

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An examination of the annual water budgets indicated that very little change in water storage occurred in the wetland during the two-year study. However, the change in storage within the wetland can be significant on a monthly time scale (Table 2). There were substantial declines in the storage from April-May to September of both 1994 and 1995. Presumably, it was runoff and ET which reduced soil and surface water storage. At a monthly time-step, there was a positive relationship between throughfall and storage ($r^2 = 0.706$, $F = 53.0$), generally indicating that the throughfall > 100 mm/month was required to maintain a constant storage. The variability in this relationship was introduced as a result of antecedent conditions. For example, a high precipitation in summer after one month or two of low rainfall did not result in increased storage.
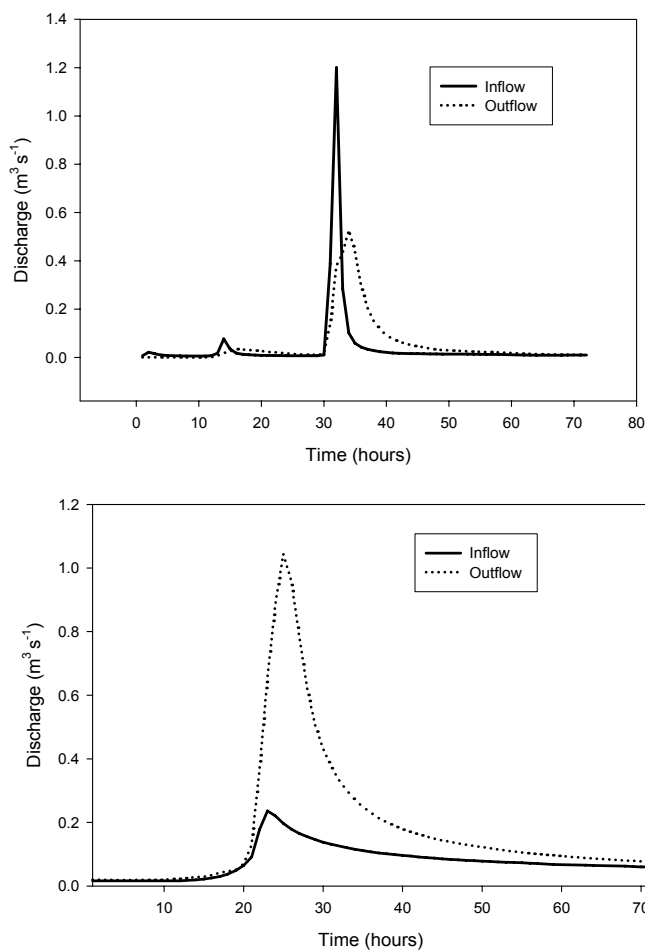

Figure 8. Inflow and outflow hydrographs for two storm flow events during 1994.

On shorter timescales natural wetlands may be considered to be hydrologic buffers by storing runoff during high rainfall events and attenuating downstream flow. The TWE did not always act as a hydrologic buffer due to its shallow nature. Figure 8 shows inflow and outflow hydrographs during two separate storm events. In the first event, the wetland peak outflow rate was significantly less than the peak inflow rate and the time to peak is also delayed in the outflow. Thus the wetland acts as a hydrologic buffer. However, during the second event, the inflow and outflow hydrographs were reversed and the wetland accelerated the downstream flooding. The TWE was created by a beaver dam and the outflow hydrograph was controlled by dam height. During larger rainfall events, when the depth of surface water exceeded the dam height, peak outflow exceeded peak inflow rates as indicated in Figure 8. This shows that shallow natural wetlands do not always attenuate flooding.

5. Summary and Conclusions

Hydrologic behavior of a small natural riparian wetland was characterized using data obtained for calendar years 1994 and 1995. The following conclusions are supported by the results of this study.

1. The rainfall (1367 and 1433 mm) and evapotranspiration (869 and 885 mm) were the dominant inflow and outflow components, respectively.

2. The groundwater flow (286 and 345 mm) accounted for approximately 20% of the total outflow. On an annual scale, very little change in water storage occurred in the wetland.

3. A significant difference in vegetation specific ET was observed across the wetland. Arranged from high to low; open water > brush > *Juncus* > deciduous > mixed coniferous. The ET in this study was found to be within the range reported in other wetland studies with similar climate conditions. An estimate of spatially-averaged annual wetland ET was approximately 70% of that obtained from Class A Pan evaporation.

4. Because of the shallow nature of the wetland, it did not always act like a hydrologic buffer and did not always attenuate flooding. Flood attenuation was more likely to occur during summer than winter.

The results obtained from this study should be applicable to other natural riparian wetlands in temperate/subtropical regions. As the usage of natural and constructed wetlands to mitigate pollution is increasing, the results should be useful in developing wetland hydrologic models, and in validating/improving existing models.

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