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A conceptual hydrologic model for a forested Carolina bay depressional wetland on the Coastal Plain of South Carolina, USA

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Abstract:

This paper describes how climate influences the hydrology of an ephemeral depressional wetland. Surface water and groundwater elevation data were collected for 7 years in a Coastal Plain watershed in South Carolina USA containing depressional wetlands, known as Carolina bays. Rainfall and temperature data were compared with water-table well and piezometer data in and around one wetland. Using these data a conceptual model was created that describes the hydrology of the system under wet, dry, and drought conditions. The data suggest this wetland operates as a focal point for groundwater recharge under most climate conditions. During years of below-normal to normal rainfall the hydraulic gradient indicated the potential for groundwater recharge from the depression, whereas during years of above-normal rainfall, the hydraulic gradient between the adjacent upland, the wetland margin, and the wetland centre showed the potential for groundwater discharge into the wetland. Using high-resolution water-level measurements, this groundwater discharge condition was found to hold true even during individual rainfall events, especially under wet antecedent soil conditions. The dynamic nature of the hydrology in this Carolina bay clearly indicates it is not an isolated system as previously believed, and our groundwater data expand upon previous hydrologic investigations at similar sites which do not account for the role of groundwater in estimating the water budget of such systems. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS Carolina bay; depressional wetland; surface water-groundwater interaction

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INTRODUCTION

Thousands of depressional wetlands exist along the Atlantic Coastal Plain of the USA. One type is the Carolina bay, named by Glenn (1895) because of the common presence of bay tree species in and adjacent to these wetlands. Carolina bays often are elliptical in shape and oriented in a north-west–south-east direction, and have a sand rim on the south-east boundary of the depression (Kaczorowski, 1977; 2007). Carolina bays and depressional wetland environments of similar geomorphology are located from New Jersey to northern Florida (Melton and Schriever, 1933; Prouty, 1952; Rasmussen, 1958; Lide *et al*., 1995). The majority is found from southern North Carolina to northern Georgia, and the formation is a function of prevailing wind direction during drier climate periods (Kaczorowski, 1977; 2007). Carolina bays range in size from less than one hectare to 10^3 ha. Richardson and Gibbons (1993) estimated that 10 000 to 20 000 bays exist along the Atlantic Coastal Plain, whereas Prouty (1952) claimed 500 000 bays exist. Some differences in estimates made over the past 40 years may be due to the fact that an estimated 97% of Carolina bays in South Carolina have been converted to other land uses, such as agricultural and industrial (Bennett and Nelson, 1991; Sharitz and Gresham, 1998).

Several hypotheses on the origin of these wetland systems have been suggested over the years as to how the shallow depressions and distinct orientation of the bays have arisen, such as coastal processes like giant sand ripples (Glenn, 1895), and solution or subsidence processes (Toumey, 1848; Smith, 1931; Johnson, 1936; LeGrand, 1953; Rasmussen, 1958). The most commonly cited explanation is that Carolina bays formed in shallow water bodies and were elongated by strong winds from the south-west and/or north-east, which created wave currents and left sand rims along the south-eastern sides of the bays and thus oriented the depressions in a north-west–south-east fashion (Thom, 1970; Bliley and Pettry, 1979; Gamble *et al*., 1977; Pettry *et al*., 1979; Ivester *et al*., 2001; Ivester and Leigh, 2003; Kaczorowski, 2007). Their location therefore appears to be a function of the location of ancestral lakes and there does not appear to be a relationship of location

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to distance from the modern coastline (Kaczorowski, 2007).

Carolina bays have important ecological functions including surface water storage, wildlife habitat, biodiversity conservation, nutrient cycling, carbon sequestration, and as a sink for other chemicals (Lugo *et al.*, 1990; US Environmental Protection Agency, 1993; Sharitz and Gresham, 1998; Whigham and Jordan, 2003). Each of these functions is considered to be dependent on climatological and hydrological processes, the variability of which is poorly understood. For example, Carolina bay hydroperiods fluctuate greatly and are not definable. Previous studies have found that precipitation (P) and evapotranspiration (ET) serve as the major input and output, respectively, in the hydrologic balance of Carolina bays (Schalles and Shure, 1989; Lide *et al.*, 1995; Sharitz, 2003; Pyzoha, 2003). Because Carolina bays are developed on low gradient coastal plains and are not adjacent to large stream networks, it is often assumed that they are 'isolated' hydrologically from the regional surface water drainage system.

Previous studies that focus on the hydrological processes of Carolina bays are limited. Groundwater was found to be important in some cases, as evidenced by artesian wells within Carolina bays (Wells and Boyce, 1953; Wharton, 1978). Surface water runoff into these wetlands was found to be minimal (Schalles and Shure, 1989) or nonexistent (Lide *et al.*, 1995) and, when present, is the result of land alteration, such as ditching and drainage in preparation for agriculture (Sharitz, 2003). Schalles and Shure (1989) first suggested the importance of groundwater and surface water interaction processes in this type of depressional wetland. They suggested the dilute chemistry of surface water in Thunder Bay, a Carolina bay located at the Savannah River Site in south-western South Carolina, was due to a subsurface hydrologic exchange that occurred, thus resulting in a long-term chemical equilibrium. A more detailed hydrologic study (Lide *et al.*, 1995) on the same bay concluded that changes in pond stage could not be explained completely by P and ET dynamics, and because surface inputs and outputs were nonexistent, net groundwater movements into and out of the bay were likely important. The difference in water table elevation relative to pond elevation strongly suggested a groundwater interaction (Lide *et al.*, 1995). Schalles and Shure (1989) inferred this subsurface water interaction to be in a lateral, not vertical, direction due to the relatively low permeability of the clay soils beneath the wetland. A related study conducted by Newman and Schalles (1990) on the water chemistry of 49 Carolina bays, specifically Ca^{2+}, Mg^{2+}, dissolved organic carbon (DOC), and silica concentrations in wetland water, rainwater, and groundwater, and their data suggested shallow subsurface water beneath Carolina bays has a strong influence on the wetland water chemistry. More recently, Pyzoha (2003) and Sun *et al.* (2006) argued that temporal fluctuations of P and ET can affect surface water–groundwater interactions in these wetlands, and during periods when P exceeds ET, Carolina bays allowed water to flow through the depression, possibly due to the subsurface topography at the site. Hydrologic studies on similar depressional wetlands such as cypress swamps on flatwoods landscapes in northern Florida suggested wetland surface water is tightly coupled with the shallow groundwater system in the watershed (Crownover *et al.*, 1995; Sun *et al.*, 2000; Bliss and Comerford, 2002). However, it is not known if similar hydrologic processes exist in Carolina bays.

This study examined the role of groundwater processes within and adjacent to Chapel Bay, a small forested, clay-based Carolina bay on the Middle Coastal Plain of south-western South Carolina, USA (Figure 1). The objectives were to: (1) determine groundwater flow directions by examining groundwater and surface water fluctuations beneath and within the wetland and its adjacent upland areas; and (2) develop a conceptual model that describes the hydrological processes in this depressional wetland system as a function of climate condition.

METHODS

Site characteristics

The landscape of the study area is characterized by upland broad flats dissected with dendritic drainage systems that are interspersed with depressional wetlands (forested or meadow Carolina bays). The overall land use at the field site for this study was a short-rotation hardwood plantation owned by MeadWestvaco located in Bamberg County, South Carolina on the Middle Coastal Plain of the south-eastern USA. We focused on one wetland at the site, Chapel Bay (Figure 1).

Chapel Bay is of area 8·0 ha (0·08 km^2). The lowest elevation within Chapel Bay is 2–2·5 m below the surrounding upland landscape. This wetland contains mostly bottomland hardwood trees including water oak (*Quercus nigra*), willow oak (*Quercus phellos*), black cherry (*Prunus serotina*), swamp tupelo (*Nyssa biflora*), sweetgum (*Liquidambar styraciflua*), and some pond cypress (*Taxodium ascendens*) at the centre. There are also loblolly pines (*Pinus taeda*) at the margins of the wetland. This Carolina bay would fit most appropriately in the 'pond cypress (*T. ascendens*) pond' type as described by Sharitz (2003). Surrounding land use is currently composed of short-rotation hardwood plantations of American sycamore (*Platanus occidentalis*) and cottonwood (*Populus deltoides*) and natural pine (mostly *P. taeda*) stands.

Soils and stratigraphy

Chapel Bay is a clay-based Carolina bay wetland with soils dominated by the Coxville series (fine, kaolinitic, thermic Typic Paleaquults). The Coxville soils are typically poorly drained, with an average 0·3 m deep sandy loam surface overlaying a sandy clay horizon between 0·5 and 2 m thick. Infiltration rate and permeability are low, and these soils typically have a water table near the surface during wet periods. Chapel Bay is surrounded

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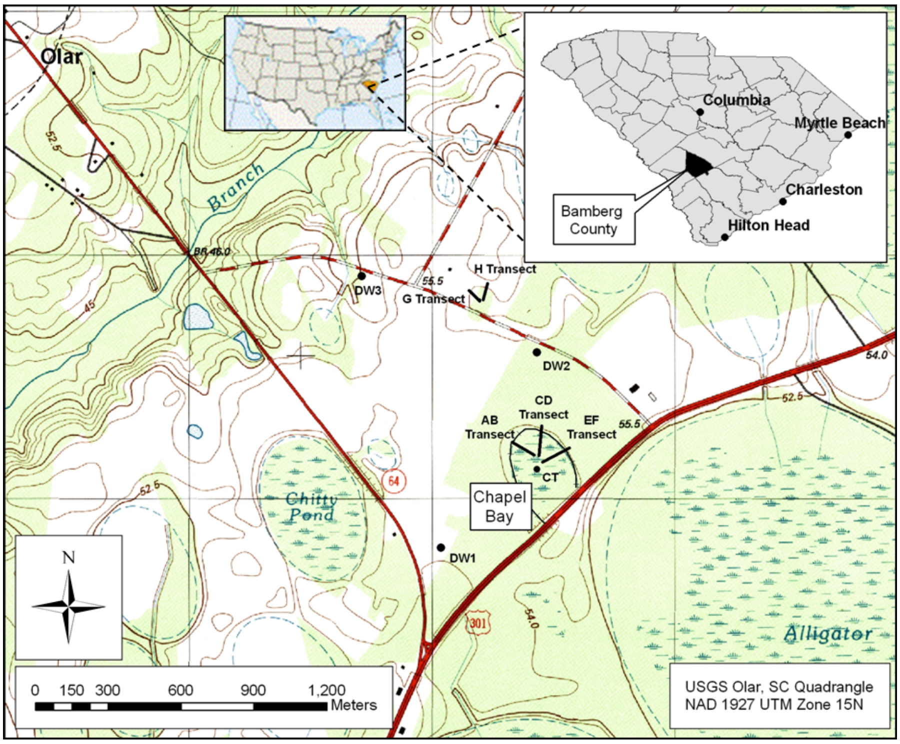

Figure 1. USGS topographic map of the study site showing the location of Chapel Bay. Transects are composed of several wells and piezometer nests

by deep, well-drained sand and loamy sand soils of the Lakeland series (thermic, coated Typic Quartzipsamments), the Goldsboro series (fine-loamy, siliceous, subactive, thermic Aquic Paleudults), and the Norfolk Series (fine-loamy, kaolinitic, thermic Typic Kandiudults). The Lakeland soil (approximately 75% of the study area) has a sandy solum, with a sandy loam or sandy clay subsoil being common at depths between 1 and 2·5 m. The Goldsboro series (approximately 17% of the study area) occupies the side slope positions towards the drainages. Goldsboro is a moderately well drained, sandy loam to sandy clay loam soil. The Norfolk series (approximately 8% of the study area) consists of a sandy surface layer and friable subsoil that ranges from sandy loam to sandy clay. Slopes within these deep, well-drained soils are characterized as level to gently sloping with a topographic gradient of 0 to 12% (US Department of Agriculture (USDA), 1966).

The surficial aquifer beneath the site has not been defined in hydrostratigraphy studies but is best classified as a moderately-conductive collection of fluvial and eolian near-shore sediments deposited on the local equivalent of the Hawthorn Formation (Logan and Euler, 1989). The top of upper Floridan group of semi-consolidated sediments (Logan and Euler, 1989) is approximately 50 m below ground surface (bgs) based on a well log constructed during the installation of a deep irrigation well at the study site. The general stratigraphy of the project area to approximately 10 m bgs was determined from logs taken during well and piezometer installation (Figure 2). Some of the well logs did not provide sufficient information on soil morphology and in such cases we relied on the USDA soil survey for Bamberg County, South Carolina (USDA, 1966) as described above.

The A and E soil horizons at the site are composed mainly of sand in the upland areas (saturated hydraulic conductivity, K, values equal to or greater than 7×10^{-5} m s^{-1}), and range from sandy loams to sandy clay loams within the wetlands ($K = 0{\cdot}6\text{–}2 \times 10^{-5}$ m s^{-1}) (USDA, 1966). The B soil horizon is composed of loamy sand in the upland areas ($K = 3{\cdot}5\text{–}7 \times 10^{-5}$ m s^{-1}), and sandy clay loam and sandy clay within the wetlands ($K = 0{\cdot}1\text{–}0{\cdot}6 \times 10^{-5}$ m s^{-1}), which may deter surface water–groundwater interactions (USDA, 1966). Soil layers below the horizons represent alternating clay and sand layers, which are characteristic of the surficial aquifer system. These clay layers may serve as aquitards to surface and groundwater interactions. Two clay layers exist approximately between 2·75 m to 4·75 m and 4·5 m to 7·5 m bgs (respectively) in the upland area adjacent to Chapel Bay. Clay layers within these approximate depths vary in thickness from 1 m to the maximum estimated range above. Sandy clay layer connectivity throughout the study site was assumed because these layers were found in all of the logs of the shallow wells installed in the wetland as well as the upland areas (Pyzoha, 2003).

Climate

Precipitation and air temperature were measured at the site with an automated tipping bucket rain gauge (Model TE525, Campbell Scientific, Inc., Logan, Utah) and a temperature probe (Model CS500, Campbell Scientific, Inc.), respectively, and data were recorded

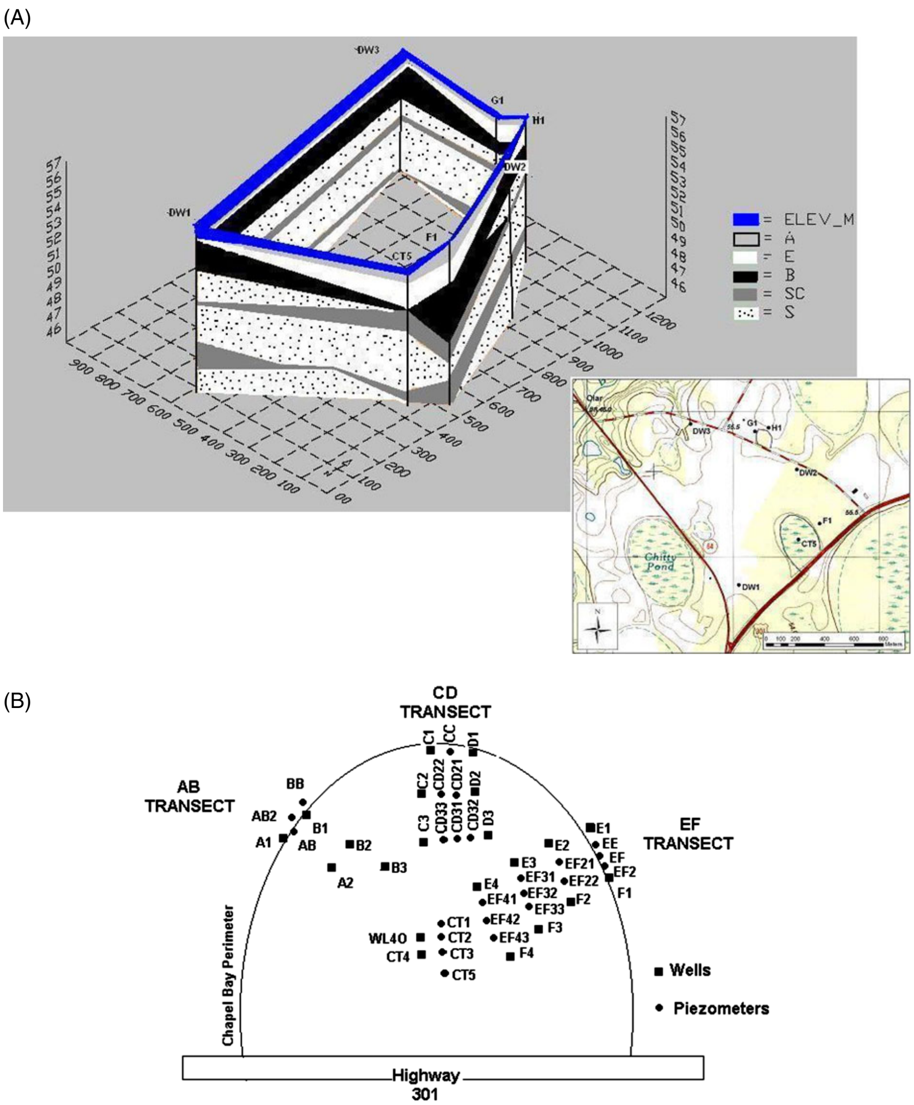

Figure 2. (A) Soil layers and shallow stratigraphy at study site, classified as follows: Horizon A (upland: sand; wetland: sandy loam to loamy sand), Horizon E (upland: sand; wetland: loamy sand), Horizon B (sandy clay loams), SC (sandy clay), S (sand). Labelled points represent well log locations. Elev_m refers to the elevation above mean sea level in metres. (B) Diagram showing piezometer and water-table well locations in and around the wetland

using a central control data recorder (Model CR10X, Campbell Scientific, Inc.). Additional weather data were obtained from South Carolina Department of Natural Resources (SC-DNR) Southeastern Regional Climate Center (SERCC) from the Bamberg, South Carolina weather station (approximately 24 km north-east of the study site) because weather station failure resulted in missing data at the field site during 2000 through 2003. Climate data from 1997 through 1999 were obtained exclusively from the weather station at the study site.

Potential evapotranspiration (PET) was used as an index of atmospheric demand and the monthly difference between P and PET was estimated as an indicator of climate and water availability. Because only temperature data were available, a temperature-based PET method was used to calculate daily PET. The Hamon method has been widely used for eastern US sites and is reported to provide reasonable PET for forested conditions (Federer and Lash, 1978; Sun *et al.*, 2002; Lu *et al.*, 2005). This method uses temperature as the major driving force for evapotranspiration, but also includes other variables such as daytime length and saturated vapour pressure.

$$PET = 0{\cdot}1651 \times DAYL \times RHOSAT \times KPEC \tag{1}$$

where PET is the forest potential evapotranspiration (mm day^{-1}); $DAYL$ is the time from sunrise to sunset in multiples of 12 h, calculated from date, latitude, slope and aspect of the watershed; $RHOSAT$ is the saturated vapor density (g m^{-3}) at the daily mean temperature ($TEMP$) in degrees Celsius and is calculated by (Sun *et al.*, 2005)

$$RHOSAT = 216{\cdot}7 \times \frac{ESAT}{TEMP + 273{\cdot}3} \tag{2}$$

and $ESAT$ is the saturated vapor pressure (millibars) and defined by

$$ESAT = 6{\cdot}108 \exp\left(\frac{17{\cdot}26939xTEMP}{TEMP + 273{\cdot}3}\right) \tag{3}$$

KPEC is a correction coefficient to adjust PET calculated using Hamon's method to realistic values. Reported values for KPEC ranged from 1·0 for Hubbard Brook, New Hampshire, USA to 1·2 for Coweeta, North Carolina, USA (Federer and Lash, 1978), and 1·2 for South Carolina (Lu *et al*., 2005).

Surface water and groundwater monitoring

Wells and piezometers were installed to measure pond stage in the wetland and groundwater elevations. It is important to note that even during times of drought (2000–2002) and the presence of a clay layer beneath the wetland surface, a perched layer of saturated soil or sediments was not observed at the site; that is, the subsurface appeared to be a saturated continuum beneath the water table. This is different from that reported at other depressional wetlands such as vernal pools (Rains *et al*., 2006). The surface water and groundwater dynamics were monitored using water-table wells and piezometers. The hydrological reservoirs were defined as follows:

- Surface water: ponded water and shallow subsurface water between the soil surface and the B-horizon; a 3 m long slotted-screen polyvinyl carbon (PVC) tube was installed to a depth of 1·5 m bgs and thus was used to track pond stage as well as depth to water table during dry periods,
- Groundwater: subsurface water between clay layers approximately 2 m to 10 m bgs (measured using piezometers installed beneath the wetland and the upland perimeters).

Three transects of wells and piezometers were installed within Chapel Bay in 1997 (Figure 1). The northern (CD) and eastern (EF) transects included piezometer nests installed at three depths (0·75 m, 1·5 m, and 2·5 m bgs) and two water-table wells (3–6 m bgs) every 12–15 m along the transects within the wetland. The western transect (AB) contained two wells every 12–15 m, however, piezometers were not added. Along the upland perimeter of the bay, all transects (AB, CD, and EF) also included two wells (between 3 and 6 m bgs) and a nest of two piezometers (includes a piezometer at approximately 9 m to 10 m and a piezometer at approximately 3 m to 5 m). In addition, three piezometers (10 m bgs) were installed in the adjacent upland area in April 2002, and one piezometer (5 m bgs) was installed at the centre of Chapel Bay in June 2002. Altogether, a total of 20 wells and 23 piezometers were installed within Chapel Bay and along the upland rim of the bay, as well as three piezometers in the adjacent upland area.

Wells were constructed from either PVC or stainless steel piping and screened the entire length to measure the elevation of the surface water table. Piezometers were constructed from sealed PVC pipes and a porous ceramic cup (approximately 0·1 m in length) at the bottom. Number 2 well screen sand was filled in the hole along their screen lengths, and bentonite pellets were added to the hole from about 0·50 m up to the soil surface to minimize surface water leakage down along the pipes. Locations of the wells and piezometers were surveyed in 2002 using a rotary laser level (Laser Plane 650, Spectra-Physics Inc., Mountain View, California), Philadelphia rod, and GPS unit (PLGR + 96, Rockwell International Corporation, Cedar Rapids, Iowa).

Water table elevations in the wells and piezometers at the study site were measured monthly between September 1997 and April 1999 and between February 2002 and August 2003 using a water level indicator (Solinst Canada Ltd., Georgetown, Ontario, Canada); data were not collected from May 1999 to January 2002 due to a dearth of funds and available support personnel to maintain the site. The land manager was able to track daily water table levels in the centre of Chapel Bay, which were recorded between 1997 and 2003 using an automated data recorder (WL40, Remote Data Systems, Whiteville, North Carolina). Data were collected from the WL40 recorder using a Hewlett Packard 48G calculator and MS-DOS Kermit software v. 1·0 (Remote Data Systems, Whiteville, North Carolina). All pond stage, water table, and piezometric head measurements were compared to a nearby geodetic benchmark and archived in a database as metres above mean sea level (m amsl).

RESULTS AND DISCUSSION

Data quality

It is critical to collect long-term data to fully understand the hydrologic variability of a wetland ecosystem. However, such intensive data collection can result in suspect data; irrespective of equipment malfunctions, sources of data error should be considered. Precipitation data collected from the automated tipping-bucket rain gauge on site were subject to a range of relative error, depending on storm intensities (e.g. ±1% error for storm intensity less than 25·4 mm h^{-1}, −3 −0% error for 25·4–50·8 mm h^{-1} storms, and −5 −0% error for 50·8–76·2 mm h^{-1} storms (Campbell Scientific, Inc., 2002)). These tolerances are theoretical; experiences at other study sites in the south-eastern USA have shown that the tipping bucket method can underestimate total precipitation by 20–30%. When tabulating daily precipitation values to compare to potential evapotranspiration calculations, the tipping bucket data were corrected using precipitation measurements from an adjacent manual rain gauge at the study site. For the period 2000 through 2003, climate data were obtained from the SERCC weather station and these data were provided at the daily time scale. The Hamon potential evapotranspiration (PET) method does not consider other meteorological variables such as solar radiation, vapour pressure deficit, and wind speed. However, it is a relatively straightforward index of atmospheric water demand. PET has been estimated to be 93% of actual evapotranspiration (AET) in the southern USA (Sun *et al*., 2002). While exact P and PET values may be suspect during the time period that the weather station on site was inoperable (2000 through 2003) because the weather station was 24 km from the study site, the data do provide high-quality information pertaining to climate trends for the site location as observed by the close correlation between P and surface water and groundwater fluctuations.

Climate and water availability

Annual P and PET differences (P–PET) over the 7 year study period are shown in Table I. According to the climate data, P and PET vary greatly within the vicinity of the study site on an annual basis. Climate data collected between 1997 and 2003 were compared to the Southeastern Regional Climate Center (SERCC) 30-year average (1971–2000) annual P for Bamberg County, South Carolina. On average, Bamberg County had a net gain of approximately of 100 mm annually. The study site was wetter than the SERCC average in 1997 and 1998, and was followed by four abnormally dry years. In 2003, P-PET was approximately eight times greater than the average. The monthly difference and cumulative difference between actual calculated P and actual estimated PET (P-PET) between 1997 and 2003 are shown in Figure 3. Weather patterns deviated from long-term average conditions between 1997 and 2003, such as (1) the relatively wet period of fall 1997 and winter 1998; (2) the drying conditions of summer 1998; (3) summer 2001, a time of severe drought conditions (annual P is 899 mm; 30-year average annual P for Bamberg County, South Carolina is 1222 mm (SERCC, 2000)); and (4) the wetting period of winter and early spring of 2003.

Surface water–groundwater interactions

Groundwater fluctuations were closely related to precipitation on site (Figure 4). The hydraulic heads for the eastern and northern transects (EF and CD, respectively) were measured using representative piezometers at the perimeter of the bay (upland piezometer), at the margin of the wetland, and at the wetland centre. The western transect (AB) did not include piezometers at the margin, and therefore water elevation data are not presented here. Refer to Figure 2 for the well/piezometer transect locations at the study site.

Pond stage in the wetland was recorded on a daily basis in the centre of Chapel Bay between 1997 and 2003 using a WL40 automated digital recording well. This high resolution dataset showed that the water table recovered quickly in Chapel Bay after the prolonged drought period of 2001 and 2002 (Figure 4). Exact response times could not be estimated because the datalogger in the wetland could not detect water levels below an elevation of 52·9 m amsl. However, water level data collected in the wetland are of particular interest during the wet periods. During the two wet periods (winter months of 1997/1998; also most of 2003), large hydraulic gradients (Figure 4) and larger values

Table I. Annual precipitation (P) and potential evapotranspiration (PET) for the study site, south-western South Carolina

Year	P (mm)	PET (mm)	P–PET (mm)
1997	1328	978	350
1998	1401	1065	336
1999	937	1001	−64
2000[a]	726	1018	−292
2001[a]	906	980	−75
2002[a]	995	1057	−62
2003[b]	1632	824	808
SERCC Average (1971–2000)	1234	1124	109

[a] Southeast Regional Climate Center (SERCC) data.
[b] P and PET data for 1 January to 31 September 2003.

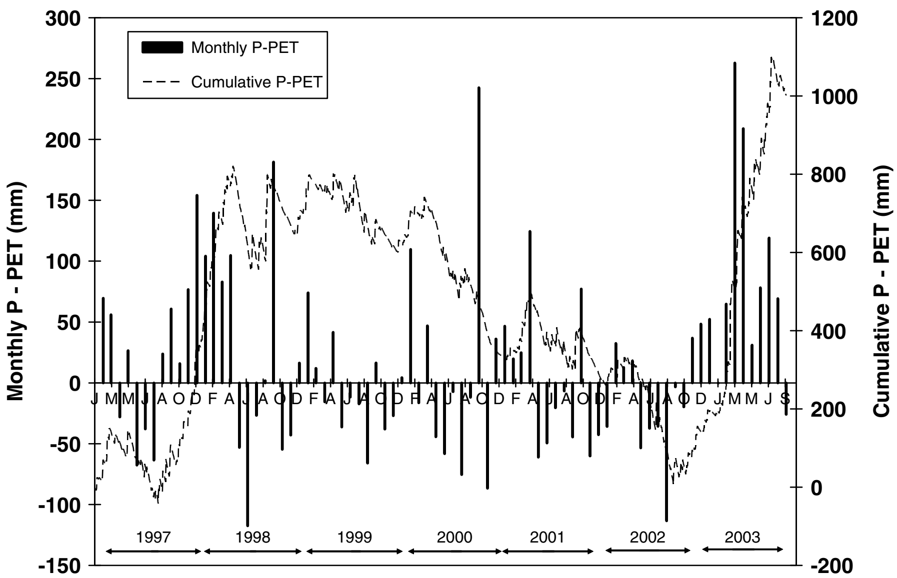

Figure 3. Monthly and cumulative differences between total precipitation (P) and potential evapotranspiration (ET) for 1997 to 2003 as obtained from an on-site rain gauge (and from the SC Department of Natural Resources SERCC weather station 24 km away in Bamberg, SC for 2000–2003), and calculated using the Hamon method (Federer and Lash, 1978; Sun *et al.*, 2002; Lu *et al.*, 2005), respectively

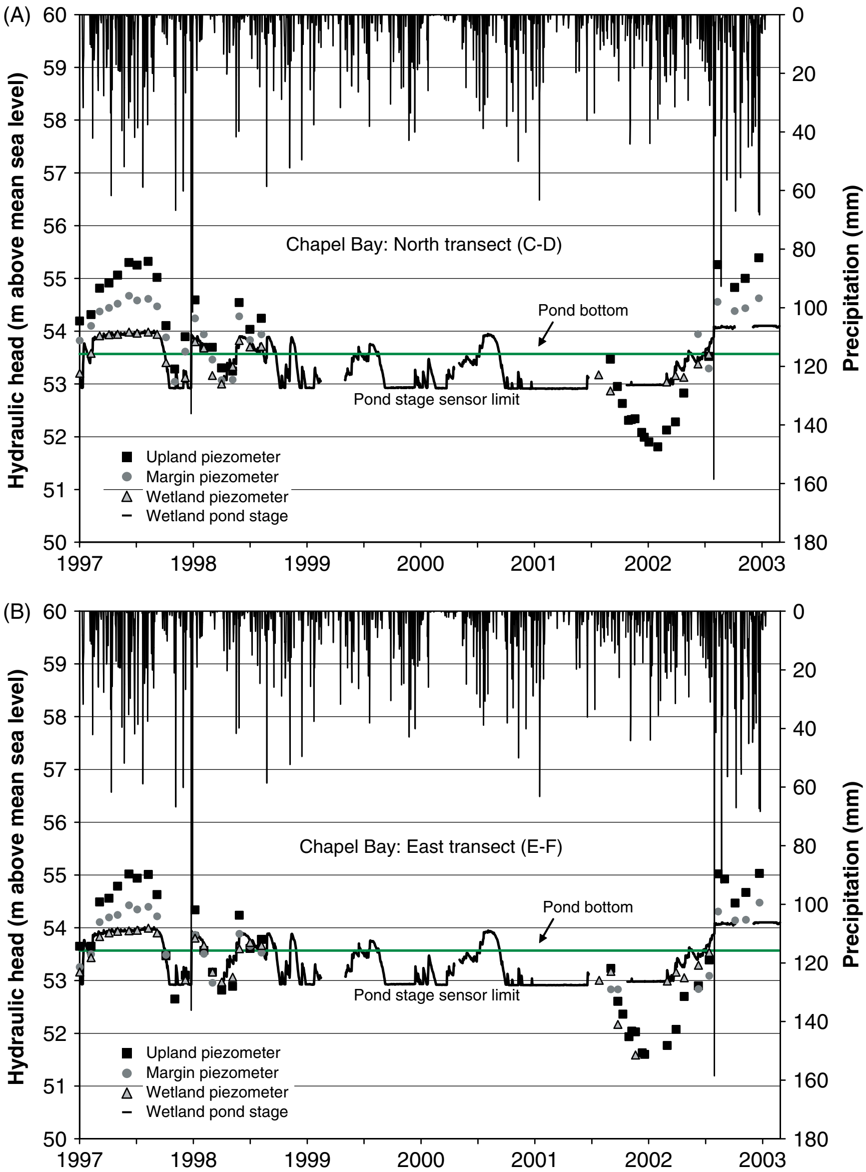

Figure 4. (A) Precipitation data and surface water-groundwater fluctuations in a representative upland piezometer (4·0 m), wetland piezometer (2·5 m), and the WL40 automatic digital recording well (1·02 m) within the western transect (AB) in Chapel Bay. (B) Precipitation data and surface water–groundwater fluctuations in a representative upland piezometer (5·9 m), margin piezometer (2·5 m), wetland piezometer (2·5 m), and the WL40 automatic digital recording well (1·02 m) within the northern transect (CD) in Chapel Bay, for the period of January 1997 to October 2003

of P–PET (Figure 3) were observed, yet water level remained constant at approximately 54 m amsl. This result could be due to (1) shallow groundwater recharge out of Chapel Bay during wet periods when water levels exceeded the holding capacity of the wetland, resulting in lateral groundwater flow; or (2) the low permeability clay layers beneath the wetland prevented significant groundwater discharge vertically into the wetland during the time of observation. In either case, the net result was groundwater recharge from the wetland. Sun *et al.* (2006) modelled the hydrology dynamics in this same wetland system and found that the topography of a restrictive clay layer beneath the site has a strong influence on the hydrological processes in the wetland. That is, Chapel Bay may serve as a flow-through system during wet climatic phases. Field inspection of the eastern edge of the wetland (Figure 1) indicated that surface water in the wetland may have exited through one area of the eastern rim of Chapel Bay as overland flow during the extreme storm events or extended wet periods.

A conceptual hydrological model for Carolina bay wetlands

Based on the observed climatic dynamics of Chapel Bay, a conceptual model was devised to illustrate the hydrology of Carolina bays for four typical conditions (Figure 5). This approach follows previous descriptions of the 'hydroperiod' (fraction of inundation time) as described by Jackson (2006), Sharitz (2003), and Mitsch and Gosselink (2000), but groundwater data are used here with the objective to more fully explain the role of groundwater in these depressional wetlands.

Condition A is depicted as a period of low water tables and no surface water in the wetland. A representative dry

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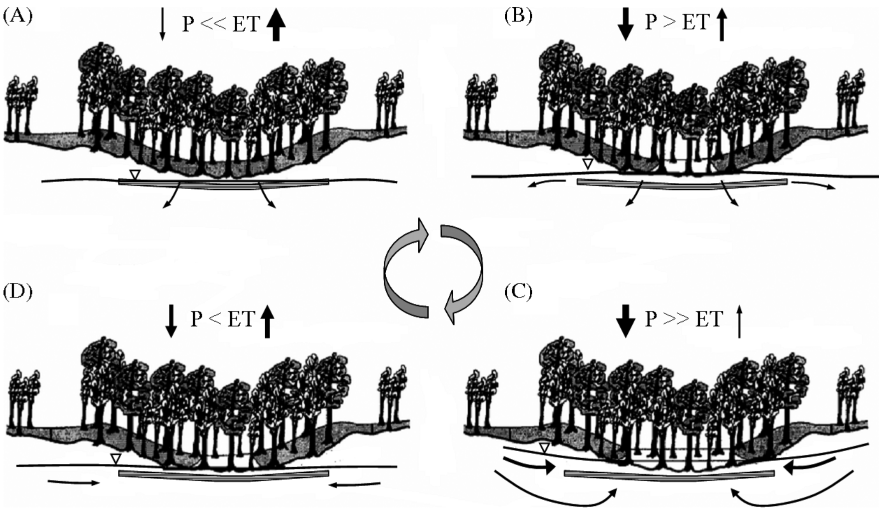

Figure 5. Conceptual hydrology responses to different P : ET conditions for a forested depressional wetland. Time scale varies from the annual (A: summer, B: autumn, C: winter, D: spring) to the weekly (high-intensity, convective rainstorm events in the summer cause P to exceed ET and induce the A–D cycle in the short-term). During drought conditions of 1999–2002 the cycle remained in the 'A' condition and cycled through to the 'C' condition within 2 weeks following a 160 mm rain event in March 2003 (Figure 4)

period at Chapel Bay was the drought of 2000–2002. Other dry periods occurred during the summer seasons during this study. The Carolina bay was nearly isolated hydraulically from the upland area except for an inferred slow groundwater recharge from the water beneath the wetland. *Condition B* is characterized by P/ET greater than 1, resulting in higher water tables in both the wetland and upland areas, some ponding near the centre of the wetland, and some lateral shallow groundwater flow away from the wetland areas. This is a transition period, typically late summer or autumn, or during any period when high-intensity convective storm events may cause large rainfall inputs in the region. *Condition C* follows a period of extensive P and relatively low ET such as the winter months. In this phase, groundwater discharge plays an even larger role in the overall hydrologic balance as discussed previously. *Condition D* also is a transition period, from a wet period to a dry period, in which ET begins to exceed P, such as the spring months. This phase was most important at the study site when the area experienced moderate P and an increase in ET (such as the onset of the growing season and increased transpiration); this phase is especially important in forested wetlands and perhaps less so in depressional wetlands dominated by meadow and marsh vegetation where ET flux is relatively low. In summary, it was found that during Conditions B–D, the wetland was hydraulically connected to the upland hydrology, but limited connections existed between wetland and upland during Condition A.

From the well and piezometer data, larger hydraulic gradients were observed at the site that corresponded to Conditions B–D in January 2003, February 1998, and June 1998, respectively, whereas very small hydraulic gradients were observed during Condition A (2001 and 2002). Hydraulic gradients between the perimeter and the interior of the wetland were as large as 0·008 in the eastern and western transects and 0·009 in the northern transect. Figure 6 shows a cross-sectional view of water elevations during Conditions A–D in the eastern (EF) transect. Hydraulic gradients indicated flow towards the centre of Chapel Bay, suggesting that shallow groundwater was flowing laterally from the upland area into the bay during these periods. Additionally, hydraulic gradients were greatest during Condition C, from which it is inferred that lateral shallow groundwater flux into the bay was greatest at this time. This trend is illustrated in both the late 1997/early 1998 wet period and the 2003 wet period.

These findings confirm the groundwater hypothesis posed (but not tested) in previous studies by Schalles and Shure (1989) and Lide *et al.* (1995). Schalles and Shure (1989) deduced that subsurface hydrologic interactions are important influences on the surface water of a Carolina bay on the Upper Coastal Plain of South Carolina (Thunder Bay) based on surface water chemistry findings, whereas Lide *et al.* (1995) suggested that changes in pond stage height within the same Carolina bay could not be purely explained by P and PET fluctuations and that groundwater was entering the bay during certain time periods.

Crownover *et al.* (1995) and Sun *et al.* (2000) examined multiple cypress swamps, which are depressional wetlands in the pine flatwoods area of northern Florida. They found that most of the wetlands were of the flow-through variety, and depressional wetlands that only receive groundwater discharge were less common. The findings of the Crownover *et al.* (1995) and Sun *et al.* (2000) studies may be applicable to Carolina bays as well; however, additional field data are necessary to assess whether Carolina bays serve as flow-through systems. Because of land ownership constraints within the southern half of Chapel Bay, well and piezometer transects could not be installed in this area and thus hydraulic head data are lacking for this section. Without data on

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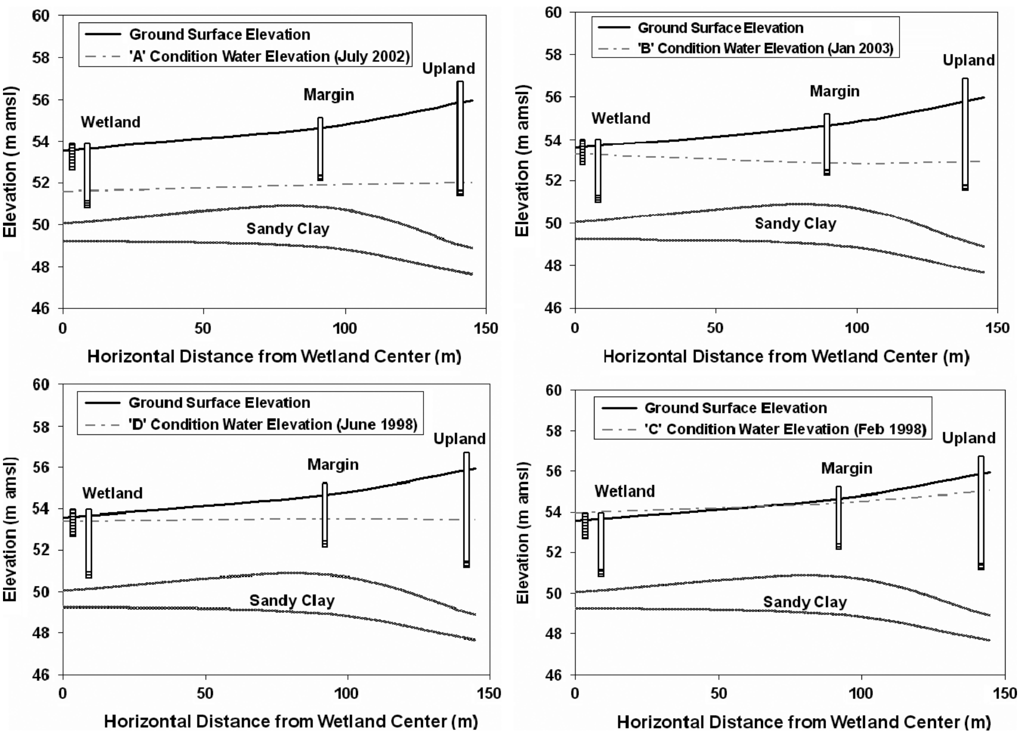

Figure 6. Cross-sectional view of a representative upland piezometer (4·6 m deep), margin piezometer (2·5 m), wetland piezometer (2·5 m), and the automatic digital recording pond gauge in the wetland (1·02 m) during the A–D cycle within the eastern transect (EF) in the depressional wetland. The role of the sandy clay sub-soil layer was to limit surface water–groundwater interaction even under relatively large hydraulic gradient conditions (e.g. condition C) and thus increasing the lateral groundwater flux

the southern end of Chapel Bay and site-specific climate data for the end of 2000 through 2003, a hydrologic budget of Chapel Bay, which may provide further support for the flow-through hypothesis, would be difficult to validate. To address this, Sun *et al.* (2006) used a deterministic hydrologic model to test this hypothesis for Chapel Bay. They found that hydrological processes may be controlled not only by climate dynamics but also by the subsurface topography, specifically that of any restrictive stratigraphic unit such as a clay-rich layer. Therefore, the conceptual model shown in Figure 5 could in some cases include an arrow depicting a groundwater recharge flux during any or all of the four climate conditions shown, and while deviations from this conceptual model may occur in some instances, this illustration depicts the general hydrology response of a Carolina bay to climate fluctuations.

CONCLUSIONS

Climatic dynamics greatly influence the hydrology of Carolina bays. Normal seasonal precipitation and evapotranspiration fluctuations and deviations from normal climate conditions greatly affect the role of surface water–groundwater interactions in the overall hydrology of these wetlands. This long-term monitoring study clearly shows the climate control on the Carolina bay hydroperiod as well as surface–groundwater interactions, and thus we infer that projected climatic change may alter Carolina bay hydrology dynamics permanently; as for the exact magnitude of the impact we are not certain.

The study found that a clay-based, forested depressional wetland of the Carolina bay type was hydraulically connected to the upland during wet periods when precipitation greatly exceeded evapotranspiration, as well as those periods near the onset of a drought and when drought-conditions were ending. It was also found that there were limited hydraulic connections between the wetland and upland during extended dry or drought conditions. These results are somewhat comparable to other depressional wetland systems where perched groundwater may exist beneath such as vernal pools and prairie potholes, however at the clay-based Carolina bay site studied here no true perched groundwater system existed; the clay layer beneath the wetland acted as a hydraulic restrictive layer but the soil and sediments were continuously saturated. The clay layer served to focus lateral groundwater flow into or out of the wetland, depending on hydraulic gradient, which in turn was strongly controlled by climatic conditions. Hydrology is affected by the soil and geology of the wetland–upland continuum, thus any efforts in wetland restoration to restore wetland hydrology must consider its landscape position, soil properties, and geology of the wetland.

The hydrology of this Carolina bay was extremely variable and so was its capacity for water storage. In times of excess precipitation (i.e. large storm events or tropical storms) Carolina bays may provide flood control along the Coastal Plain by collecting large water volumes from the adjacent area. While beyond the scope of this study, watershed-scale hydrology dynamics may influence the water quality by increasing the residence

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time of runoff water from nearby agricultural areas or intensively-managed hardwood plantations. In order to fully understand the role of Carolina bays along the Atlantic Coastal Plain of the USA, future studies should focus on large-scale analyses that incorporate several of these wetland features across the Coastal Plain landscape.

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REFERENCES

Bennett S, Nelson J. 1991. *Distribution and Status of Carolina Bays in South Carolina*. Nongame and Heritage Trust Publication No. 1. South Carolina Wildlife & Marine Resources Department, Columbia, South Carolina.

Bliley D, Pettry D. 1979. Carolina Bays on the eastern shore of Virginia. *Soil Science Society of America Journal* **43**: 558–564.

Bliss C, Comerford N. 2002. Forest harvesting influence on water table dynamics in a Florida flatwoods landscape. *Soil Science Society of America Journal* **66**: 1344–1349.

Campbell Scientific, Inc., 2004. Instruction Manual: TE525 Tipping Bucket Rain Gage. Online resource available at http://www.campbellsci.com/documents/manuals/te525.pdf. Accessed March 2003.

Crownover S, Comerford N, Neary D. 1995. Water flow patterns in cypress pine flatwoods landscapes. *Soil Science Society of America Journal* **59**: 1199–1206.

Federer C, Lash D. 1978. *BROOK: A hydrologic simulation model for eastern forests*. Water Resources Research Center, University of New Hampshire, Durham, NH. Research Report 19.

Gamble E, Daniels R, Wheeler W. 1977. Primary and Secondary Rims of Carolina Bays. *Southeast Geology* **18**: 199–212.

Glenn L. 1895. Some Notes on Darlington Bays. *Science* **2**: 472–475.

Hamon R. 1963. *Computation of Direct Runoff Amounts from Storm Rainfall*. International Association of Scientific Hydrology Publication 63. Wallingford, Oxon, UK.

Ivester A, Leigh D, Godfrey-Smith D. 2001. Chronology of inland eolian dunes on the Coastal Plain of Georgia, USA. *Quaternary Research* **55**: 293–302.

Ivester A, Leigh D. 2003. Riverine dunes on the Coastal Plain of Georgia, USA. *Geomorphology* **51**: 289–311.

Jackson C. 2006. Wetland hydrology. In *Ecology of Freshwater and Estuarine Wetlands*, Batzer D, Sharitz R (eds). University of California Press: Berkeley, CA.

Johnson D. 1936. Origin of the supposed meteorite scars of Carolina. *Science* **84**: 15–18.

Kaczorowski R. 1977. *The Carolina bays: a comparison with modern oriented lakes*. Technical Report No. 12-CRD. Coastal Research Division, Department of Geology, Columbia, South Carolina.

Kaczorowski R. 2007. Geomorphological history of the Carolina Bays. Geological Society of America Abstracts with Programs **39**(2): 6.

LeGrand H. 1953. Streamlining of the Carolina Bays. *Journal of Geology* **41**: 52–66.

Lide R. Meentemeyer V, Pinder III J, Beatty L. 1995. Hydrology of a Carolina bay located on the upper coastal plain of western South Carolina. *Wetlands* **15**: 47–57.

Logan W, Euler G. 1989. *Geology and ground-water resources of Allendale, Bamberg, and Barnwell Counties and part of Aiken County South Carolina*. Water Resources Commission Report No. 155. South Carolina Water Resources Commission, Columbia, South Carolina.

Lu J, Sun G, McNulty S, Amatya D. 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *Journal of the American Water Resources Association* **41**: 621–633.

Lugo A, Brown S, Brinson M. 1990. Concepts in wetland ecology. In *Forested Wetlands*, Lugo A, Brinson M, Brown S (eds). Elsevier Science: Amsterdam.

Melton F, Schriever W. 1933. The Carolina bays. *Journal of Geology* **41**: 52–66.

Mitsch W, Gosselink J. 2000. *Wetlands* (3rd ed.). J. Wiley and Sons: New York; 920.

Newman M, Schalles J. 1990. The water chemistry of Carolina bays: a regional survey. *Archiv fuer Hydrobiologie* **118**: 147–168.

Pettry D, Scott J, Bliley D. 1979. Distribution and nature of Carolina bays on the eastern shore of Virginia. *Virginia Journal of Science* **30**: 3–9.

Prouty W. 1952. Carolina bays and their origin. *Geologic Society of America Bulletin* **63**: 167–224.

Pyzoha J. 2003. *The role of surface water and groundwater interactions within Carolina bay wetlands*. MS Thesis, College of Charleston, Charleston, South Carolina.

Rasmussen W. 1958. *Geology and hydrology of the "bays and basins" of Delaware*. PhD Dissertation, Bryn Mawr College, Bryn Mawr, Pennsylvania, 65–05 269.

Rains MC, Fogg GE, Harter T, Dahlgren RA, Williamson RJ. 2006. The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California. *Hydrological Processes*, **20**: 1157–1175.

Richardson C, Gibbons J. 1993. Pocosins, Carolina bays, and mountain bogs. In *Biodiversity of the Southeastern United States*, Martin W, Boyce S, Echternacht A (eds). John Wiley & Sons: New York; 257–311.

Schalles J, Shure D. 1989. Hydrology, community structure, and productivity patterns of a dystrophic Carolina bay wetland. *Ecological Monographs* **59**: 365–385.

Sharitz R. 2003. Carolina bay wetlands: unique habitats of the southeastern United States. *Wetlands* **23**: 550–562.

Sharitz R, Gresham D. 1998. Pocosins and Carolina bays. In *Southern Forested Wetlands: Ecology and Management*, Messina M, Conner W (eds). Lewis Publishing: Boca Raton, Florida; 343–378.

Smith L. 1931. Solution depressions in sandy sediments of the coastal plain in South Carolina. *Journal of Geology* **39**: 641–652.

Southeastern Regional Climate Center (SERCC). 2000. *Historical climate summary for Station 380 448, Bamberg County, South Carolina*. South Carolina Department of Natural Resources. On-line database, available at http://www.water.dnr.state.sc.us/water/climate/sercc/products/historical/historical_sc.html. Accessed December 2003.

Sun G, Riekerk H, Kornak J. 2000. Groundwater table rise after forest harvesting on cypress-pine flatwoods in Florida. *Wetlands* **20**: 101–112.

Sun G, McNulty S, Amatya D, Skaggs R, Swift Jr L, Shepard J, Riekerk H. 2002. A comparison of the watershed hydrology of coastal forested wetlands and mountainous uplands in the southern U.S. *Journal of Hydrology* **263**: 92–104.

Sun G, McNulty SG, Lu J, Amatya DM, Liang Y, Kolka RK. 2005. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. *Journal of Hydrology* **308**: 258–268.

Sun G, Callahan T, Pyzoha J, Trettin C. 2006. Modeling the climatic and subsurface stratigraphy controls on the hydrology of a Carolina bay wetland in South Carolina, USA. *Wetlands* **26**: 567–580.

Thom B. 1970. Carolina bays in Horry and Marion Counties, South Carolina. *Geologic Society of America Bulletin* **81**: 783–813.

Toumey M. 1848. *Report on the Geology of South Carolina*. Geologic Survey of South Carolina, Columbia, South Carolina.

U.S. Department of Agriculture (USDA). 1966. *Soil Survey of Bamberg County, South Carolina*. USDA Soil Conservation Service and South Carolina Agricultural Experiment Station Series 1962, No. 10, Washington, D.C.

U.S. Environmental Protection Agency. 1993. Carolina bays: a natural wastewater treatment program. In *Constructed Wetlands for Wastewater Treatment and Wildlife Habitat* EPA832-R-93-005, pp. 11–18.

Wells B, Boyce S. 1953. Carolina bays: additional data on their origin, age, and history. *Journal of the Elisha Mitchell Scientific Society* **69**: 119–141.

Wharton C. 1978. *The Natural Environments of Georgia*. Geologic and Water Resources Division and Resource Planning Section, Office of Planning and Research, Georgia Department of Natural Resources, Atlanta, Georgia.

Whigham D, Jordan T. 2003. Isolated wetlands and water quality. *Wetlands* **23**: 541–549.