Long-Term Water Table Dynamics of Forested Wetlands: Drivers and their Effects on Wetland Hydrology in The Southeastern Atlantic Coastal Plain

D. M. Amatya, G. M. Chescheir, T. M. Williams, R. W. Skaggs & S. Tian

Wetlands
Official Scholarly Journal of the Society of Wetland Scientists

ISSN 0277-5212
Volume 40
Number 1

Wetlands (2020) 40:65-79
DOI 10.1007/s13157-019-01153-y

Springer

Your article is protected by copyright and all rights are held exclusively by US Government. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com”.

Springer

Author's personal copy

Wetlands (2020) 40:65–79
https://doi.org/10.1007/s13157-019-01153-y

SILVICULTURE IN FORESTED WETLANDS

Long-Term Water Table Dynamics of Forested Wetlands: Drivers and their Effects on Wetland Hydrology in The Southeastern Atlantic Coastal Plain

D. M. Amatya[1] · G. M. Chescheir[2] · T. M. Williams[3] · R. W. Skaggs[2] · S. Tian[2]

Received: 12 June 2018 / Accepted: 27 March 2019 / Published online: 17 June 2019
© US Government 2019

Abstract

Sustainable management of forested wetlands requires an understanding of water Table (WT) dynamics affected by rainfall and evapotranspiration (ET) and management practices, designed to sustain water quality, quantity, and ecosystem functions and productivity. In this paper analysis of long-term data from four drained and six undrained sites on coastal forested wetlands showed that their growing season WT dynamics depends upon ET as affected by vegetation stand age, with undrained sites yielding deeper WT than the drained young sites but shallower than the mature ones. Wetland hydrology criterion was not met on any of the drained sites including with controlled drainage and one unditched site with moderately well-drained sandy soil, where the WT was within 30 cm of the surface for <8% of the time compared to 31% or greater on undrained sites. WT response was similar on both drained and undrained watersheds soon after vegetation removal compared to the baseline level. Similarly, the WT dynamics on all soil types and vegetation behaved similarly during extreme storms. No trend was found in limited annual mean WT data. These results may have implications for coastal wetland forest restoration and modeling studies relating wetland hydrology as affected by anthropogenic and natural disturbances.

Keywords Drained forests · Poorly drained soils · Precipitation · Evapotranspiration · Extreme event

Introduction

Forests control about 60% of the regional hydrology in the Southeastern U.S. (Sun et al. 2002). Forested wetlands of the southeastern Coastal Plain occur on a variety of hydrogeomorphic classes (Brinson 1993). Forest management occurs on two predominate forested wetland types (silviculture classes) – pine plantations/forests and hardwood forests (Harms et al. 1998; Wylie 2016). Wetland hardwood forests occur primarily on slope and riverine wetland classes and management depends greatly on natural regeneration. Pine plantation management of wetland forests is concentrated on wet flat classes, both wet mineral flats and wet organic flats as described by Rheinhardt et al. (2002). Wet flats are characterized by sites with rainfall as the primary source of excess moisture and very gentle slopes resulting in a high water Table (WT) on a seasonal or more frequent basis. Sandy surface layers are often underlain at various depths by clayey subsurface layers which can restrict internal drainage. Recently, Williams and Amatya (2016) provided an analysis and discussion of the relationship of major soils, water table, and drainage in Atlantic Coastal Plain forested landscapes. Detailed descriptions of southern forested wetlands can also be found in Messina and Conner (1998) and Williams et al. (2016).

Unlike upland watersheds dominated by hillslope processes with sustained runoff (Sun et al. 2002), wet flat forested wetlands on coastal plain sites, respond rapidly to rainfall and evapotranspiration (ET) (Young and Klaiwitter 1968; Williams 1978; Riekerk 1986; Amatya et al. 1996; Sun et al. 2000; Amatya and Skaggs 2011), influencing wetland hydrology, functions, and productivity. Water budget components of naturally drained wet flat forested wetlands are presented in Fig. 1a. Wetlands are found in low-energy environments—

✉ D. M. Amatya
devendra.m.amatya@usda.gov

[1] Center for Forested Wetlands Research, Southern Research Station, USDA Forest Service, 3734 Highway 402, Cordesville, SC 29434, USA

[2] Biological and Agricultural Engineering Department, North Carolina State University, Box 7625, Raleigh, NC 27695, USA

[3] Baruch Institute of Coastal Ecology and Forest Science, Clemson University, Highway 17,, Georgetown, SC 29442, USA

Author's personal copy

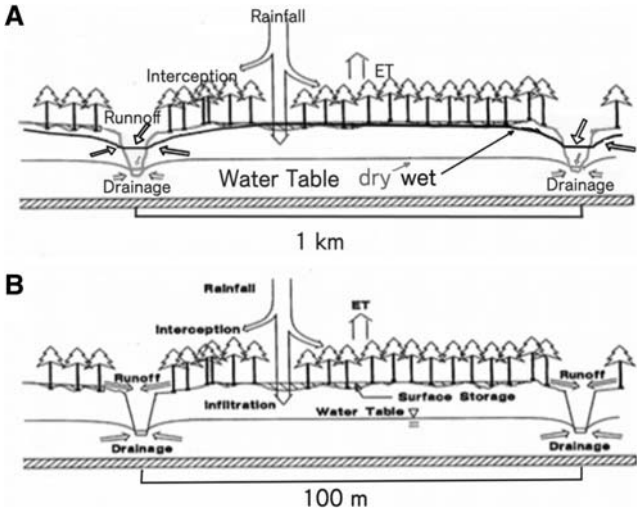

Fig. 1 **a** Schematic of water balance components for a naturally drained forested watershed (*Modified from* Buol 1973). Shallow water table position varies depending on the balance of rainfall and ET (Evapotranspiration = Interception + Transpiration + Soil/litter/water evaporation). Shallow water table position during dry periods (rain < ET) is near stream channel bottoms, and during wet periods (Rain >> ET) the water table approaches the surface in the broad inter-stream area. **b** Silvicultural drainage reduces distance between drainage streams, increasing subsurface flow, and reducing period of surface flooding during wet periods (*Modified from* Skaggs et al. 1991). A restrictive clay layer is generally found within 5 m of the soil surface with negligible deep seepage

that is, in areas where water normally flows with a slow velocity (USEPA 2008). The lower southeastern coastal plain is characterized by marine terrace topography with wide areas of low topography located between sparsely spaced (around 1 km) stream channels draining the headwaters. On this landscape, moderately well-drained soils are restricted to stream channel edges and the broad areas distant from streams tend to have very poorly drained soils with seasonally high water tables (Buol 1973). The rates of lateral subsurface flow and soil moisture storage vary widely with the balance of rainfall and ET. Under natural drainage conditions, WT rise during wet periods results in saturated soils in much of the inter-stream area. During dry periods (Rain < ET), soil moisture storage, both saturated and unsaturated, is depleted and the WT drops to near or below stream bottoms and little lateral drainage occurs (Fig. 1a).

A diagnostic feature of wetlands is the proximity of the water surface (or water table below the surface) relative to the ground surface (USEPA 2008). Wetland hydrology exists on a site if, during the growing season, the WT is normally within 30 cm of the surface for a continuous critical duration (Skaggs et al. 2011a). The U.S. Army Corps of Engineers Wetland Delineation Manual (USACE 1987) specifies the critical duration as 5% to 12.5% of the length of the growing season. For many years, the growing season has been defined as the period between the average last date of −2 °C in the spring to the average first date of −2 °C in the fall, as given in the published county soil survey reports (Skaggs et al. 2011a). On naturally drained southeastern forested sites, the critical period that determines wetland hydrology is the early spring of the growing season, as ET exceeds rainfall later in the growing season and summer tropical systems are not sufficiently frequent to meet the 50% of the time criterion (Skaggs et al. 1994, 2011b; Amatya and Skaggs 2011; Dai et al. 2013; Williams et al. 2016). In addition to the water balance of rainfall, ET, and soil-water storage (WT position), wetland hydrology and its functions are also influenced by site characteristics like sub-surface flow, soil texture, slope, surface depressional storage, and vegetation ET demand (Lu et al. 2009; Skaggs et al. 2011a, b; Amoah et al. 2012; Williams et al. 2016).

Although these forested coastal wetlands are highly productive if well managed, they are also vulnerable to the effects of ongoing rapid development, with altered hydrology, degraded water quality, and potential loss of other ecological functions and systems (Callahan et al. 2012; Sun and Lockaby 2012; Dai et al. 2013; Marion et al. 2013; Hitchcock et al. 2014; Lõhmus et al. 2015). Furthermore, drought, ditching, and other local or regional management factors can affect the hydrology of wetlands making them drier than they would under unaltered conditions (US EPA 2017).

Large tracts of wet flat forested wetlands in the southeastern coastal plain are drained with ditch networks and intensively managed for silviculture (Amatya and Skaggs 2001; Beltran et al. 2010). These lands are important economically to the communities where they occur (Stelk and Christie 2016). Improved drainage is needed in regions where precipitation exceeds ET and on lands where natural lateral subsurface flow processes are not sufficient to remove excess water, resulting in long periods of soil saturation (Skaggs et al. 2016). Over 1 million ha of poorly drained coastal forests were drained with a network of canals (~1.6 km apart) and lateral ditches (~100 m apart) (Fig. 1b) in the late 19th to mid-twentieth century to improve soil trafficability for silvicultural operations and to improve tree productivity (McCarthy and Skaggs 1992; Amatya and Skaggs 2011; Hughes 2014; Lõhmus et al. 2015; Skaggs et al. 2016). Water balance components of a drained forest system (Fig. 1b) are similar to the natural case, except for increased rates of subsurface flow to the ditches, which are much more closely spaced than natural stream channels. Although subsurface flow increases due to higher gradients, the region of lowered WT may be restricted to near the stream or a ditch (Phillips et al. 2010). Jaeschke (2013) noted that the WT of a pocosin in Hoffmann Forest, North Carolina (NC) was not influenced by a ditch located more than 300 m away from his observation well.

Although our understanding of forest drainage impacts on hydrology has improved in recent years (Amatya et al. 1996, 1997, 2002; Sun et al. 2001; Skaggs et al. 2011b, 2016; Lõhmus et al. 2015; Zietlow 2015), only a limited number of

Author's personal copy

studies are available relating WT dynamics of drained systems with intensive silvicultural management practices to the impacts of natural and anthropogenic disturbances on these systems. Little is known about historical hydrological conditions within most wetlands, such as water levels and extent of inundation. Furthermore, determining how and where ditches for silviculture cause wetlands to become uplands is extremely difficult because of a lack of long-term field monitoring of such wetlands (USEPA 2017). Minor drainage using ditches should not convert wetlands to uplands, but this appears to be happening in some circumstances. Skaggs et al. (2011a) presented results of a DRAINMOD simulation study to determine the impacts of minor drainage for silviculture on wetland hydrology on 13 different soils and soil profile combinations in Atlantic and Gulf coastal states. In this volume, Skaggs et al. examines the impacts of drainage and maturation of plantation pine on field effective hydraulic conductivity and transmissivity of the soil profile, which may, in turn, affect wetland hydrologic status. One of the findings was that increases in hydraulic transmissivity of the profile can increase drainage rates such that wetland hydrology no longer exists on the site.

The goal of this paper was to address WT dynamics, wetland hydrology driven by WT, and effects of disturbances on the WT using both published literature as well as long-term WT data of four drained and six undrained forest sites on the Atlantic Coastal Plain. The first objective was to compare the hydrology (WT, Outflow and ET) of these forest sites based on their hydro-climatology, field drainage types, soil types, and management practices, including raised weir outlets on drained systems with a potential to maintain wetland hydrology. Secondly, we assess wetland hydrology status of the drained sites compared to the undrained ones using long-term daily WT data to test a hypothesis that an undrained site will maintain wetland hydrology compared to the drained sites. We also assessed the WT frequency duration for those sites to determine the frequency of wet and dry periods based on the soil, vegetation type and management practice. Many ecological functions of wetlands are influenced by wet-periods, i.e., the time interval when groundwater table is continuously near the land surface (Liu and Kumar 2016), whereas the dry low-flow periods are also important from the perspective of assessing droughts and environmental requirements (Richter et al. 1996; Marion et al. 2013). The data were also analyzed further to examine the WT response of post-anthropogenic (e.g. clearcut harvesting on drained sites) and post-natural disturbances (e.g. hurricane on an undrained site) on these coastal forests. Finally, we hypothesize that under extreme climatic conditions (high precipitation events) average WT response on poorly drained and well drained soils would not be significantly different, and is independent of soil type. All analyses provide a basis for assessing wetland hydrology, drivers of, and their effects on, wetland hydrology of coastal forested landscapes.

Methods

Site Description and Hydro-Meteorologic Measurements

Data used for this study were from ten long-term experimental sites with land surface elevations within <11 m a.m.s.l. on lands classified as forested wetlands or wet pine flats, based on soil types, soil hydrologic groups, and vegetation (Table 1). Soils on all sites varied from very poorly to somewhat poorly drained, except the moderately well drained Goldsboro site in South Carolina (SC). Restrictive layers at all of the sites were within 3–4 m depths from the surface (Skaggs et al. 2011b; Williams and Amatya 2016). All sites had shallow fluctuating WT primarily driven by rainfall and ET, typical of the hydrology of lower coastal plain sites (Williams 1979, 2007; Skaggs et al. 1991, 1994; Eshleman et al. 1994; Amatya et al. 1996; Amatya and Skaggs 2001; Harder et al. 2007; Williams and Amatya 2016). ET on all sites was in general energy-limited, with mean annual rainfall between 1320 to 1510 mm, exceeding potential evapotranspiration (PET) between 1010 mm to 1135 mm. Surplus water generally leaves the site by surface and/or subsurface flow (outflow) (Skaggs et al. 1994). A multi-site study of hydrology and water quality conducted on mostly drained pine forests (Fig. 1b) in coastal NC by Chescheir et al. (2003) showed approximately 30% of the annual rainfall was lost to outflow, leaving about 70% for ET. That was consistent with Amatya and Skaggs (2011)'s 21-year results for a drained forest (D1) in NC, with an average growing season WTD of 1.12 m (Fig. 2; Table 1). Unfortunately, most of the sites reviewed by Chescheir et al. (2003) did not have WT records. The average outflow for drained sites in NC was higher compared to an undrained Turkey Creek forest watershed in SC (Figs.1A; and 3) with a 10-yr average runoff coefficient of 0.23 (Amatya et al. 2016a).

Four sites in NC were drained with open ditches (Fig. 1b) to remove excess soil moisture and lower WT for improved silvicultural production (Amatya and Skaggs 2001). The remaining six in SC were on naturally drained forests without ditches (Fig. 1a) with only minimal silvicultural operations (e.g., thinning and prescribed burning for restoration purposes Amatya et al. 2016a). Ditches at the drained sites may be cleaned periodically to maintain their original depth, or sometimes allowed to silt in over the course of a 25 to 35-year rotation (Skaggs et al. 2011a; Lõhmus et al. 2015).

Carteret Site, NC

Twenty-one years (1988–2008) of data were used from three adjacent artificially drained managed loblolly pine (*Pinus taeda*) forest watersheds (D1, D2, and D3) on Weyerhaeuser lands in coastal Carteret County, NC (Fig. 2; Table 1), described earlier by Amatya and Skaggs (2011) and Tian et al.

Author's personal copy

Table 1 Features of study watersheds at North Carolina (NC) and South Carolina (SC) study sites

Study Site Drainage Condition	Carteret, NC Drained	Carteret, NC Drained	Carteret, NC Drained	Parker, NC Drained	Santee EF, SC Undrained	Santee EF, SC Undrained	FMNF, SC Undrained	FMNF, SC Undrained	FMNF, SC Undrained	FMNF, SC Undrained
Watershed name/Drain Type	D1/100 m spacing; 1.2 m deep ditch	D2/100 m spacing; 1.2 m deep ditch	D3/100 m spacing; 1.2 m deep ditch	F6/90 m spacing; 1.0 m deep ditch	WS80/ Ephemeral stream	WS77/ Ephemeral stream	Turkey Creek-Ra/ Intermittent Stream	Turkey Creek-Ly/ Intermittent Stream	Turkey Creek-Go/ Intermittent Stream	Turkey Creek-Le/ Intermittent Stream
Latitude/ Longitude	34° 48′ N; 76° 42′ W	34° 48′ N; 76° 42′ W	34° 48′ N; 76° 42′ W	35°48’ N; 76°40’ N	33° 9' N; 79° 48' W	33° 9' N; 79° 48' W	33°08’N; 79°47’W	33°08’N; 79°47’W	33°08’N; 79°47’W	33°08’N; 79°47’W
Elevation, m	3.0	3.0	3.0	8.0	4.0 to 6.0	5.8 to 9.8	10.95	9.65	10.30	10.39
Slope, %	0.1	0.1	0.1	0.5	< 2.0	2	<1.0	<1.0	<1.0	<1.0
Area, ha	25	26	27	100	160	155	N/A	N/A	N/A	N/A
Planted Year	1974	1974; 1997	1974	1992	Regenerated 1989	Regenerated 1989	Regenerated 1989	Regenerated 1989	Regenerated 1989	Regenerated 1989
Vegetation Type	Loblolly Pine	Loblolly Pine	Loblolly Pine	Loblolly Pine	Pine mixed hardwood	Pine mixed hardwood	Longleaf/Loblolly	Longleaf/ Loblolly	Loblolly	Longleaf/ Loblolly
Silvicultural Treatment	None - Control	Controlled Drainage/ Harvest	Controlled Drainage/Thin-ning	Thinning	None - Control	Prescribed burning/ Thinning	Prescribed burning/ Thinning	Prescribed burning/ Thinning	Prescribed burning/ Thinning	Prescribed burning/ Thinning
Wetland, %	0	0	0	0	30	11	N/A	N/A	N/A	N/A
Soil Type	Deloss fine sandy loam	Deloss fine sandy loam	Deloss fine sandy loam	Belhaven organic loam	Mostly Wahee clay loam	Wahee and Craven clay loam	Rains fine loamy sand	Lynchburg fine sandy loam	Goldsboro fine sandy loam	Lenoir clayey mixed
Drainage Class	Very Poorly drained	Very Poorly drained	Very Poorly drained	Very Poorly drained	Somewhat poorly drained	Somewhat poorly drained	Poorly drained	Somewhat poorly drained	Moderately well drained	Somewhat poorly drained
Soil Hydro-logy group	B/D	B/D	B/D	C/D	D	D	B/D	C	B	D
Mean annual Rainfall, mm	1510	1513	1559	1320	1370	1370	1370	1370	1370	1370
Mean annual PET, mm	1010	1010	1010	1060	1135	1135	1135	1135	1135	1135
Dryness Index	0.67	0.67	0.65	0.80	0.86	0.86	0.83	0.83	0.83	0.83
WT Data Period	1988–2008	1988–2008	1988–2008	1993–2016	2005–2016	2005–2016	2007–2016	2007–2016	2007–2016	2007–2016
Mean GS WTD, cm	112	112	114	91	105.4	74.5	45.8	83.5	122.0	46.4
# of years GS WTD < 30 cm Cons.	1	0	0	1	10	10	10	9	1	10
Longest Ponding Days/Year	19/1989	12/1989	13/1989	24/1993	193/ 2015	140/ 2008	250/ 2015	160/ 2008	69/ 2008	226/ 2015
Annual WT Trend	No trend; $p = 0.80$	No trend; $p = 0.72$	No trend; $p = 0.69$	No trend; $p = 0.88$	No trend; $p = 1.0$	No trend; $p = 1.0$	No trend; $p = 0.84$	No trend; $p = 0.48$	No trend; $p = 1.0$	No trend; $p = 0.28$
References that had related studies with water table	Amatya and Skaggs (2011); Tian et al. (2012a)	Tian et al. (2012b); Amatya et al. (2006a)	Tian et al. (2012b); Amatya et al. (2006a)	Zhu et al. (2017); Diggs (2004)	Harder et al. (2007); Dai et al. (2013)	Amoah et al. (2012); Dai et al. (2013)	Amatya et al. (2016b, 2018); Callahan et al. (2012)	Amatya et al. (2016b, 2018); Callahan et al. (2012)	Amatya et al. (2016b, 2018); Callahan et al. (2012)	Amatya et al. (2016b, 2018); Callahan et al. (2012)

Author's personal copy

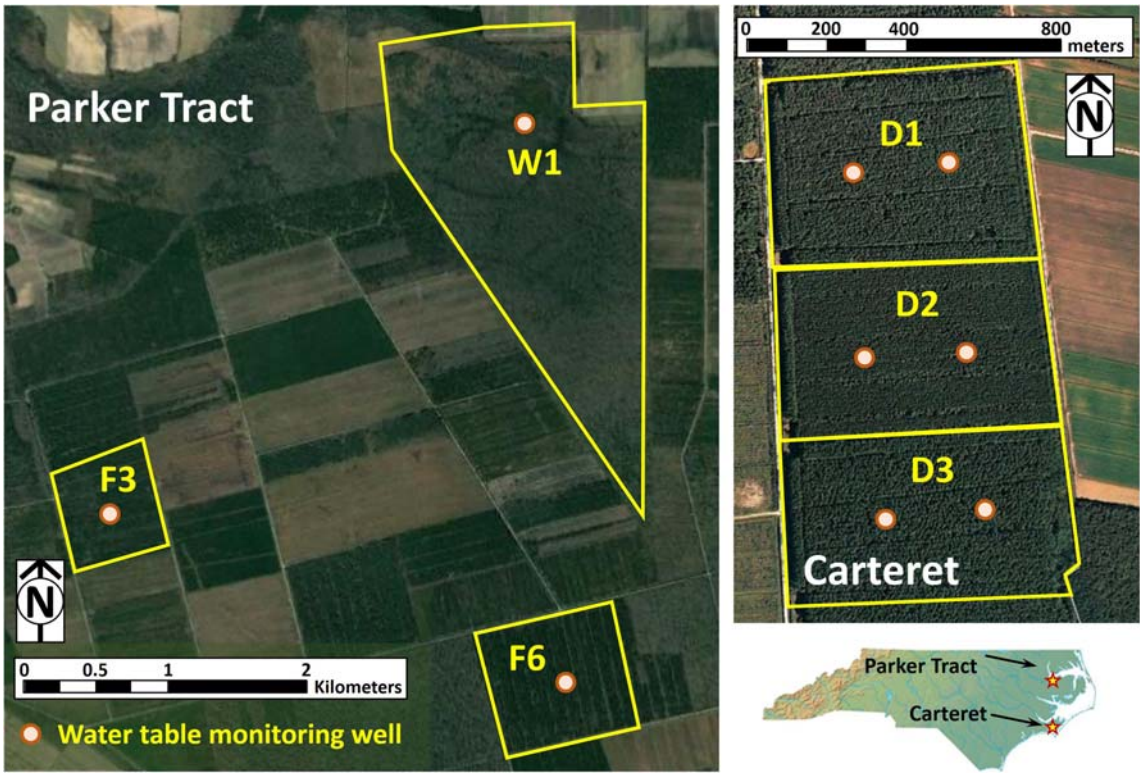

Fig. 2 Location of the Parker Tract and Carteret sites in North Carolina. Three study watersheds at the Parker Tract are shown on a 2012 image. Long-term (1993–2016) water table data were recorded from F6 and short-term (1993–1996) data were recorded from F3 and W1. Three study watersheds at the Carteret site are shown on a 2008 image. Long-term (1988–2008) water table data were recorded at D1, D2, and D3

(2012a, 2012b). Watershed D1 was without any disturbance and served as a control (reference) watershed. Until 1995 watershed D2 was under controlled drainage with a raised weir during the growing season to manage for productivity, and D3 was under controlled drainage with a raised weir during the spring season for reducing off-site impacts (Amatya et al. 1996, 2000). Watershed D2 was harvested in June 1995, with site preparation in 1996 followed by planting in 1998 for regeneration (Amatya et al. 2006a; Tian et al. 2012b). Details of the watersheds are given in Table 1.

WT elevations were measured in two recording wells located at mid-points between ditches on the east and west side of each watershed. Hourly data from each recorder were averaged and integrated to obtain the daily average for the watersheds. Rainfall was continuously recorded by an automatic rain gauge backed up by a manual gauge located at the western corner of each watershed. Details of hydro-meteorologic measurements are given elsewhere (Amatya and Skaggs 2011; Tian et al. 2012a).

Parker Tract, NC

Twenty-four years (1993–2016) of daily WT data were collected from an artificially drained watershed (F6) (Fig. 2) on a managed loblolly pine forest on Weyerhaeuser lands at Parker Tract in northern coastal NC (Diggs 2004; Tian et al. 2015; Zhu et al. 2017). Hourly WT elevation was recorded midway between ditches (Diggs 2004). An automatic and a manual rain gauge on the middle of the watershed collected rainfall data on a continuous basis. Details of the watershed are provided in Table 1,

Three years (1992–1995) of data were collected from another 43 ha drained forest watershed (F3) planted with loblolly pine in 1983 and from a natural forested wetland (W1) in the vicinity of the F6 watershed at Parker Tract (Skaggs et al. 2011b) (Fig. 2). The ditches on F3 are spaced 80 m apart and are 1.0 m deep (Diggs 2004). The soil on F3 is classified as Cape Fear series with dark sandy loam in the top 0.25 m with 5–15% organic matter, sandy clay loam at 0.25 to 0.60 m depth, sandy loam at 0.60 to 0.75 m depth. The natural wetland (W1) was an undrained nonriverine, palustrine forested hardwood wetland, a schematic water balance for which is shown in Fig. 1a. The 350 ha wetland had not been logged or otherwise disturbed for over 60 years. The predominant soil type was a Portsmouth sandy loam. Schematic water balance for all other watersheds including three at the Carteret site, NC is represented in Fig. 1b. The watersheds F3 and W1 were not listed in Table 1 with other sites because of the limited duration of data (3.5-years) available for analysis.

Santee Experimental Forest, SC

Fourteen years (2004–2017) of data were used from a minimally disturbed undrained reference watershed (WS80) and a

Author's personal copy

paired adjacent treatment watershed (WS77). These pine and hardwood mixed forest watersheds are located on the US Forest Service Santee Experimental Forest (SEF) in coastal South Carolina (Fig. 3) described earlier by (Amatya et al. 2006b; Amatya and Trettin 2007; Harder et al. 2007; Dai et al. 2010a, 2010b, 2013; Amoah et al. 2012; Epps et al. 2013; Jayakaran et al. 2014). WS80 was last logged before 1937 when US Forest Service acquired the lands for experimental research. This is a naturally drained forested watershed. There is an old plugged ditch of about 1.2 to 1.5 m depth and 3–4 m top width dug somewhat inside of the eastern side of the road that serves as the watershed boundary. However, it is not connected to an outlet and is unlikely to have any effect on water table measurements in the watershed. Details of the control (WS80) and treatment (WS77) watersheds are presented in Table 1. The treatment watershed undergoes periodic thinning and prescribed burning as minimal operational management practices of the National Forest.

WT in the well H on the upland part of WS80 and well J on the west side of WS77 (Table 1) has been measured on an hourly basis since 2004 using the WL-15 until 2006 and WL-16 pressure transducers with a datalogger thereafter (Fig. 3). WT data measured from 2004 to 2016 are analyzed in this paper. Rainfall was recorded using an automatic rain gauge backed up by a manual gauge on WS80 and WS77.

Turkey Creek Watershed, SC

Nearly 12-years (2006–2017) of data from ground water wells at four different locations on the left bank of the large 5240 ha Turkey Creek watershed (Fig. 3) was collected by the US Forest Service at Francis Marion National Forest (FMNF) (Amatya et al. 2018; Callahan et al. 2012; Morrison 2016). The soil types vary from very poorly drained to moderately well drained (Table 1). These wells are within less than 4 km of each other and are on pine and mixed hardwood forests with frequent (every 2–3 years) prescribed burning for understory biomass removal to restore longleaf pine as well as red-cockaded woodpecker (*Picoides borealis)* habitat. There are no constructed drainage ditches in the vicinity of the site. Observation wells are located on Rains soil in a depressional wetland and on Lynchburg soil between two creeks draining two small catchments. Two other wells on Lenoir and Goldsboro soils are located at somewhat higher elevations. WTD in all the wells was measured on an hourly basis since mid-2006 using the WL-16 pressure transducer with a

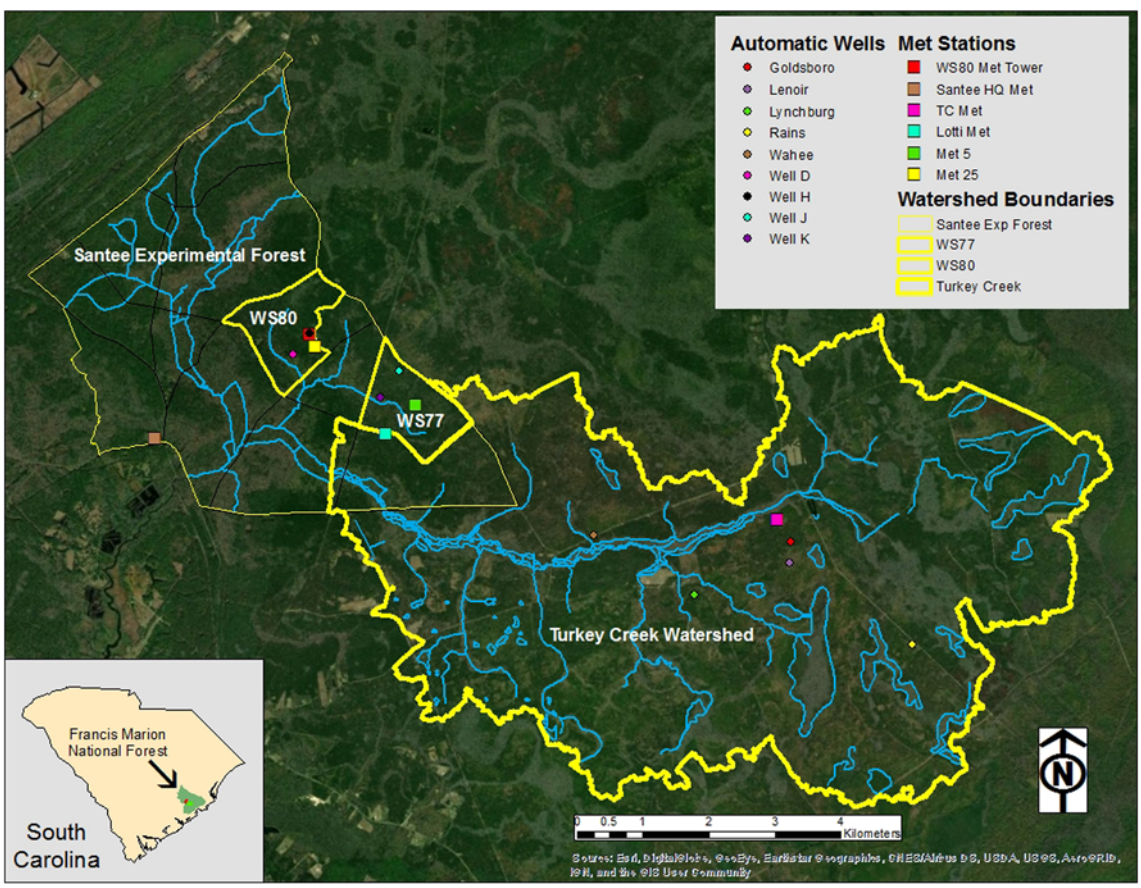

Fig. 3 Location map of Santee Experimental Forest in coastal South Carolina showing locations of all ground water wells, rain and flow gauging stations on watersheds. Thick yellow boundary represents Turkey Creek watershed

Author's personal copy

datalogger. Rainfall was recorded since late 2005 by an automatic rain gauge at a weather station located near the four wells (Fig. 3). Detailed physical, hydro-meteorologic, and vegetation characteristics and silvicultural practices of each of these study sites are provided in Table 1.

Hydro-meteorologic and water table data for sites at Santee Experimental Forest and Turkey Creek watershed can be accessed at https://www.srs.fs.usda.gov/charleston/santee/

Data Analysis

Hourly water table depth (WTD) data were integrated to obtain daily average WTD at all the sites. These data were analyzed to derive basic statistics including mean, standard deviation, maximum, and minimum for the length of the record as well as for the growing season of each year of record. The growing season period for the SC sites and the all sites in NC was based on the frost free period as defined in the NRCS (Natural Resources Conservation Service, formerly Soil Conservation Service (SCS)) County Soil Survey Reports (SCS 1980, 1981). Daily WTD data from sites with various silvicultural and water management practices were also used to a) identify wetland hydrology status (WTD < 30 cm for 14 consecutive days during the growing season (Skaggs et al. 2011a) in >50% of the years of the period of record) and b) derive WTD frequency and duration curves using Weibull distribution plotting method to examine the frequency of ponding, saturation, and dry periods, and c) examine the annual mean WTD trend (decline or increase) using Mann-Kendall non-parametric correlation coefficients for significance testing (Burn and Elnur 2002; Hamed 2008). The null hypothesis is that there is no temporal trend or change of mean annual water table (i.e., Mann-Kendall computed $p > 0.05$), although an increasing temperature trend in this region has been reported (Dai et al. 2013; Marion et al. 2013). Furthermore, the effects on WTD due to a) an extreme precipitation in 2015 at the SC site, and b) the aftermath of Hurricane Hugo (natural disturbance) in 1989 on the WS80, SC site were examined using 1992–1993 data and then compared with the aftermath of harvesting (anthropogenic disturbance) of pine forest at D2 in NC in mid-1995 using 1998–1999 data.

Results and Discussion

Water Table, Outflow, and ET

Comparison of 3.5 years of WTD for a mature drained pine forest and a natural forested wetland showed that the WT was deeper under the mature drained forest (F3) than under the wetland (W1) at all times (Fig. 4). The WT in the wetland site was at or above the surface for extended periods in the winter and spring months of all three years, except for the very dry 1993 summer with higher ET demands. This is consistent with Amatya et al. (2003b) who also found the WT in the SC undrained forested wetland (WS80) site (Fig. 3) near the surface for extended periods of time than for the drained NC pine forest site (D1) (Fig. 2) (Table 1). Compared to the young forest (F6), the WTD of the natural wetland was deeper during the dry period in the summer and fall of the first year and was shallower during the wet periods in the winter and spring, (Fig. 4). This was likely due to lower ET from the shallow rooted young pine trees when water was limited. The WTD of the young drained forest became deeper relative to those of the natural wetland as the trees grew (Fig. 4). Similar to this, Amatya et al. (2003b) reported deeper WT (below the recorder range of 2.6 m) during the growing season on the undrained SC site compared to a maximum depth of about 2 m on drained NC site as also shown below in Fig. 5. This was attributed possibly due to increased growing season ET from pine mixed hardwood stand on the undrained WS80 site, potentially resulting in reduced average annual outflow (22% of rainfall) compared to pine only forest on the drained site (D1) with 31% of the rainfall as outflow. This is consistent with Jayakaran et al. (2014) who also found less runoff from the WS80 site compared to the pine dominated paired watershed (WS77) on the same soils (Fig. 3). However, the above difference in outflow between the undrained SC and drained NC site found by Amatya et al. (2003b) may also be due to difference in rainfall and ET between the two sites as Skaggs et al. (2011a) found annual outflows from the wetland site (W1) similar to the drained forest site (F6) (Fig. 4) in the same area with an average annual rainfall of 1287 mm for a limited three-year period.

Mean annual ET (estimated as rainfall – runoff) at both the drained Carteret site (D1) and the undrained SC site (WS80) were similar, probably because ET was more limited by energy with rainfall > PET at both sites (1510 mm rain and 1010 mm PET at Carteret D1 and 1370 mm rain and 1135 mm PET at WS80) (Table 1). The SC site may be seasonally moisture limited during dry years as observed in 2006 and 2007 as will be shown below. Similar ET of about 1040 mm at both the sites (Tian et al. 2012a; Dai et al. 2013) indicates ditching did not limit ET on the NC site. Similar results were found for the drained highly organic soils on the F6 watershed at Parker Tract in NC and the SC site (WS80) with dominant clayey soils. ET/rain ratios were 0.75 or higher in both cases, indicating no apparent effects of drainage ditches on mean ET. These results contradict a recent finding by Wu et al. (2016) who found a significant difference in mean annual ET obtained by the Eddy Covariance -method for a heavily drained deep and a more functional shallow wetland, both categorized as herbaceous depressional wetlands with only scattered pine trees, in a subtropical Florida site. The contradiction can be mainly attributed to the significant reduction of open water area, which not only directly

Author's personal copy

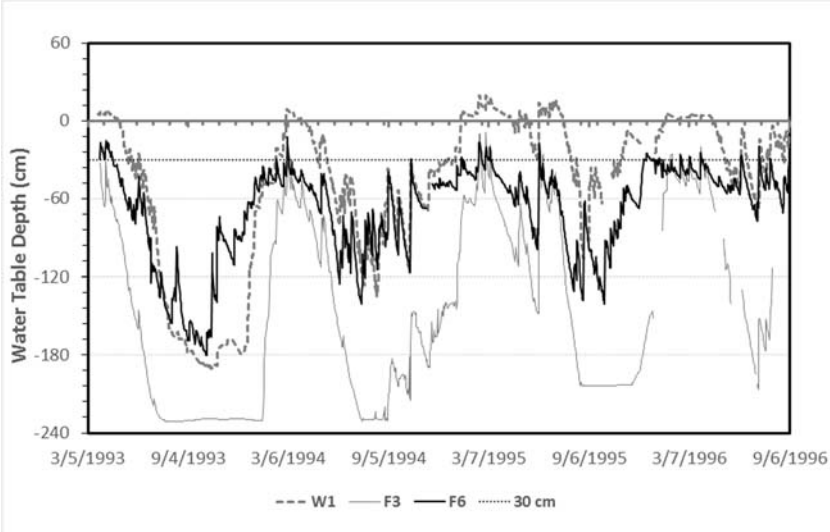

Fig. 4 Daily water table depths measured on two drained managed pine (F3 and F6) and one natural wetland (W1) forest sites for 1993–1996 in coastal North Carolina

reduced ET by reducing open water surface dominated water flux, but also indirectly affected ET flux by changing net radiation and local relative humidity. Another contributing factor could be the different root depths between dominate vegetation: mature pine forests versus short herbaceous plants. Skaggs et al. (2011b) noted that higher ET of deeper rooted forests potentially resulted in deeper WT on drained forest than in drained agricultural crop sites, indicating ET from deep rooted vegetation could be less responsive to WT drawdown compared to that from shallow rooted vegetation.

Despite somewhat deeper WTD of the undrained sites than the drained ones during the growing season (Fig. 5), the long-term mean growing season WTD of the undrained sites was found to be shallower, than that of the drained sites (Table 1). Exceptions are results for the poorly drained site at WS80 (compared to F6 site only) and the naturally well drained Goldsboro site (Table 1).

Growing season average WTD for the 21-year period was similar (1.12 to 1.14 m) on all three NC Carteret watersheds (D1, D2, and D3) (Table 1) despite various silvicultural and water management operations applied to D2 and D3 (Amatya et al. 1996, 2000, 2003a, 2006a, Tian et al. 2012a, b). Short term increased WT levels (shallower WTD) at midpoints of watersheds were reported during controlled drainage with weirs raised up to 60 cm from the ground surface at the outlets of D2 during the growing season (June–September) and up to 40 cm from the ground surface at D3 during the spring season (March–June) of 1990–1994 (Amatya et al. 2000). However, the WTD was well below 30 cm from the average ground surface, with no potential for wetland hydrology. WTD on the D3 watershed was not affected by a raised weir with a 0.15 m diameter orifice outlet at about 0.3 m above ditch bottom throughout the 1995–2000 period (Amatya et al. 2003a). This type of data from the controlled drainage watersheds could be used for examining wetland hydrology but were limited. In another companion study, Amatya et al. (2006a) reported increased WT levels (shallower WTD) soon after harvesting in mid-1995 on D2 (with no controlled

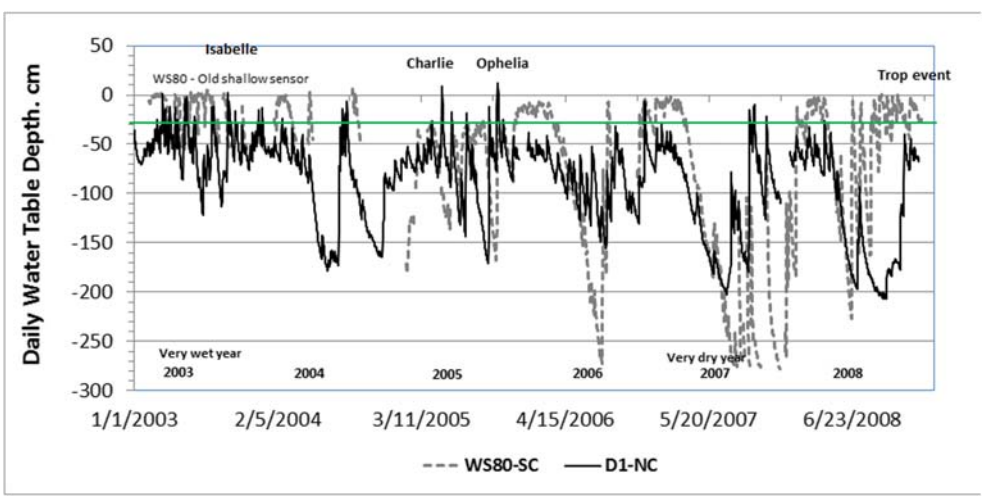

Fig. 5 Daily water table depths measured from the ground surface at well H on WS80, watershed (SC) and D1 watershed (NC) for 2003–2008

Author's personal copy

drainage) and then returned back to base line level by 2003, with no evidence of wetland hydrology being met in any year until the recovery.

Average WTD on the poorly drained Rains and somewhat poorly drained Lenoir soils in the undrained Turkey Creek watershed site in SC were 0.46 m compared to >1.1 m at the drained forest sites in NC (Table 1). The WTD on the moderately well-drained Goldsboro soil within the undrained Turkey Creek watershed was, however, deeper than at all of the four drained NC Sites. Average WTD for the other three sites in SC were shallower than the drained NC sites.

A trend analysis using the Mann-Kendall non-parametric test showed no significant ($\alpha = 0.05$) trend in annual mean WTD on any of the above study sites. The *p*-values for tests of significance varied from 0.28 for Lenoir soil on the Turkey Creek watershed to 1.0 on the WS80 well site (Table 1). An earlier study on the D1 site at the Carteret, NC site also showed no trend (Marion et al. 2013). Citing the lack of these type of long-term data, Liu and Kumar (2016) used a physically based, fully distributed hydrologic model to simulate long-term wet-period variations in 10 inland forested wetlands in a southeastern US watershed. The authors found wet-period start date and duration varying by more than 6 months during the 32-year simulation period and 60–90% of these variations were explained using regressions based on seasonal precipitation and PET in most wetlands.

Wetland Hydrology

Wetland hydrology status was determined for all study sites based on the criterion that the WTD below ground surface was <30 cm for a continuous period of at least 14 days during the growing season in 50% or more of the years of record. All of the undrained sites with soils classified as either poorly drained or somewhat poorly drained under natural conditions (Wahee on WS80 and Rains, Lenoir, and Lynchburg on Turkey Creek watersheds, SC) met the criterion. The moderately well-drained Goldsboro soil on Turkey Creek watershed did not. The first three soils met the criterion in 10 out of 10 years while the Goldsboro soil met the criterion only once during the wet year of 2008 (Table 1). None of the artificially drained sites, met the wetland hydrology criterion. This is not surprising as drainage was installed on these sites in the early to mid-1970s before wetland regulations were developed. It is possible to install minor drainage systems that will provide the needs for silviculture while maintaining wetland hydrology on most of the area affected (Skaggs et al., this volume). However, this requires an improved understanding of the effect of forest vegetation and its evolution on soil properties that affect the performance of the drainage system. This analysis showed that the undrained forest sites (no ditches) on soils classified as poorly drained under natural conditions met the wetland hydrology criterion. This was not the case for an undrained site on a soil classified as moderately well drained. Further, if the drainage intensity of drained sites in NC was much reduced, say with drainage ditches at a spacing of 400 m rather than 100 m, and, say, 60 cm depth instead of 100 cm, wetland hydrology would likely have been maintained. Additional work is needed to test such a hypothesis.

Despite higher excess moisture (Rain – PET = 400 mm) at the Carteret, NC sites (D1, D2, and D3) than at all five SC sites (Rain – PET = 235 mm) (Table 1), the Carteret sites did not satisfy the criterion for wetland hydrology. Controlled drainage (ditch outlet weir levels raised up to about 0.3 m below average ground surface during the spring season on D3 from 1990 to 1993; Amatya et al. 1996) did not result in wetland hydrology. However, the weir levels were lowered to drain depth relatively early in the growing season. Haahti et al. (2017) also reported only a limited effect of the use of structures to raise ditch water level on field WT. Some studies suggest that plugging ditches with raised weirs to the ground surface throughout the year may restore wetland hydrology (Euliss et al. 2013) although more multi-site experimental data are needed to verify this approach. Lõhmus et al. (2015) notes that although ditches deteriorate in time, they remain functional for decades after abandonment, and pre-drainage ecosystem features may not recover without active intervention (Similä et al. 2014) or at all (Holden et al. 2006).

Most of the above studies investigated wetland hydrology in drained forests with parallel ditch systems. Skaggs et al. (2005) developed methods to determine effects of a single ditch on wetland hydrology (i.e., to calculate the distance of influence of a single ditch constructed through a wetland, where the distance of influence is defined as the width of a strip adjacent to the ditch that is drained such that it will no longer satisfy the wetland hydrologic criterion). The discovery that water table conditions barely satisfying the wetland hydrologic criterion are well correlated to the time required for water table drawdown of 25 cm (T_{25} values) makes it possible to predict the effects of subsurface drains on wetland hydrology.

Water Table Depth Frequency Duration Analysis

Data in Fig. 6a show the daily WTD frequency duration plots for groundwater wells on six soil types on undrained watersheds at Santee Experimental Forest, SC (Fig. 3; Table 1). The plot shows that the WT on the poorly drained Rains soil was at and above the surface with ponding for 33% of the time followed by Lenoir for 10% of the time, and Lynchburg for nearly 1% of the time over more than 10 years of record. During the extreme rainfall event of October 3–4, 2015 (nearly 500 mm of rainfall), the maximum daily average ponding depth was 41 cm on the Lenoir soil site, followed by 32 cm on the Rains site. Ponding on the moderately drained Goldsboro soil was only 1.6 cm during that event. Well H on Wahee soil

Author's personal copy

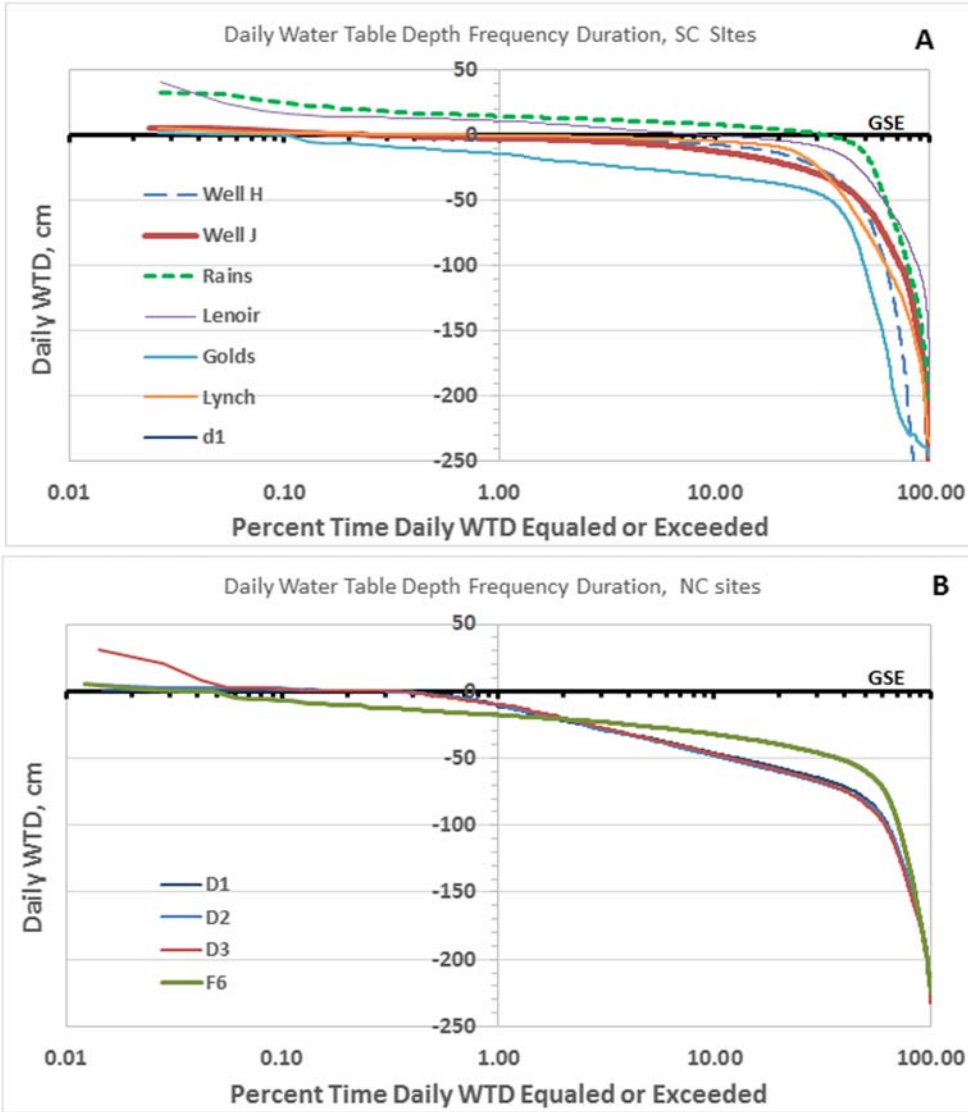

Fig. 6 Daily water table depth frequency duration curves (**a**) for six sites in SC and (**b**) for four sites in NC

(WS80) and Lynchburg soil response was intermediate without any ponding.

As with the ponding depth and duration, frequency of saturation was greatest in poorly drained Rains and Lenoir soils, with WTD less than 30 cm for 56% and 50% of time, respectively. One reason for a longer duration of ponding and saturation on the Rains site was its location in a depression (Callahan et al. 2012). WTD in the moderately well-drained Goldsboro soil was less than 30 cm only about 8.5% of the time for the 10+ year record period. The remaining three wells (well H on WS80, well J on WS77, and the well on the Lynchburg soil) had WTD at or above 30 cm depth between 31 to 35% of the time for the period of record. Median WTD also followed NRCS drainage classes with median depths on Rains and Lenoir soils at 14 cm and 30 cm, respectively, and wells H (WS80) and J (WS77) on Wahee and Turkey Creek Lynchburg soil at 58 cm, 54 cm and 71 cm, respectively, and on the moderately well drained Goldsboro soil at 102 cm.

In contrast to the undrained forests, daily WTD on all four drained sites was at or above the surface for less than 0.3% of the time and only 0.05% on the F6 watershed in the Parker Tract site. The daily WTD at F6, however, was within 30 cm of the surface 7.7% of time on organic soil compared to just 3.2 to 3.6% of the time on three other mineral soil sites (D1, D2, and D3). While the differences in WTD frequencies between the drained NC and undrained SC sites may be attributed to drainage effects, the difference within the NC sites may also be attributed to differences in both the rainfall (Carteret > Parker) and soil types (Table 1).

A recent study by McCauley et al. (2015) showed that water surface areas of consolidated wetlands in extensively drained landscapes were 197% greater than those with no drainage and now require more extreme drought conditions to dry out. They also found wetlands in extensively drained catchments were larger, dry out less frequently, and have more surface-water connections to other wetlands via ditches.

Author's personal copy

However, how these findings play a role in the overall discussion of effects of minor silvicultural drainage on wetland hydrology, a focus of this special issue, is yet to be investigated.

Effects of Natural and Anthropogenic Disturbance on Water Table

In September 1989 Hurricane Hugo (a natural disturbance), devastated more than 80% of the forest canopy on WS80 (Hook et al. 1991). The mean WTD on WS80 was elevated substantially (18.5 cm depth below the ground surface) until 1992. In 2005 after complete regeneration of the forest stand a mean depth of 70.4 cm was observed on WS 80 (Jayakaran et al. 2014), despite somewhat higher rainfall in 2005 compared to 1992 (Table 2).

After a complete harvest (anthropogenic disturbance) of the drained pine forest at Carteret (D2) in 1995, the observed mean WTD of 60 cm in 1998 was less, as expected, than the mean depth of 80 cm measured in 2005 (Table 2) after complete regeneration of the pine forest with hydrology similar to baseline levels (Amatya et al. 2006a). WTD on regenerated stands of both watersheds (WS80 and D2) also responded very similarly during very wet (with WT within 12 cm) and dry years (WT within 230–280 cm) (Table 2). Thus both drained and undrained watersheds behaved similarly after vegetation removal, either by extreme natural or anthropogenic disturbance, compared to the baseline level, supporting our hypothesis. In contrast, a recent study by Jutras et al. (2006) in eastern Canada forested wetlands used for timber production found a persistent water table level rise (watering-up) until 10 years after clearcutting of drained stands. This delayed the stand and hydrologic recovery compared to the uncut stands.

Data in Table 2 also indicate that, despite higher rainfall at the NC drained site D2 in both post-harvest and after regeneration years compared to the undrained natural pine mixed hardwood forest site in SC, its mean WTD were relatively deeper than that of undrained WS80. This was likely due to higher outflows caused by the drained system (Amatya et al. 2003b). The effect of ET was ruled out because the mean annual ET at both sites were similar (Tian et al. 2012a; Dai et al. 2013).

Effects of Extreme Climatic Conditions on Water Table

During Hurricane Fran in September of 1996 and Hurricane Bonnie in August of 1998 the WT on both the control (D1) and treatment (D3) watersheds at the Carteret, NC site rose to near the surface (average elevation of 2.8 m). In both cases, 24-h rainfall was greater than 200 mm. Similar observations were made during Hurricane Dennis in late August-early September 1999 followed by Hurricane Irene in October (Amatya et al. 2003a). During dry conditions in 2001 (annual rainfall less than 46% of the long-term mean) at the drained Carteret NC watersheds, WTD was as deep as 2.3 m below the surface (Amatya and Skaggs 2001; Amatya et al. 2006a). The response of the WTD at the undrained WS80 watershed in SC was as deep as 2.8 m in 2007 with 33% lower rainfall than the long-term average (Dai et al. 2010a) (Table 2). Hourly water table data recorded at seven recording wells on various soil types during September and October 2015 are presented in Fig. 7 along with the hourly rainfall recorded at Santee Headquarters gauge.

Wet conditions due to a cumulative rainfall of 170 mm 5 days prior to October 3 resulted in ponding at the wells in the Rains and Lenoir soils. Surface ponding depths of 46.3 cm for the Lenoir well and 40.7 cm for the Rains well were recorded by late night of October 3, with 24-h rainfall intensities up to 60 mm/h in all four gauges. Similarly, the WS80 site also experienced ponding by as much as 7.5 cm in September 2003 in response to a 24-h rain of 176 mm with prior wet conditions. Results showed that the WT in all soil types responds similarly during both extreme wet (Amatya et al. 2016b) and dry events, supporting our hypothesis.

Summary and Conclusions

This study characterized wetland hydrology using 10 or more years of daily data on groundwater table for four drained managed pine forests and six undrained pine mixed hardwood forests on the Atlantic Carolina Coastal Plain. During the period studied, anthropogenic (silvicultural and water management practices) and natural (extreme events) disturbances

Table 2 Measured mean water table depth in response to extreme events of natural disturbance (Hurricane Hugo, 1989) in SC and anthropogenic (Clearcutting, 1995) disturbance in NC

WS80 watershed, Santee, SC				D2 watershed, Carteret, NC			
1992 (post-Hugo)		2005 (after regeneration)		1998 (post-harvest)		2005 (after regeneration)	
Rain mm	WTD cm	Rain mm	WTD cm	Rain mm	WTD cm	Rain mm	WTD cm
1473	18.5	1540	70.4	1617	60	1777	80
2008 wet period		2007 dry period		2003 wet period		2001 dry period	
2171	−12.5	923	280	2331	−7.5	852	230

Author's personal copy

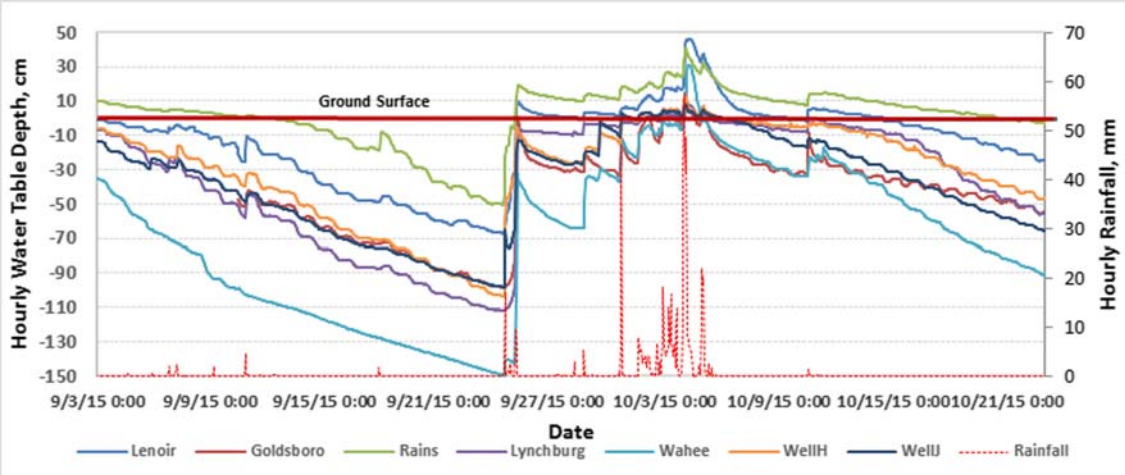

Fig. 7 Hourly water table depths measured on seven different locations at Santee Experimental Forest, SC before, during, and after the extreme precipitation event of October 3–4, 2015. Hourly rainfall recorded at Santee Headquarters gauge is also shown (*After* Amatya et al. 2016a, b)

affected short-term WT dynamics, but much less on the annual WTD. Drainage effects on hydrologic processes were similar to those proposed in Fig. 1a, b. Rainfall exceeded PET on all study sites on poorly drained shallow WT soils. There, was no evidence that drainage had a major effect on ET, which, along with rainfall, is a major driver of hydrology on these sites. Forest drainage appears to primarily result in less frequent and shorter duration ponding and deeper median water table depths than undrained sites. Adding drainage ditches at closer spacing than the natural stream density of young coastal sediments results in deeper water tables between the ditches. The decline of WTD with increase in subsurface drainage flow does not appear to substantially limit ET of deeply rooted forests. Our results showed that during extreme dry conditions, forest ET lowers the WT over 2 m below the surface, well below the ditch bottom; ditching has no obvious impact on that depth. Likewise, extreme rainfall associated with tropical storms exceeds the capacity of the drainage system, both natural and artificial, to remove water and creates soil saturation across the landscape.

The hydrologic criterion for wetlands was not satisfied for any of the drained forested lands considered in this study. In the absence of artificial or man-made drainage, in general, NRCS drainage class is a good indicator of average WTD, although there are differences in average depth and variability caused by subsurface texture (Williams and Amatya 2016). The results of this study suggest that forest drainage causes forest soils to behave as if they were in a higher drainage class. The drainage spacing examined in this paper tended to make very poorly drained soils behave as if they were moderately well drained. It should be noted that all the drainage ditches in this study were installed during the mid-twentieth century, well before wetlands regulations and the wetlands hydrology criteria were developed. Assessment of wetland hydrology of the forested wetlands (both drained and undrained) on poorly drained soils using long-term data from multiple site-years including those in this study is needed to identify the historic and projected trends in WT dynamics and wetland hydrology of forested wetlands. Similarly, it may be worthwhile to study the water table dynamics of sites, particularly on the poorly drained soils, managed with lower basal area for potentially increasing the water yield as was recently shown by McLaughlin et al. (2013). It is possible that the increase in water yield may also be attributed to rise in water table (for that soil moisture) meeting the wetland hydrology. These assessments will be improved using model simulation studies informed by long term data sets (Sun et al. 1998; Lu et al. 2009; Skaggs et al. 2012; Tian et al. 2012a, b; Amatya et al. 2018). This would provide land managers and policymakers a state-of-the-science ability to assess not only wetland hydrology but also potential thresholds for wetland hydrology due to minor silvicultural drainage, responses of these systems to innovative best management practices, anticipated climate changes, trends, and extremes as was recently done by Marion et al. (2013) for water supplies in the Southeast.

Acknowledgements The authors would like to acknowledge Cliff Tyson of Weyerhaeuser and Andy Harrison and Julie Arnold of USDA Forest Service for providing data support from the NC and SC study sites, respectively, and also former USDA Forest Service personnel Dennis Law and Bill Hansen for providing support for well installation on Turkey Creek watershed.

References

Amatya DM and Skaggs RW (2001) Skaggs RW (2001) hydrologic modeling of pine plantations on poorly drained soils. Forest Science 47(1):103–114

Amatya DM, Skaggs RW (2011) Long-term hydrology and water quality of a drained pine plantation in North Carolina, U.S.A. Transactions of the ASABE 54(6):2087–2098

Amatya DM, Trettin CC (2007) Development of watershed hydrologic studies at Santee experimental Forest, South Carolina. In: Furniss M,

Author's personal copy

Clifton C, Ronnenberg K (eds) Proceedings of the Forest Service National Earth Sciences Conference. PNW-GTR-689, vol I. USDA, Forest Service, Pacific Northwest Research Station, Portland, pp 180–190

Amatya DM, Skaggs RW, Gregory JD (1996) Effects of controlled drainage on the hydrology of a drained pine plantation in the North Carolina Coastal Plains. Journal of Hydrology, 181(1996), 211–232

Amatya DM, Skaggs RW, Gregory JD, Herrmann R (1997) Hydrology of a forested Pocosin watershed. Journal of American Water Resources Association 33(3):535–546

Amatya DM, Gregory JD, Skaggs RW (2000) Effects of controlled drainage on storm event hydrology in a loblolly pine plantation. Journal of the American Water Resources Association 36(1):175–190

Amatya DM, Chescheir GM, Skaggs RW, Fernandez GP (2002) Hydrology of poorly drained coastal watersheds in Eastern North Carolina. Paper #022034, St. Joseph, MI: ASAE

Amatya DM, Skaggs RW, Hughes JE (2003a) Effects of an orifice and a weir on the hydrology and water quality of a drained forested watershed. Southern Journal of Applied Forestry 27(2):130–142

Amatya DM, Sun G, Trettin CC, Skaggs RW (2003b) Long-term Forest Hydrologic Monitoring in Coastal Carolinas. *In Proc.* Renard, Kenneth G., McElroy, Stephen A., Gburek, William J., Canfield, H. Evan and Scott, Russell L., eds. First Interagency Conference on Research in the Watersheds, October 27–30, 2003. U.S. Department of Agriculture, Agricultural Research Service, pp: 279–285

Amatya DM, Skaggs RW, Blanton CD, Gilliam JW (2006a) Hydrologic and water quality effects of harvesting and regeneration of a drained pine forest. In Proc. of the ASABE-Weyerhaeuser sponsored Int'l conference on hydrology and Management of Forested Wetlands, eds. Williams and Nettles, New Bern, NC, April 8-12, 2006

Amatya DM, Miwa M, Harrison CA, Trettin CC, Sun G (2006b) Hydrology and water quality of two first order watersheds in coastal South Carolina. Paper # 062182, St. Joseph, MI: ASABE

Amatya DM, Callahan TJ, Trettin CC (2016a) Synthesis of 10 Years of Studies on Turkey Creek Watershed. *In:* Headwaters to estuaries: advances in watershed science and management (pp23–33), Proc. of the 5th Interagency Conference on Research in the Watersheds. Editors: Stringer, C. E.; Krauss, K. W.; Latimer, J. S., e-Gen. Tech. Rep. SRS-211. Asheville, NC: USDA Forest Service, Southern Research Station

Amatya DM, Harrison CA, Trettin CC (2016b) Hydro-meteorologic assessment of October 2015 extreme precipitation event on Santee experimental Forest watersheds, SC. Journal of South Carolina Water Resources 3(1):19–30

Amatya DM, Fialkowski M, Bitner A (2018) A daily water table depth computing model for poorly drained soils. Wetlands 39:39–54. https://doi.org/10.1007/s13157-018-1069-7

Amoah J, Amatya DM, Nnaji S (2012) Quantifying watershed depression storage: determination and application in a hydrologic model. Processes 2012, DOI: https://doi.org/10.1002/hyp.9364

Beltran B, Amatya DM, Youssef MA, Jones M, Skaggs RW, Callahan TJ, Nettles JE (2010) Impacts of fertilization additions on water quality of a drained pine plantation in North Carolina: a worst case scenario. Journal of Environmental Quality 39:293–303

Brinson MM (1993) A hydrogeomorphic classification for wetlands. Wetlands research program technical report WRP-DE-4, US Army engineer waterways Experiment Station, Vicksburg MS

Buol SW (ed) (1973) Soils of the southern United States and Puerto Rico. Southern cooperative series, bulletin # 174. Agricultural Experiment Stations of the southern United States and Puerto Rico Land Grant Universities, Fort Worth TX

Burn DH, Elnur MAH (2002) Detection of hydrologic trends and variability. Journal of Hydrology 255:107–122

Callahan TJ, Vulava VM, Passarello MC, Garrett CG (2012) Estimating groundwater recharge in lowland watershed. Hydrological Processes. https://doi.org/10.1002/hyp.8356

Chescheir GM, Lebo ME, Amatya DM, Hughes JE, Gilliam JW, Skaggs RW, Herrmann RB (2003) Hydrology and water quality of forested lands in eastern North Carolina. Technical bulletin no. 320, N. C. State Univ., Raleigh, NC

Dai Z, Trettin CC, Li C, Amatya D, Sun G, Li H (2010a) Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. Journal of the American Water Resources Association 46(1):1–13

Dai Z, Amatya DM, Sun G, Trettin CC, Li C, Li H (2010b) A comparison of MIKESHE and DRAINMOD for modeling forested wetland hydrology in coastal South Carolina, U.S.a., proceedings, 9th international drainage symposium at the XVIIth world congress of the CIGR, Quebec, Canada, June 12-14, 2010

Dai Z, Trettin CC, Amatya DM (2013) Effects of climate variability on Forest hydrology and carbon sequestration on the Santee experimental Forest in coastal South Carolina. USDA Forest Service Southern Research Station, General Technical Report SRS-172:32p

Diggs JA (2004) Simulation of nitrogen and hydrology loading of forested fields in eastern North Carolina using DRAINMOD-N 11. M.S. Thesis, North Carolina State University, Raleigh, NC, 155 p

Epps T, Hitchcock D, Jayakaran AD, Loflin D, Williams TM, Amatya DM (2013) Characterization of storm flow dynamics of headwater streams in the South Carolina lower coastal plain. Journal of American Water Resources Association 49(1):76–89. https://doi.org/10.1111/JAWR.12000

Eshleman K, Pollard J, O'Brien A (1994) Interactions between groundwater and surface water in a Virginia coastal plain watershed, 1. Hydrological Flowpaths. Hydrological Processes 8:389–410

Euliss Jr NH, Brinson MM, Mushet DM, Smith LM, Conner WH, Burkett VR, Wilcox DA, Hester MW, Zheng H (2013) Ecosystem services: developing sustainable management paradigms based on wetland functions and processes. In: wetland techniques: volume 3: applications and management, Anderson JT, Davis CA (eds.), Springer Science, 270 p

Haahti K, Nieminen M, Finer L, Martilla H, Kokkonen T, Leinonen A, Koivusalo H (2017) Model-based evaluation of sediment control in a drained peatland forest after ditch network maintenance. Canadian Journal of Forest Research 48(2):130–140

Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. Journal of Hydrology 349.3–4 (2008): 350–363

Harder SV, Amatya DM, Callahan TJ, Trettin CC, Hakkila J (2007) Hydrology and water budget for a forested Atlantic coastal plain watershed, South Carolina. Journal of American Water Resources Association 43(3):563–575

Harms WR, Aust WM, Burger JA (1998) Wet Flatwoods. In: Messina MG, Conner WH (eds) Southern Forest wetlands. Lewis Pub, Boca Raton, pp 421–444

Hitchcock DR, Jayakaran AD, White DL (2014) Green infrastructure in coastal landscapes: hydrological function, ecological design and sustainable land use guidance. Journal of South Carolina Water Resources 1(1):35–38

Holden J, Evans MG, Burt TP, Horton M (2006) Impacts of land drainage on peatland hydrology. Journal of Environmental Quality 35:1764–1778

Hook DD, Buford MA, Williams TM (1991) Impact of Hurricane Hugo on the South Carolina Coastal Plain Forest. Journal of Coastal Research (Special Issue No. 8) pp. 291–300

Hughes J (2014) History of coastal Forest drainage in North Carolina. A presentation at USDOE BETO workshop, Weyerhaeuser, New Bern, NC, March 04:2014

Jaeschke EM (2013) The hydrology of a Pocosin site in the Hofmann Forest, North Carolina, USA. Unpublished M.S. Thesis, North Carolina University, Raleigh, NC

Jayakaran A, Williams TM, Ssegane HS, Amatya DM, Song B (2014) Trettin CC (2014) hurricane impacts on a pair of coastal forested

Author's personal copy

watersheds: implications of selective hurricane damage to Forest structure and streamflow dynamics. Hydrology and Earth System Sciences (HESS) 18:1151–1164

Jutras S, Plamondon AP, Hökkä H, Bégin J (2006) Water table changes following Precommercial thinning on post-harvest drained wetlands. Forest Ecology and Management 235:252–259

Liu Y, Kumar M (2016) Role of meteorological controls on interannual variations in wet-period characteristics of wetlands. Water Resources Research 52:5056–5074. https://doi.org/10.1002/2015WR018493

Lõhmus A, Remm L, Rannap R (2015) Just a ditch in Forest? Reconsidering draining in the context of sustainable Forest management. Bioscience 65(11):1066–1076

Lu JG, Sun S, McNulty G, Comerford NB (2009) Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, U.S.A. Wetlands 29(3):826–836

Marion DA, Sun G, Caldwell PV, Ford CR, Ouyang Y, Amatya DM, Clinton BD, Conrads PA, S. Gull-Laird, Dai Z, Clingenpeel JA, Liu Y, Roehl EA Jr, Moore Meyers JA, Trettin CC (2013) Chapter 9: Managing Forest Water Quantity and Quality Under Climate Change. In Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystems, Eds. Vose, J. and K. Kleipzig, November 7, 2013 by CRC Press, 496 Pages

McCarthy EJ, Skaggs RW (1992) Simulation and evaluation of water management systems for a pine plantation watershed. South Journal of Applied Forestry 16(1):48–56

McCauley LA, Antaeau MJ, van der Burg MP, Wiltermuth MT (2015) Land use and wetland drainage affect water levels of remaining wetlands. Ecosphere 6(6):1–22

McLaughlin DL, Kaplan DA, Cohen MJ (2013) Managing forests for increased regional water yield in the southeastern U.S. coastal plain. Journal of the American Water Resources Association (JAWRA):1–13. https://doi.org/10.1111/jawr.12073

Messina MG, Conner WH (1998) Southern forested wetlands: ecology and management. Lewis Publishers, Baca Raton

Morrison AE (2016) Storm event analysis at varying watershed scales: Turkey Creek, Santee experimental Forest, South Carolina. M.S. thesis, environmental studies program, College of Charleston, Charleston, SC. 315 p, June 2016

Phillips BD, Skaggs RW, Chescheir GM (2010) A method to determine lateral effect of a drainage ditch on wetland hydrology: field testing. Transactions of the ASABE 53(4):1087–1096

Rheinhardt RD, Rheinhardt MC, Brinson MM (2002) A regional handbook for applying the hydrogeomorphic approach to assessing wetland function of wet pine flats on mineral soils in the Atlantic and Gulf Coastal Plains. Wetlands Research Program ERDC/EL TR-02-9. US Army Engineer Waterways Experiment Station, Vicksburg MS

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Riekerk H (1986) Hydrologic effects of Flatwoods silviculture. In Phillips, D.R. Proceedings of the fourth biennial southern Silvicultural research conference. USDA Forest Service, southeastern Forest Research Station, general technical report SE-42. Pp.321-326

SCS (1980) Soil survey of Berkeley County, South Carolina. USDA Soil Conservation Service, Washington, D.C.

SCS (1981) Soil survey of Washington County, North Carolina. USDA Soil Conservation Service, Washington, D.C.

Similä M, Aapala K, Penttinen J (2014) Ecological restoration in drained peatlands: best practices from Finland. Metsähallitus Natural Services

Skaggs R, Gilliam J, Evans R (1991) A computer simulation study of Pocosin hydrology, Wetlands, 11(special issue), 399–416, 1991

Skaggs RW, Amatya DM, Evans RO, Parsons JE (1994) Characterization and evaluation of proposed hydrologic criteria for wetlands. Journal of Soil and Water Conservation 49(5):354–363

Skaggs RW, Chescheir GM, Phillips BD (2005) Method to determine lateral effects of a drainage ditch on wetland hydrology. Transactions of ASAE 48(2):577–584

Skaggs RW, Phillips B, Chescheir GM, Trettin CC (2011a) Effect of minor drainage on hydrology of forested wetlands. Transactions of the ASABE 54(6):2139–2149

Skaggs RW, Chescheir GM, Fernandez GP, Amatya DM, Diggs J (2011b) Effects of land use on soil properties and hydrology of drained coastal plain watersheds. Transactions of the ASABE 54(4):1357–1365

Skaggs RW, Youssef MA, Chescheir GM (2012) DRAINMOD: Model use, calibration, and validation. Transactions of the ASABE 55(4): 1509-1522

Skaggs RW, Tian S, Chescheir GM, Amatya DM, Youssef MA (2016) Chapter 8: Forest drainage. In: Forest hydrology- processes, management and assessment, editors Amatya, DM, TM Williams, L Bren, and C de Jong. CABI Publishers, U.K., pp 124–140

Stelk MJ, Christie J (2016) Challenges & solutions in coastal wetlands: findings. Gaps & Priorities, Association of State Wetland Managers, Windham, Maine

Sun G, Lockaby G (2012) Chapter 3: Water quantity and quality at the urban-rural interface. In: Laband, D.N., B.G. Lockaby, and W. Zipperer (eds). Urban-Rural Interfaces: Linking People and Nature. PP26–45. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. Madison, WI

Sun G, Riekerk H, Comerford NB (1998) Modeling the forest hydrology of wetland-upland ecosystems in Florida. Journal of the American Water Resources Association 34(4):827–841

Sun G, Lu J, Gartner D, Miwa M, Trettin CC (2000) Water budgets of two forested watersheds in South Carolina. Proceedings of the Spring Special Conference, American Water Resources Association, Miami, FL, In, pp 199–202

Sun G, McNulty SG, Shepard JP, Amatya DM, Riekerk H, Comerford NB, Skaggs RW, Swift L Jr (2001) Effects of timber management on hydrology of wetland forests in the southern United States. Forest Ecology and Management 143(2001):227–236

Sun G, McNulty SG, Amatya DM, Skaggs RW, Swift LW Jr, Shepard JP (2002) Riekerk H (2002) a comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the southern US. Journal of Hydrology 263:92–104

Tian S, Youssef MA, Skaggs RW, Amatya DM, Chescheir GM (2012a) DRAINMOD-FOREST: integrated modeling of hydrology, soil carbon, and nitrogen dynamics, and plant growth for drained Forest. Journal of Environmental Quality 41:764–782

Tian S, Youssef MA, Skaggs RW, Amatya DM, Chescheir GM (2012b) Modeling water, Carbon and Nitrogen Dynamics for Two Drained Pine Plantations under Intensive Management Practices Forest Ecology and Management 264:20–36 (2012)

Tian S, Youssef MA, Sun G, Chescheir GM, Noormets A, Amatya DM, Skaggs RW, King JS, McNulty S, Gavazzi M, Miao G (2015) Domec JC (2015) testing DRAINMOD-FOREST for predicting evapotranspiration in a mid-rotation pine plantation. For Ecol Manag 355:37–47. https://doi.org/10.1016/j.foreco.2015.03.028

USACE (1987) USACE wetlands delineation manual. Tech. Report Y-87-1. Vicksburg, Miss.: U.S. Army Corps of Engineers, environmental laboratory

USEPA (2008) Methods for Evaluating Wetland Condition: Wetland Hydrology. Office of Water, U.S. Environmental Protection Agency, Washington, D.C., EPA-822-R-08-024

USEPA (2017). Summary findings of pilot studies conducted by the interagency coastal wetlands workgroup. Accessed at http://www.floods.org/n-news-hottopics/article.asp?id=513 on December 11, 2017

Author's personal copy

Williams TM (1978) Response of shallow water tables to rainfall. P 363–370 In Balmer, W.E. Proceedings: Soil Moisture-Site productivity symposium USDA Forest Service Southeastern Area State and Private Forestry

Williams TM (1979) Implications of hydrologic response to the practice of forestry on coastal forests. In: Smith WH (ed) Proceedings: Forest practice and water, 1979 annual meeting. Florida Section, Society of American Foresters, pp 92–102

Williams TM (2007) Evidence of runoff production mechanisms in low gradient coastal forested watersheds, paper presented at 2007 ASAE Annual Meeting, American Society of Agricultural and Biological Engineering, St. Joseph, MI

Williams T, Amatya DM (2016) Coastal plain soils and geomorphology: A key to understanding forest hydrology. *In:* Headwaters to estuaries: advances in watershed science and management (pp 14–21), Proc. of the 5th Interagency Conf. on Research in the Watersheds. Editors: Stringer, C. E.; Krauss, K. W.; Latimer, J. S, e-GTR SRS-211. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station

Williams TM, Krauss KW, Okruszko T (2016) Hydrology of flooded and wetland forests. In: Chapter 7, Forest hydrology- processes, management and assessment, editors: Amatya, DM, TM Williams, L Bren, and C de Jong, CABI Publishers, UK, pp:103–123

Wu CL, Shukla S, Shrestha NK (2016) Evapotranspiration from drained wetlands with different hydrologic regimes: drivers, modeling, and storage functions. Journal of Hydrology, 538 (2016): 416–428

Wylie M (2016) Section 404 and the Silviculture exemption. An abstract from a presentation at the special Sympsoium on "Silviculture in forested wetlands of the southeastern and gulf Coastal Plains: exploring wetland impacts, communication hurdles, best practices, and future directions", annual meeting of Society of Wetland Scientists, Corpus Christi, TX, May 31-June 3, 2016

Young CE Jr, Klaiwitter RA (1968) Hydrology of wetland forest watersheds. Proceedings of CUCOH hydrology conference. Clemson University, March 28-29, 1968: 29-38

Zhu J, Sun G, Li W, Zhang Y, Miao G, Noormets A, McNulty SG, King JS, Kumar M (2017) Wang X (2017) modeling the potential impacts of climate change on the water table level of selected forested wetlands in the southeastern United States. Hydrol Earth Syst Sci 21: 6289–6305. https://doi.org/10.5194/hess-21-6289-2017

Zietlow DRG (2015) Energy and water balance of wetland use change in the lower North Carolina coastal plain. Unpublished MS thesis, North Carolina State University, Raleigh, NC 45 p

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.