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WETLANDS AND CLIMATE CHANGE

Method to Assess Climate Change Impacts on Hydrologic Boundaries of Individual Wetlands

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Abstract

Potential impacts of climate change on the position of the wetland-hydrology boundary were estimated for four sites in the Eastern U.S. Precipitation and temperature predictions were obtained from the Hadley general circulation model (UKMO-HadCM3) because it most closely approximated observed precipitation for the period 1950–2000. The DRAINMOD hydrologic model was used to compute daily water table levels over two time periods: 1983–2012 (current conditions) and 2041–2070 (future conditions). For each site and time period, the model simulated water table depths for a soil pedon (Typic Paleaquult) that previous work demonstrated was on the wetland-hydrology boundary. Results for the Pitt County site in NC showed that by 2070 the wetland-hydrology boundary would have moved "downhill" to a point that was approximately 17 cm lower in elevation than where the boundary was in 2012 due to a 20% increase in evapotranspiration. Similar analyses were done for hypothetical wetland soils in Miami FL, Easton MD, and Portland ME where the wetland hydrology boundaries were estimated to drop in elevation by 5, 10 and 25 cm, respectively. Our results demonstrated that climate change may have significant impact on wetland boundaries.

Keywords DRAINMOD · Hydropedology · Wetland-hydrology boundary · Hadley model

Introduction

Wetlands in the United States are protected by state and federal laws and have three characteristics (termed parameters): wetland hydrology, hydric soils, and hydrophytic plants (Environmental Laboratory 1987; USACE 2010). The wetland hydrology parameter requires that a water table be within 30 cm of the soil surface for a continuous period of 14 d or more during the growing season, and with a frequency of at least 5 out of 10 years (USACE 2005). Where this condition occurs marks the *wetland-hydrology boundary* in a given landscape, and areas upslope of this boundary are not wetlands. Hydric soils are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part [of the soil] (Federal Register 1994). Hydrophytic plants are those that are adapted to living in saturated, anaerobic soils. Areas that meet all three requirements are wetlands. While climate change could affect the location for where each of the three parameters will be met, wetland hydrology is the parameter that will be immediately affected by changes to temperature and precipitation.

A change in the position of the wetland-hydrologic boundary as a result of climate change will have a direct impact on how a land owner will be able to use his or her property. If the wetland boundary contracts, or moves downhill for example as a result of climate change, then more land might become available for residential development or agriculture. Contracting wetland boundaries would also mean less wetland area will be protected under the current regulatory framework. Such changes can have a large impact on land values as well as on how land owners will be able use their property. Estimates of changes to hydrologic boundaries should be made for specific wetlands if they are to be useful to landowners, but few such estimates have been made to date due to a lack of methodology for doing so.

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Isolated freshwater wetlands are those that are not connected to streams, lakes, or the ocean, and as a result they depend primarily on precipitation as their water input and evapotranspiration as the major way water is lost. These wetlands will be particularly affected by climate change where substantial changes to temperature or precipitation occur (Erwin 2009; Hopkinson et al. 2013; Zhu et al. 2017). Wetland hydrology in isolated, freshwater wetlands is characterized by measuring changes in water table depth over time (Skaggs et al. 1994). Hydrologic models that incorporate predictions of how temperature and precipitation will change over time can estimate water table depths and durations in response to climate change (Skaggs 1978, 1982). Models such as DRAINMOD (Skaggs 1978), MODFLOW (McDonald and Harbaugh 1988), and PIHM-Wetland (Zhang et al. 2018) can be used to both understand the hydrology of natural wetlands as well as to predict the hydrology of those wetlands that have been restored or created for mitigation purposes. The DRAINMOD model was developed for the flat Coastal Plain landscapes that were of interest here. Its reliability to simulate water table levels has been proven in numerous studies of wetlands in the Southeastern U.S. (e.g., He et al. 2002, 2003; Amataya et al. 2006; Caldwell et al. 2007).

Johnson et al. (2010) modeled how climate change will affect the hydrology of the wetlands in the Prairie Pothole Region (PPR). They predicted that the western portion of the PPR would become drier as temperatures rise by 2 to 4 °C due to increased evapotranspiration which would cause a reduction in the duration of saturation at the soil surface. The frequency of droughts was also expected to increase. The net result was that the major duck breeding area in the PPR would shift eastward and decrease in size overall.

Zhu et al. (2017) estimated climate change impacts on five precipitation-driven wetlands in North Carolina (2 wetlands), South Carolina (1 wetland), and Florida (2 wetlands). Water table levels were predicted using a statistically-based hydrologic model whose inputs included precipitation, potential evapotranspiration (PET), and water table depth prior to the time of interest. Daily mean data for temperature and precipitation were obtained from 20 General Circulation Models for intermediate and high greenhouse gas scenarios (representative concentration pathways (RCPs) of 4.5 and 8.5) (IPCC 2013). Mean annual air temperatures by 2099 were estimated to rise by approximately 4 °C compared to the baseline period of 1980 to 1999. Potential evapotranspiration was estimated to increase by 13 to 23% depending on the emission scenario. Precipitation increased by approximately 40 to 60 mm for wetlands in NC and SC, but decreased by about 21 mm for the wetlands in FL. Increases in PET were greater than those for precipitation, and as a result the average annual water table depths dropped, with changes ranging from −4 to −22 cm below the surface across all wetlands for the high emissions scenario. While this study quantified the effect of climate change on water table depths within the wetlands, it did not assess the impact on the location of the wetland boundary which will be critical to know as this could affect wetland area as well as function.

The purpose of this study was to test a method that determines how climate change may affect the wetland hydrology boundary of individual wetlands defined by federal regulation. The method could be used to make estimates of wetland area changes resulting from climate change. The objectives of this study were to: 1) develop procedures for predicting the impacts of climate change on the elevation of the wetland hydrology boundary for a given isolated wetland, and 2) compare changes in the elevation of the wetland hydrology boundary among selected sites in the eastern U.S. The impacts of climate change on wetland vegetation and hydric soils were not investigated and were considered outside the scope of the study.

Materials and Methods

The site used to develop the initial hydrologic model for this study was an isolated depressional wetland (wet mineral flat) in Pitt County, NC (Fig. 1), which lies in the Lower Coastal Plain land region (Daniels et al. 1999). The site was approximately 5.1 km southwest of Greenville at N 35° 34′ 10″ and W 77° 26′ 26″. The wetland contained the Rains loamy sand

Fig. 1 Location of sites. The site in the Greenville location contained the modeled wetland. The remaining sites were used to assess climate change impacts for a range in temperature and precipitation conditions for the wetland modeled in Greenville, NC

mapping unit (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults). Precipitation and evapotranspiration are the major water inputs and outputs to these wetlands. Hydraulic gradients in the flat landscapes of this portion of the Coastal Plain are small (Daniels et al. 1999). The site was selected because soil and hydrology data were collected previously and were used to calibrate the DRAINMOD model (Hayes and Vepraskas 2000; He et al. 2002, 2003).

General Circulation Model Selection

General Circulation Models (GCMs) provide estimates of future temperature, precipitation, and other climate variables in three dimensions by incorporating interactions between the atmosphere, oceans, land surface, and greenhouse gas emissions. Statistically downscaled climate projections from 16 GCMs were made publically available as part of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) Climate Projections (Maurer et al. 2007; Meehl et al. 2007). Monthly GCM temperature and precipitation predictions were downscaled and biased corrected from their native grid resolutions to a resolution of 12 × 12 km as part of CMIP3. These climate projections have been used extensively to assess climate change impacts due to their availability over large domains and long time periods (e.g. USEPA 2013; Vose and Klepzig 2013; Wear and Greis 2013). For these reasons we selected our future climate projections from the CMIP3 database.

Our goal was to identify a single GCM that reasonably predicted historic precipitation for the specific area of interest in order to demonstrate the utility of our method to assess climate change impacts on wetland hydrology boundaries in individual wetlands. We recognized that multiple models are commonly used for such assessments over large geographic areas, however, we hypothesized that a single model would be appropriate and preferred if it was well correlated with historic climate data near the individual wetland of interest. Three GCMs were initially selected for the area of interest in Pitt County, NC: Hadley (UKMO-HadCM3) (Wood et al. 1999; Gordon et al. 2000; Pope et al. 2000), U.S. Dep. of Commerce/NOAA (GFDL-CM2.0) (Delworth et al. 2006; Gnanadesikan et al. 2006; Stouffer et al. 2006; Wittenberg et al. 2006), and Canadian Centre for Climate Modeling & Analysis (CGCM3.1) (Flato and Hibler 1992; Flato and Boer 2001; Kim et al. 2002; Kim et al. 2003). The Intergovernmental Panel on Climate Change's (IPCC) 4th Assessment Report (AR4) A1B emission projection was selected to provide climate projections under intermediate emission levels (Trenberth et al. 2007).

To assess the accuracy of each GCM in predicting historical precipitation and temperature for our study site, we compared each GCM's downscaled and bias corrected predictions of monthly precipitation and temperature to measured values obtained from local weather stations for the period 1950–2000. Daily weather data for Greenville NC were obtained through the State Climate Office of North Carolina http://www.nc-climate.ncsu.edu/cronos. These data included daily total precipitation and daily maximum and minimum air temperature. The best climate model to use for the prediction of future temperature and precipitation data for the Greenville NC site was identified using a simple linear regression analysis to compare measured to predicted precipitation values from 1950 through 1999 at the monthly, annual, and decade scale.

Temporal Downscaling of GCM Climate Data

Daily values of temperature and precipitation were needed to compute daily water table levels with our hydrologic model, but were not available for future projections over our area of interest. All of the predicted data from the climate models were monthly sums of precipitation and average monthly temperature. To acquire daily values with the GCM model selected, we temporally downscaled the monthly climate projections using the Constant Scaling Method (Mpelasoka and Chiew 2009). The Constant Scaling Method generates a reasonable representation of the precipitation and temperature frequency distribution, however it assumes stationarity in the temporal precipitation distribution and the magnitude and frequency of events. A record of daily measured precipitation for each site was obtained for the years 1950 through 2009 from the nearest available weather station. A long period of time was preferred to account for variations in temperature and precipitation such as experienced during droughts and hurricanes. We generated a daily precipitation record for the period 2010 through 2070 by multiplying the daily values for a given month by a ratio of monthly data determined by the monthly total divided by the measured monthly total. These years were selected to give a 60-year record that again would reflect natural climatic variations from droughts and hurricanes. For example, the monthly sum of predicted precipitation for January 2010 was divided by the sum of measured precipitation for January 1950 to result in a correction factor. That correction factor was then used to multiply every measured daily precipitation value for the month of January 1950 to get the daily predicted precipitation for January 2010. This resulted in the same monthly predicted sum of precipitation for January 2010, but the distribution of precipitation events is the same as for January 1950. This process was repeated for all months and for the temperature data.

Estimating Climate Change Impacts on the Wetland-Hydrology Boundary

The DRAINMOD hydrology model (Skaggs 1978) was used to predict current and future water table levels for this study. The model assumes a network of parallel drainage ditches or drain tiles at a given depth and spacing above a restrictive layer, and calculates the water table depth midway between the two drains. The relationship between the water table depth (m) and the drainage rate (q) is determined by (Hooghoudt 1940):

$$q = \frac{8K_1 D_e m + 4K_2 m^2}{L^2} \quad (1)$$

where K_1 is the effective lateral saturated hydraulic conductivity of the soil above the drain, K_2 is the effective lateral hydraulic conductivity of the soil below the drain, L is the lateral distance between drain tiles, and D_e is the effective depth of the restrictive layer below the drain. The D_e parameter was computed separately as a function of the drain depth. An hourly water balance was computed based on inputs of weather (e.g., hourly precipitation and daily maximum and minimum temperatures used to calculate evapotranspiration losses), soil properties (depressional storage, soil water characteristic and saturated hydraulic conductivity data for each soil horizon that lies above a restrictive layer), and simulated drainage rates over a unit area of the soil pedon. A soil pedon is essentially the volume of soil (approximately $1m^2$ in area and 1 m in depth) that contains the properties illustrated in a soil profile such as all the horizons. DRAINMOD disaggregates daily precipitation into hourly data based on inputs of the average starting hour of storm events and average duration. Evapotranspiration (ET) is computed using the Thornthwaite equation (Thornthwaite 1948) with inputs of daily maximum and minimum air temperatures and site latitude. Monthly correction factors for ET allow the Thornthwaite ET estimates to be seasonally adjusted based on ET computations from more complex algorithms such as Penman-Monteith (Monteith 1965). To simulate natural wetlands without artificial drainage systems, like the wetlands used here, the parameters in eq. [1] were treated as calibration parameters that were adjusted to bring the model into agreement with measured water table data (He et al. 2002; Caldwell et al. 2007).

The DRAINMOD model used in this study was based on a calibrated model for the Rains benchmark soil in Pitt County NC. The Rains is a hydric soil commonly found in wetlands in the Coastal Plain region. He et al. (2002) provided details on model development and calibration for the site. Briefly, the drainage system parameters in Eq. 1 were adjusted to minimize the average absolute error between observed and predicted daily water table depths collected over a 3-year period. The average absolute error over the 3-year calibration period was 16 cm for the Rains plots. Greatest errors occurred during the summer months when water tables were deep (>1 m), or during periods of intense storms when precipitation data were difficult to measure accurately. For the months of November to April the average absolute error was 9 cm, ranging from 4 to 11 cm over the 3-year calibration period. During these months the water table was within 30 cm of the surface continuously (He et al. 2002).

Using the calibrated DRAINMOD model, the drainage parameters (i.e. drain depth and spacing) were adjusted again to determine the Threshold Drainage Intensity (TDI) for each site (Skaggs et al. 2005). The TDI is defined as the drainage intensity (mm/day) that exactly meets the wetland hydrologic criterion of 14 days of saturation during the growing season at a depth of 30 cm in 50% of the years. A soil pedon in the landscape meeting the TDI would lie on the wetland-hydrology boundary. For drainage intensities (i.e., drainage rates) greater than the TDI, the wetland hydrologic criterion would not be satisfied because the soil pedons having these would drain quickly and would be too dry to meet the wetland hydrology criteria. They would likely lie "uphill" of the wetland-hydrology boundary. For drainage intensities less than the TDI, the wetland hydrology criterion would be satisfied, but the pedons having these will be wetter than absolutely necessary to exactly satisfy the criterion, and they would be "downhill" of the wetland-hydrology boundary at the site.

For this study, two TDIs were determined for each site: one to represent the hydrologic boundary under the current climate (TDIc) and the second to represent the hydrologic boundary under a future climate (TDIf). The two TDIs had different drainage parameters and would be found at different positions in the landscape. To determine a TDIc at the wetland hydrology boundary at the site of interest, the model was adjusted to compute a water table depth over time that exactly met the minimum requirements for wetland hydrology (Table 1) using the climate data that represented the current condition (Steps 1 and 2, Table 2). The DRAINMOD model was then run using the future climate projections for precipitation and temperature to estimate the future water table depth and frequency for a soil pedon located at the TDIc (Step 3, Table 2). These future data were used to determine if the current wetland hydrology boundary would become wetter or drier over time. In addition, a TDIf for the wetland in the future was also determined using future temperature and precipitation data to simulate conditions for the wetland hydrology boundary at the later time (Step 4, Table 2).

The concept we used to estimate changes in elevation of the wetland hydrology boundary is illustrated in Fig. 2. Assume that we found (in Step 5, Table 2) that the wetland hydrology boundary in 2070 actually occurs *today* at a point toward the center of the wetland that is saturating for 22 days at a depth of 30 cm (Fig. 3). We then estimated the depth at which this period of saturation would be found in a soil pedon that was placed at the position of the wetland hydrology boundary in 2012 (Step 6, Table 2). If the depth for 22 days of saturation occurred at 70 cm in the pedon on the wetland hydrology boundary in 2012, then we assumed that the wetland hydrology boundary would drop in elevation on the landscape by 40 cm (70 cm – 30 cm = 40 cm) by 2070.

The analyses described for the Pitt County NC site were repeated for sites in Portland ME, Easton MD, and Miami FL to provide an estimate of potential climate change impacts on

Table 1 The minimum requirements for meeting the wetland hydrology criterion of the U.S. Army Corps of Engineers (USACOE 2005). Growing season dates were obtained from USDA, NRCS (2019)

Factor	Value	Comments
Water Table Depth	30 cm	The maximum depth a water table can be below the surface for wetland hydrology conditions to be met.
Period	Frost free Growing Season	For Greenville, NC this is between March 16 and November 18
Duration	14 days during the growing season	This is the minimum threshold for wetland hydrology
Frequency	Occurring in 50% of the years	This is assumed to be the "normal" condition

wetland hydrology across a range of hydroclimatic settings (Fig. 1). These sites were selected to give a broad range in latitude and climate gradient along the eastern U.S., as well as a range in growing season lengths (Table 3). Growing season dates were determined from the USDA-NRCS's 'Climate Analysis for Wetlands Tables' (WETS tables) for each location (USDA, NRCS 2019). For the growing season we selected values for a 50% probability and air temperature of −2 °C (28 °F). No specific wetland site was used for these sites outside NC. Locations were determined by where observed historical precipitation and temperature data were obtained (Table 3). Growing season dates were not adjusted for this study.

The DRAINMOD model used for each location was calibrated initially for the soil properties of the Rains benchmark soil in Pitt County NC (Skaggs et al. 1994; He et al. 2002). This model was calibrated against measured water table data at the NC site. However, TDI's were determined for each location separately by adjusting drain depth and spacing in order to simulate conditions at the wetland hydrology boundary at each location using both current and future climate data for each location.

Results

Climate Model Selection

Results of the linear regression results for decadal predictions are shown in Table 4 for the three climate models tested using the climate data for Greenville NC. The Hadley model

Table 2 Steps used for estimating the impact of climate change on wetland hydrology conditions

Step	Description
1.	Determine the Threshold Drainage Intensities (TDI) for wetland hydrology for the Rains soil under current weather conditions (1983–2012). This is a TDIc model determined by adjusting DRAINMOD's drain depth and spacing to modify the water table depth, frequency, and duration to achieve the minimum requirements for the wetland hydrology boundary (Table 1).
2.	Run the TDIc model using current climate data (1983–2012). The frequency distribution for percentage of years the water table is at a depth $\leq$ 30 cm represents what would be expected to be found with a monitoring well placed at the exact point where the minimum requirements for wetland hydrology are met on a landscape (i.e., wetland-hydrology boundary). An example is shown in Fig. 5.
3.	Run the TDIc model using predicted daily temperature and precipitation data for 2041–2070, and plot a frequency distribution over time for water table levels. This analysis shows how the soil at the current hydrology boundary would adjust to future changes in precipitation and temperature. An example is shown in Fig. 5.
4.	Using future climate data (2041–2070), adjust the DRAINMOD model to determine the TDIf model that produces a water table frequency distribution for the point where the minimum requirements for the wetland hydrology are just met. An example is shown in Fig. 7.
5.	Using the TDIf model developed in step 4, input the precipitation and temperature data for the period 1983–2012 and plot a frequency distribution for the results. These data estimate the duration the water table would be at a depth of $\leq$30 cm, and at a 50% probability value. Results show the conditions for the wetland-hydrology boundary of the future under the current climate. Use the data to determine the number of days the water table was at a depth of $\leq$30 cm. An example is shown in Fig. 7.
6.	Run the TDIc model for current climate conditions (1983–2012) to determine durations the water table was at depths of $\leq$30, $\leq$45, and $\leq$ 60 cm at the 50% probability level. Use these data to estimate the depth that the water table occurred at for the duration determined in Step 5. This depth marked elevation of the future wetland-hydrology boundary. Its distance below a depth of 30 cm shows the change in elevation of the wetland-hydrology boundary between current and future climates. An example is shown in Fig. 8.

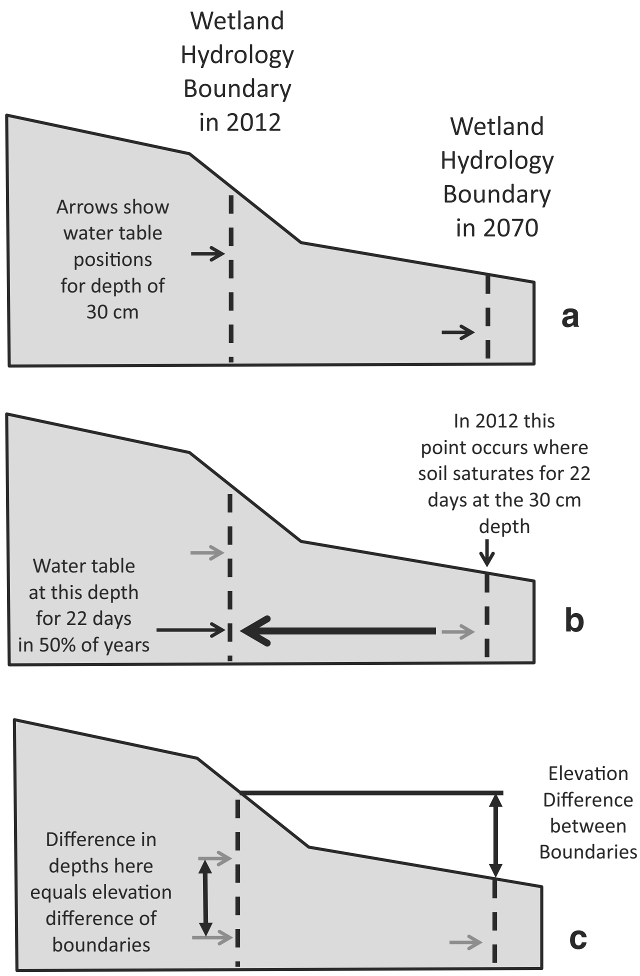

Fig. 2 Method used to extrapolate the elevation drop in the wetland hydrology boundary predicted for the period 2041–2070 to its location in the landscape. **a** The DRAINMOD model was adjusted to simulate the wetland hydrology boundaries for current (labelled 2012) and future conditions (labelled 2070). The boundaries shown are hypothetical in that it is not known where on a landscape they would occur. They mark points where the water table is at a depth of $\le$30 cm for 14 d during the growing season in 50% of the years. **b** The wetland hydrology boundary for 2070 occurred in 2012 at a point where the soil saturated for 22 days at a depth of 30 cm in 50% of the years. This is marked by the gray arrow on the right. Also shown is the depth where saturation occurred for 22 days at the wetland-hydrology boundary for 2012. **c** The difference in the two depths shown by arrows for the wetland hydrology boundary in 2012 (left) is equal to the elevation change at the surface between the wetland hydrology boundaries between 2012 and 2070

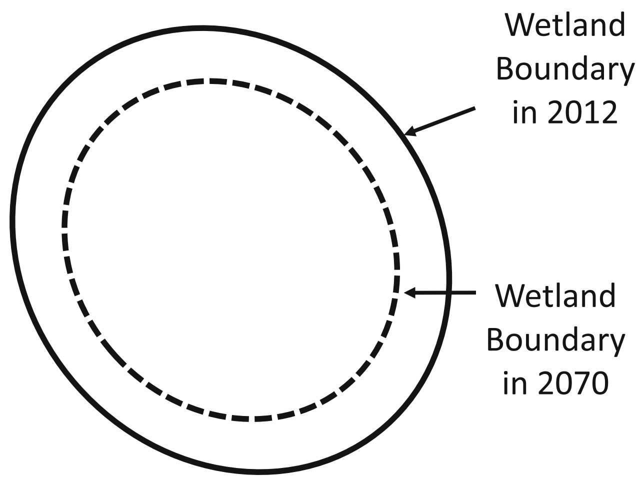

Fig. 3 Potential changes in the wetland hydrological boundary for two time periods in a hypothetical wetland. The boundaries in 2014 and 2070 are where the soils are saturated for 14 days during the growing season at a depth of 30 cm in 50% of the years. In this illustration the wetland has contracted as the hydrologic boundary moved downhill. The boundary in 2070 will be at a point in 2014 where the soils are saturated for longer periods than 14 days, and for discussion we have used 22 days to illustrate the concept

produced the best correlation of the three models and was selected for use in this study as a result of this analysis. Temperature was analyzed similarly, but differences in temperature correlations were small among models.

Similar regression analyses were done at the other wetland sites in Florida, Maryland, and Maine. The Hadley model was again used for all sites. Correlation coefficients for the relationship between measured and predicted monthly precipitation amounts (averaged over a decade) were found to be approximately 0.80 for all three of the models shown in Table 4 for Florida, but were less than 0.30 for data from Maryland and Maine for all models. As shown in Fig. 4, when measured and predicted precipitation data from all sites were compared using the Hadley model the correlation coefficient was high ($r^2 = 0.88$). Data for Maryland and Maine had a narrow range of values, but still appeared to conform to the 1:1 line shown despite their low individual r^2 values. Precipitation and temperature predictions from the Hadley model were considered appropriate for all sites.

Estimates of Climate Change Impacts on Wetland Hydrology in NC

Frequency diagrams for water table durations (30 cm depth) for the North Carolina site are shown in Fig. 5 that were generated using a TDIc model developed for the site. Results are shown for current climate conditions (years 1983–2012) and for predicted changes due to climate change (years 2041–2070) using the TDIc model. The current hydrologic boundary occurred for a saturation frequency of 50% of the years at a duration of 14 days when the water table was at a depth $\le$ 30 cm. When the predicted future climate data were used in the TDIc model for this site, we found that in 50% of the years the water table would occur for approximately 7 days as opposed to 14 at a depth of $\le$30 cm. This indicated that in the 2041–2070 timeframe the simulated pedon, which was on the wetland hydrology boundary in 2012, would become drier and would no longer be considered in a wetland as it no longer would meet the requirements for wetland hydrology. The wetland hydrology boundary would effectively have moved downslope or to a lower elevation in this wetland.

Table 3 Locations of sources for measured temperature and precipitation data used in the study along with growing season dates. Two locations were needed for Maryland and North Carolina in order to compile complete records. Growing season data were obtained from USDA, NRCS (2019)

State	Location for Climate Data	Latitude	Longitude	Growing Season
		Degrees		
Maine	Portland International Jetport	43.646557	−70.309710	20 April-1 October
Maryland	Easton/Newnam Field Airport	38.804231	−76.069282	19 March-18 November
"	Royal Oak Weather Station	38.742301	−76.177837	
North Carolina	Greenville Airport	35.633261	−77.387752	16 March-18 November
"	Camp Lejeune Marine Corps Base	34.569444	−77.440556	
Florida	Miami International Airport	25.798124	−80.285641	1 January-31 December

The reduction in duration of saturation in the upper 30 cm soil during the growing season was related to the projected changes in temperature and precipitation for the North Carolina site (Fig. 6). Precipitation was predicted to increase slightly over time. However, evapotranspiration was estimated to increase by approximately 20% as a result of increasing air temperature. The increase in evapotranspiration will cause water tables to drop, and as a result, the wetland area will be reduced over time and the wetland hydrology boundary would move downhill.

Using future climate data (years 2041 to 2070) the DRAINMOD model was adjusted to establish the TDIf for the North Carolina site. This modeled the future wetland-hydrology boundary at the site. This TDIf model was then run with the current climate data (years 1983–2012) to estimate where the wetland hydrology boundary in 2070 would be found in 2012. Results from this analysis are shown in Fig. 7. The wetland hydrology boundary in 2070 would occur in 2012 where a soil pedon was saturating for approximately 22 days in 50% of the years at a depth $\le$ 30 cm. Such saturation durations would be found in 2012 toward the center of the wetland away from the edge.

To estimate the change in elevation of the wetland hydrology boundary in 2070 from where it was in 2012, we determined frequency diagrams for water table durations during the growing season for three depths (30, 45 and 60 cm) for the period 1983–2012 using the TDIc model developed for the North Carolina site (Fig. 8). We then estimated the depth at which the soil pedon on the wetland hydrologic boundary in 2012 would be saturated for 22 days during the growing season in 50% of the years. The 22-day value was the duration of saturation in 2012 for the soil pedon that will be saturated for only 14 days at a 30 cm depth in 2070, because the hydrologic boundary will be moving toward the center of the wetland over time. Below the current (2012) hydrology boundary we found that 22 days of saturation occurred at a depth of 47 cm in the Rains soil. This is 17 cm below the depth that was used for establishing the current boundary (30 cm). Thus, the difference in elevation between the wetland hydrology boundaries in 2012 and 2070 was estimated to be approximately 17 cm.

Results for Other Regions

In order to see if such results might occur in three other locations (Table 3), we repeated the analyses beginning with the same DRAINMOD model used for the North Carolina site. Using the current and future climate data from the other locations, TDIc and TDIf models were developed for each site individually. Estimates of changes in precipitation, temperature, evapotranspiration, and elevation of the wetland-hydrology boundary for hypothetical wetlands in Miami FL, Easton MD, and Portland ME are shown in Table 5 along with the results from the North Carolina site. Precipitation was predicted to increase over current values in Maine and Maryland, but decrease in North Carolina and Florida. Relative changes in evapotranspiration, between current and future periods for a given site, were predicted to increase approximately six-fold in going from Miami to Portland (i.e., from 5 to 32%). This change is due to predicted increases in temperature. The net effect of the changes in temperature and precipitation are shown in Table 6. The wetland hydrology

Table 4 Correlation coefficients (r^2) for comparisons of measured monthly precipitation data to predicted data for each of the three climate models. Greenville NC was the area of interest. Data were summed by decade (e.g., 1950–1959, 1960–1969, etc.) for these comparisons

Climate Model	r^2 for Monthly Data Summed by Decade
Hadley: UKMO-HadCM3	0.71
USDC/NOAA/GFDL-CM2.0	0.53
Canadian Centre for climate Modeling & Analysis CGCM3.1	0.46
All	0.57

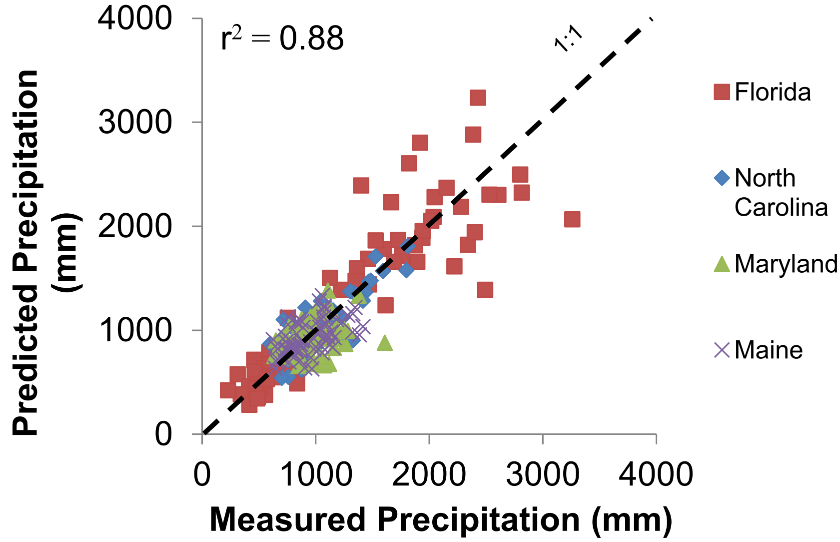

Fig. 4 Comparison of measured precipitation to the corresponding precipitation predicted by the Hadley model for the four sites studied. Data points represent monthly values averaged over a decade. Data from all sites display a symmetrical relationship around the 1:1 line indicating that the Hadley model was appropriate for all sites

boundary line was predicted to drop in elevation at all locations in amounts ranging from −5 to −25 cm.

Discussion

The results shown in Table 6 indicate that the wetland hydrology boundary was predicted to move downhill by 2070 at all sites but to varying degrees. The changes were due largely to increases in evapotranspiration that were predicted to occur at all sites as a result of increased temperatures. Precipitation changes varied across sites, increasing slightly for the sites in Maine and Maryland, and decreasing slightly in North Carolina and Florida. These results are very similar to those of Zhu et al. (2017) who evaluated climate change impacts on average water table depths in five wetlands in North Carolina, South Carolina, and Florida that were similar to those studied here. Zhu et al. (2017) predicted annual water table levels would drop by 4 to 22 cm across sites due to potential evapotranspiration exceeding precipitation as a result of global warming. Our results of estimated changes ranged from 5 to 17 cm for sites in North Carolina and Florida which covered the region studied by Zhu et al. (2017). The similarity of results is encouraging because of the difference in methods used. Zhu et al. (2017) obtained climate data from an ensemble of 20 GCM models, while we used a single GCM model that showed a good correlation with historical precipitation data. One difference, however, was that Zhu et al. (2017) showed the largest change in annual water table depth would occur in Florida, while our results predicted the smallest change in water table levels for that location. This difference could be due to the difference in GCM models used.

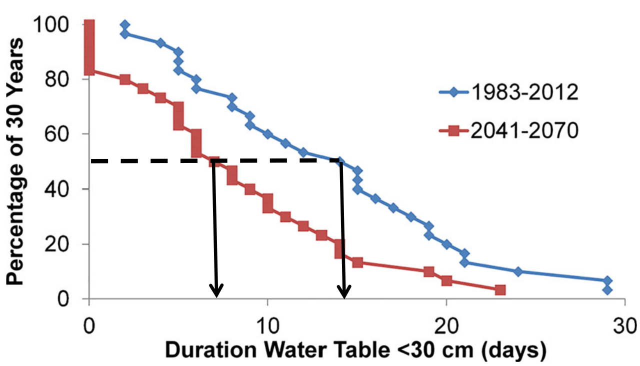

Fig. 5 Frequency diagram showing percentage of years the water table was at a depth ≤ 30 cm during the growing season for the Rains soil in Pitt County NC for varying durations. Results for two periods are shown which were determined with the TDIc model developed for the site. Black arrows indicate saturation durations for 50% probability. For the period 1983–2012, the pedon was on the hydrologic boundary, because it was saturated for 50% of years at a depth of 30 cm for exactly 14 days during the growing season. For the period 2041–2070 the same pedon was predicted to be outside (upslope) of the wetland hydrology boundary because it is saturating for approximately 7 days at the 30 cm depth

Prediction of climate change impacts is uncertain, in part because of the uncertainty in GCM climate projections. Many studies have advocated the use of multiple GCMs in an attempt to bound the range of uncertainty. This is justified when predicting global values for a climate variable. The approach used here was to identify a single GCM model based on its high correlation with historic precipitation and temperature data for the specific site of interest. As shown in Table 4, use of a group of models would have lowered the r^2 value as compared to using only the Hadley model. Our assumption was that if a GCM model was best for predicting historic precipitation and temperature then it would be the best model to use for making future predictions for the site of interest.

There is also uncertainty associated with temporal downscaling of monthly GCM precipitation and temperature predictions. In addition to this uncertainty, there is uncertainty associated with the spatial downscaling performed for the original World Climate Research Programme's (WCRP)

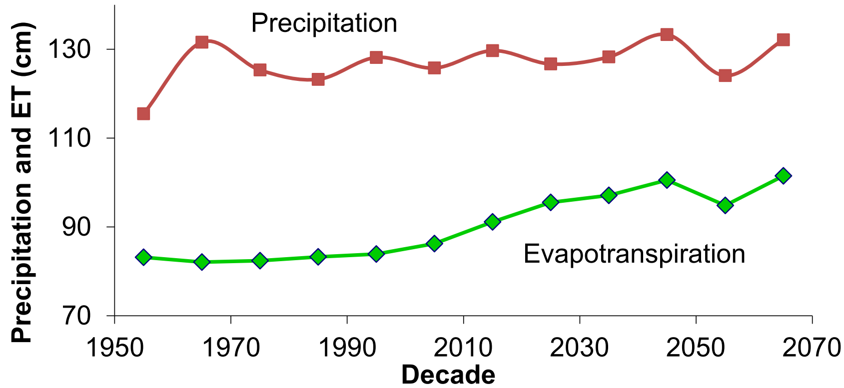

Fig. 6 Estimated changes in precipitation and evapotranspiration (ET) expected for the Rains soil under forest in Pitt County NC during the growing season. Note that precipitation is expected to increase slightly over time in contrast to evapotranspiration where much larger (>20%) changes are expected. This indicates wetlands will tend dry up earlier in the year with time

Coupled Model Intercomparison Project phase 3 (CMIP3) Climate Projections, as well as with the raw GCM predictions themselves. As GCMs improve and computing capacity increases these uncertainties will decrease over time. Since completion of this project, statistically downscaled climate projections have been made available at the daily timestep (e.g., MACA CMIP5; www.climatologylab.org/maca.html), making the temporal downscaling step unnecessary. It was beyond the scope of this study to repeat our modeling work with the recently available daily GCM data. However, we believe this study remains a novel contribution to the literature that examines potential climate change impacts on wetland hydrology. The temporal downscaling procedure we used here has been well-tested in other studies where such downscaling was necessary.

Adding to the uncertainty associated with GCM projections, there is uncertainty in how hydrological response is modeled using limited driving variables. For example, evapotranspiration is controlled by temperature, solar radiation, vapor pressure deficit, and wind speed (Monteith 1965). Unfortunately, air temperature is the only widely available climate parameter available from GCM projections that can be used to estimate potential evapotranspiration. Here we used the Thornthwaite temperature-based potential evapotranspiration model (Thornthwaite 1948) and acknowledge that our use of this simplified method could add uncertainty to our hydrologic predictions. Further, increased atmospheric CO_2 concentration may alter stomatal conductance and have an influence on evapotranspiration (Ainsworth and Rogers 2007; Leakey et al. 2009; Cao et al. 2010). However, temperature-based evapotranspiration models remain the best solution for climate change impact studies because: 1) they have been well-tested and used for decades under a wide range of hydroclimatic conditions, and 2) additional climatic variables are rarely available from GCM outputs and even if available, would have an associated uncertainty.

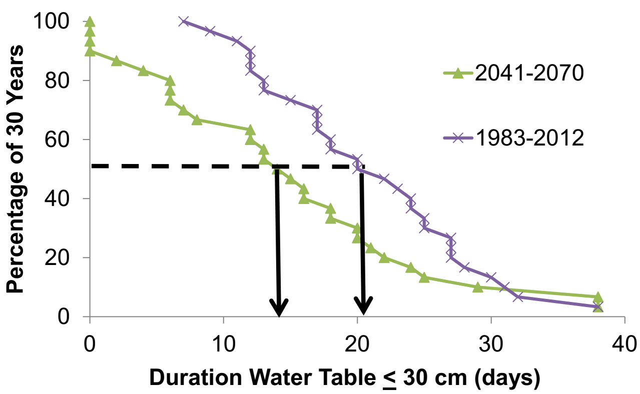

Fig. 7 Frequency distribution for water table results similar to those shown in Fig. 5 for Pitt County NC but determined using a TDIf model. Using predicted temperature and precipitation data for the period 2041–2070, inputs to the DRAINMOD model were adjusted to simulate a pedon where the water table would be at a depth of 30 cm for 14 days during the growing season (on the wetland-hydrology boundary). Precipitation and temperature data for 1983–2012 were then input into the model to estimate the duration of saturation for the pedon under current conditions. As shown, the pedon satisfying wetland hydrology criteria in 2041–2070 would be found in 2012 toward the center of the wetland at a point where it is saturated for 22 days in 50% of the years. This means the wetland hydrology boundary would be moving downhill over time

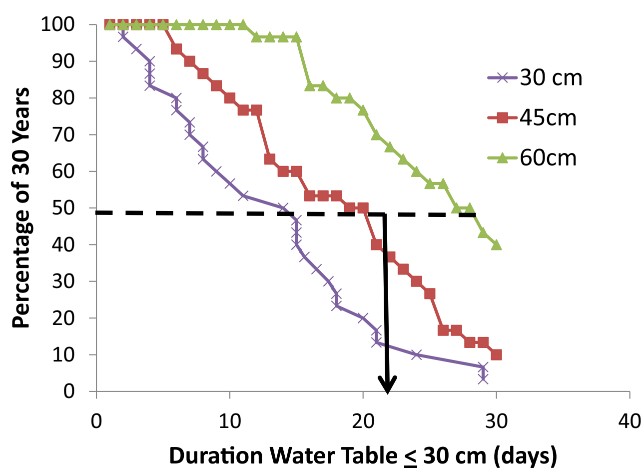

Fig. 8 Frequency distribution for water table results similar to those shown in Fig. 7 for Pitt County NC but determined using a TDIc model. Temperature and precipitation data for the 1983–2012 time period where used to estimate saturation durations for three depths. Using data points for a 50% probability it was estimated that the soil pedon would saturate for 22 days at a depth of 47 cm. This result was used to determine the drop in elevation of the wetland hydrology boundary in 2070

Table 5 Predicted changes in precipitation, evapotranspiration, and temperature between the years 1983–2012 and 2041–2070 for the four sites evaluated

Site	Change in:		
	Precipitation	Evapotranspiration	Temperature
	cm		°C
Portland, ME	6 (5)[†]	18 (32)	3 (12)
Easton, MD	9 (8)	18 (18)	2 (8)
Greenville, NC	−1 (−1)	9 (9)	2 (6)
Miami, FL	−10 (−6)	5 (5)	1 (5)

[†] Numbers in parentheses are percentage of change

Our use of a single "model" wetland soil that was initially calibrated for a wetland in North Carolina, but was adjusted for the TDIs found at each location, worked well for this study as shown by the similarity in the results between this study and those of Zhu et al. (2017). However, the model wetland was not calibrated for the detailed hydrologic conditions in other locations beyond climate and the TDIs. We also assumed that the modeled TDIs were valid throughout the entire periods being modeled at each site. This was a reasonable assumption for the forested conditions we considered to be present throughout the years of interest. The assumption would not be valid if the sites were converted to agriculture at some point, for example, where a new drainage system were to be installed. The model wetland approach used here is appropriate for surveying potential hydrologic changes across large areas where precipitation driven wetlands (e.g., depressional wetlands) occur. Wetlands whose water budgets include large components for flooding or tides were not evaluated here, but could be using a model other than DRAINMOD.

Table 6 Estimates of elevation change of wetland hydrology boundary line for two time periods at all sites

Site	Saturation durations (30 cm depth) for wetland hydrology line during two time periods:			
	Line in 1983–2012 will be in 2041–2070 where saturation is occurring for:	Line in 2041–2070 will be in 1983–2012 where saturation is occurring for:	Depth at which saturation duration in column 3 occurs in 2012	Elevation change of hydrology line over time
	Days		cm	
Portland ME	7	28	55	−25*
Easton MD	11	19	40	−10
Greenville NC	7	22	47	−17
Miami FL	13	16	35	−5

*Difference between value in column 4 and 30 cm

While our focus on wetland hydrology ignored the impacts of climate change on hydrophytic vegetation and hydric soils, we don't believe this a major problem for our assessment. Wetland hydrology must be present for the site to have hydrophytic plants as well as hydric soils. Changes in elevation to the wetland hydrology boundary should create changes in hydrophytic vegetation, but additional studies would be needed to confirm this. Hydric soil boundaries may or not change in response to changes in hydrology, because hydric soils can be drained and still retain the hydric classification (USDA-NRCS 2010). Hydric soils are identified by the presence of field indicators, based on soil color and organic C contents, and as long as the soils retain a hydric soil field indicator it is considered a hydric soil (USDA-NRCS 2010).

We believe that the method described herein is valid for estimating the wetland area to be lost due to climate change and increasing ET. The elevation changes shown in Table 6 could be used with soil maps and digital elevation models to estimate and compare the area of wetlands under current and future conditions. Soil maps showing the boundaries of hydric soils would approximate current wetland areas. The digital elevation models could then be used to compute changes in the boundary elevations and estimate how much wetland area would change as a result of climate change in the future.

Summary

Our results suggest that changes in wetland hydrologic boundaries should be expected as a result of global warming. The boundaries would decrease in elevation by ≤25 cm, and will result in a reduction in wetland area. On flat landscapes such elevation changes could have relatively large impacts on the areas of wetlands affected. The next step in this work would be to estimate the area of wetlands that may be affected by climate change. This can be done using the results in Table 6 along with soil maps and topographic information. Determining how much wetland area could be affected by changes to wetland hydrology through climate change is required to better understand the magnitude of the impact of climate on wetlands.

The method presented here in principle could be applied to depressional wetlands across the eastern U.S. where precipitation and evapotranspiration are the major water inputs and outputs for the wetland. Our approach is not appropriate for wetlands affected by sea level rise or flooding for example because these hydrologic components are not considered in the DRAINMOD model. We used the DRAINMOD model because it was developed for Coastal Plain landscapes that are flat, have relatively small hydraulic gradients, and are not affected by river flooding or tides. Precipitation is the major water input and evapotranspiration the major way water is lost. Groundwater inflow or outflow from the soil of interest is usually small in the Coastal Plain.

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