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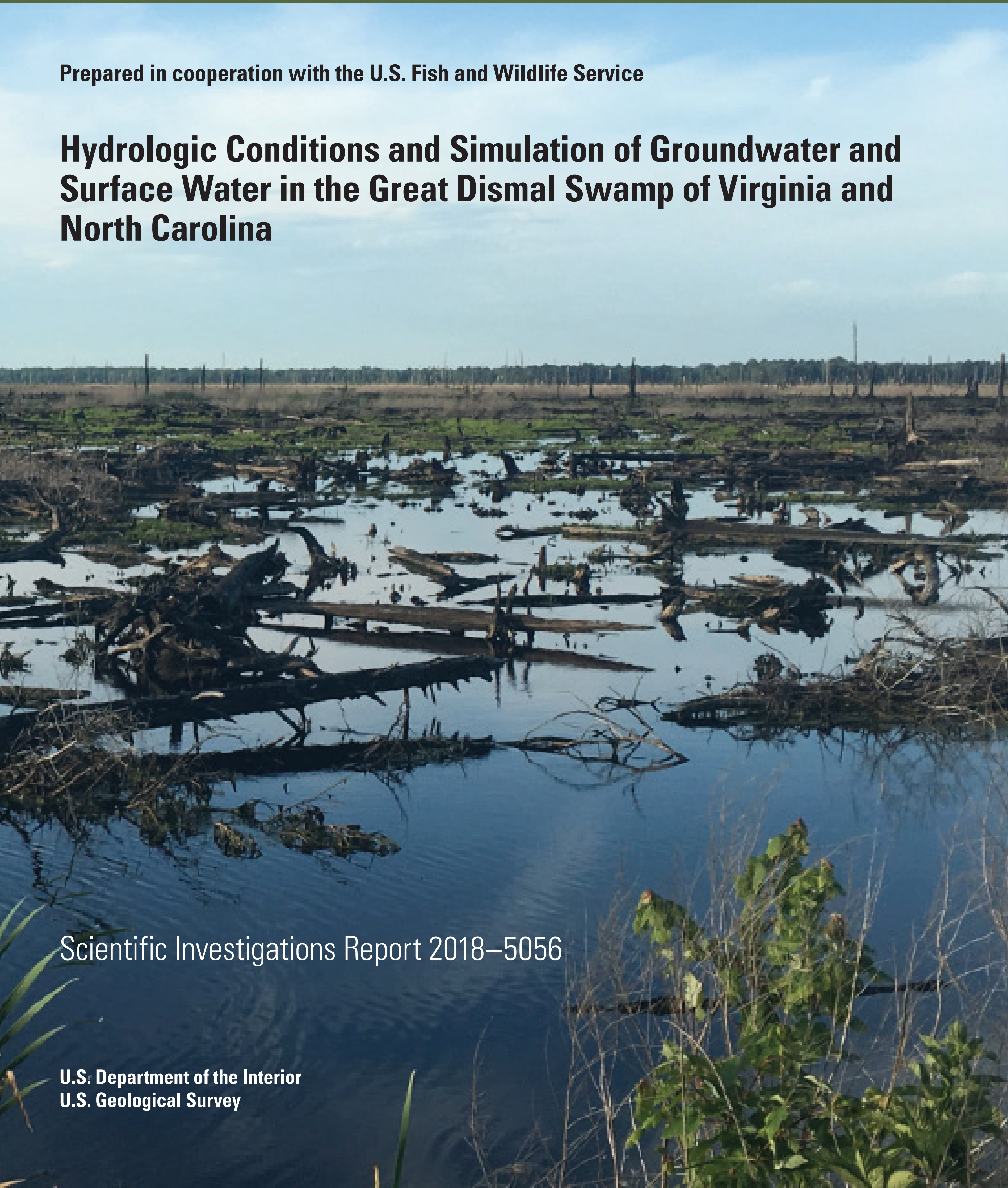
Hydrologic Conditions and Simulation of Groundwater and Surface Water in the Great Dismal Swamp of Virginia and North Carolina



Scientific Investigations Report 2018–5056

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photo of the area burned during the 2011 Lateral West fire, Great Dismal Swamp, Virginia and North Carolina. Ground view looking northeast from Corapeake Ditch, photograph taken by Frederic Wurster, U.S. Fish and Wildlife Service, June 2014.

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RYAN K. ZINKE, Secretary

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
foot (ft)	12.0	inch (in.)
mile (mi)	5280.0	feet (ft)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	86,400.0	cubic foot per day (ft^3/d)
cubic foot per second (ft^3/s)	0.53817	million gallons per day (Mgal/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

DSWE	Dynamic Surface Water Extent
EPA	U.S. Environmental Protection Agency
ET	Evapotranspiration
GDSNWR	Great Dismal Swamp National Wildlife Refuge
InSAR	Interferometric Synthetic Aperture Radar
K	Hydraulic conductivity
lidar	Light detection and ranging
NCDENR	North Carolina Department of Environment and Natural Resources
NCDSSP	North Carolina Dismal Swamp State Park
NOAA	National Oceanic and Atmospheric Administration
PET	Potential evapotranspiration
RMSE	Root mean square error
SAR	Synthetic Aperture Radar
SMWA	South Mills Water Association
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VADEQ	Virginia Department of Environmental Quality
WCS	Water control structure

Hydrologic Conditions and Simulation of Groundwater and Surface Water in the Great Dismal Swamp of Virginia and North Carolina

By Jack R. Eggleston1[1], Jeremy D. Decker[1], Jason S. Finkelstein[1], Frederic C. Wurster[2], Paul E. Misut[1], Luke P. Sturtevant[1], and Gary K. Speiran[1]

Abstract

The U.S. Geological Survey (USGS), in cooperation with the U.S Fish and Wildlife Service, has investigated the hydrology of the Great Dismal Swamp (Swamp) National Wildlife Refuge (Refuge) in Virginia and North Carolina and developed a three-dimensional numerical model to simulate groundwater and surface-water hydrology. The model was developed with MODFLOW-NWT, a USGS numerical groundwater flow modeling program, in combination with the Surface-Water Routing Process, a software package that simulates dynamic surface-water flows, water control structure management, and groundwater/surface-water interactions.

The steady-state model was calibrated to average spring conditions by using automated parameter estimation software (PEST) to reduce simulation errors and assess model parameter sensitivity. The model was then used to simulate wet and dry climatic conditions and a variety of hypothetical scenarios in which water levels in the Swamp were raised and lowered by simulated management of water control structures. Results of the model simulations indicate that, under average spring conditions, precipitation is the primary water input (92%); surface-water (5%) and groundwater (3%) inflows make up the remainder. The primary outflow (or loss) is evapotranspiration (55%), with surface outflows (about 41%) and groundwater outflow (about 4%) making up the remainder.

Simulated adjustment of water control structure weir levels demonstrates that groundwater levels are affected by water levels in adjacent ditches and that surface-water and groundwater levels can be controlled through management of water control structures, allowing the Refuge to better manage fire risks and preserve forested-wetland ecosystems in the Refuge. The 13 water control structures proposed in the simulated scenario representing possible future conditions effectively raised simulated water levels in the northeastern corner of the study area, a goal of the Refuge management.

Results of this study demonstrate use of MODFLOW with the Surface-Water Routing Process for simulating water management options in peat wetlands and will help Refuge managers to better understand existing hydrologic conditions, assess the hydrologic effects of planned changes to water control structures, and apply the new simulation tool to guide water management on the Refuge.

Introduction

The Great Dismal Swamp is one of the iconic wetlands of the United States and home of the largest National Wildlife Refuge in the U.S. Fish and Wildlife Service northeast region (Dennis, 1988; Simpson, 1990; Mitsch and Gosselink, 2007). The Great Dismal Swamp (Swamp) is a peatland historically dominated by several types of ecologically important and sensitive forested-wetland ecosystems (fig. 1). The Swamp is estimated to have originally covered nearly 1,500,000 acres in southeastern Virginia and northeastern North Carolina (Shaler, 1890). Since colonial times, however, the forest ecosystems have been altered by timber harvesting, wildfires, and hydrologic modifications caused by the construction of the Dismal Swamp Canal and numerous drainage ditches with adjacent spoil piles. The first ditches in the Swamp were constructed between 1763 and 1768 by a company formed by George Washington and several associates to facilitate timber harvesting and prepare the land for agriculture (Hansen, 2010). The 32-mile-long Dismal Swamp Canal, on the east side of the Great Dismal Swamp National Wildlife Refuge (Refuge), is the largest canal in the Swamp. Construction commenced in 1793 and ended in 1805, and the canal has been dredged and expanded since. The canal was built to allow commerce between Albemarle Sound (not shown) to the south and Chesapeake Bay to the north (not shown) and is the oldest continuously used man-made waterway in the United States (Trout, 1998). Additional ditches have been constructed within the Swamp through the years, resulting in the current 144-mile (mi) ditch network.

[1] U.S. Geological Survey.

[2] U.S. Fish and Wildlife Service.

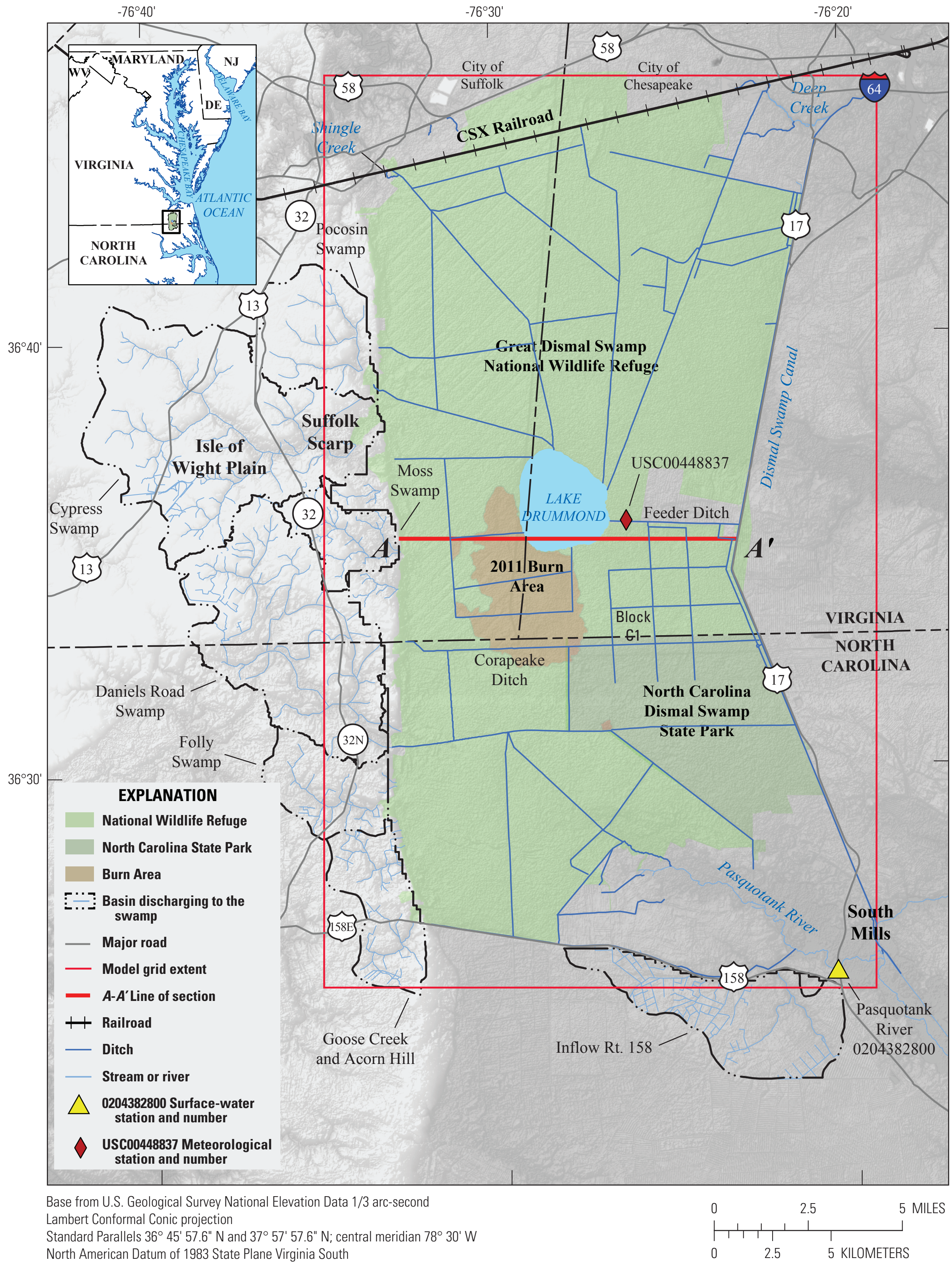


Figure 1. Location of the Great Dismal Swamp study area, Virginia and North Carolina. (Cross section shown in figure 4)

In 1974, the U.S. Congress established the Refuge with the U.S. Fish and Wildlife Service (USFWS) responsible for managing 49,100 acres in southeastern Virginia and northeastern North Carolina (U.S. Fish and Wildlife Service, 2006) (fig. 1). The Refuge has since expanded to its current 112,000 acres, making it the largest National Wildlife Refuge in the USFWS northeast region. An additional 14,432 acres of wetland forest is protected by the North Carolina Dismal Swamp State Park (NCDSSP), adjacent to the Refuge to the southeast. The combined 126,432 acres protected by the Refuge and NCDSSP are bounded by the Dismal Swamp Canal to the east and the Suffolk Scarp, a Pleistocene-age, marine shoreline (Oaks and Coch, 1973), to the west.

Although streams flow across the Suffolk Scarp into the Swamp and ditches extend throughout the Swamp, groundwater is a major part of the hydrologic system. The high permeability of the peat and the good hydraulic connection between the peat and the ditch network make the ditches major sinks for groundwater discharge, lowering groundwater levels and making much of the Swamp drier than pre-ditching conditions. Spoil piles adjacent to ditches were converted to logging roads and form barriers to water flow, causing land upgradient from roads to be wetter than pre-ditching conditions (Shaler, 1890). The road and ditch network has fundamentally changed the Swamp's hydrology, leading to tree stress and mortality, lowering of the land-surface elevation through oxidation and compaction of peat, and increasing the risk of severe wildfire (USFWS, 2006).

The USFWS has worked to mitigate the hydrologic effects of ditch and road construction by installing more than 49 water control structures (WCSs) in ditches since the Refuge was established. WCSs were installed in order to manage Swamp water levels to better preserve, re-establish, and maintain the Swamp's unique forested-wetland ecosystems (USFWS, 2006). In addition, the USFWS is working to improve its understanding of the Swamp's hydrology by regularly monitoring water levels and flows. In response to the South One fire which burned nearly 5,000 acres of forest and peat in 2008, an intensive water monitoring program was undertaken by Refuge staff to collect data for better describing Swamp hydrology. Data collected since 2008 have provided a valuable foundation for the research described in this report.

The U.S. Geological Survey (USGS), in cooperation with the USFWS, has developed a numerical, steady-state simulation model of water in the Swamp, which is described in this report. The model can simulate the effects of WCS management on surface-water and groundwater flows and levels. This enables compilation of water balances and mapping of contributing areas to important WCSs. Through development of the model and running simulations, a better understanding of the Swamp's complex hydrology has been obtained. The model can be used in the future to guide water-resource management strategies and answer additional questions about WCS management in the Swamp, such as where WCSs should be added or removed and how weir elevations should be set.

Purpose and Scope

This report describes the development of a two-dimensional (2-D), steady-state, numerical simulation model of a portion of the Swamp; development of a three-dimensional (3-D), steady-state model of the entire Swamp; and simulation of selected climatic conditions and water control structure management alternatives. The three-dimensional numerical model developed in this study simulates water levels and flows within the study area under steady-state conditions. Once calibrated, the model is used to determine water balances, groundwater and surface-water flow fields, and contributing areas to major flow outlets and WCSs. The model then is applied to simulate swamp hydrology under various climatic conditions and alternative WCS management strategies. Simulation results are then analyzed to assess the effects of water-resource management decisions on inundation, depth to water table, and flows at major WCSs. Results of this study will help Refuge managers to better understand existing hydrologic conditions, to assess the hydrologic effects of planned changes to WCSs, and to apply the new simulation tool to guide water management on the Refuge. The results also have broader application to other drained Coastal Plain peatlands of the mid-Atlantic and southeastern United States with hydrologic conditions similar to those of the Swamp. A data product associated with this report has been published (Eggleston and others, 2018), which is available online and contains a model archive and associated data files.

Previous Investigations

The hydrologic effects of the 144-mi ditch network have long been assumed (Lichtler and Walker, 1974; USFWS, 2006), and restoring the hydrology of the Swamp by partly blocking ditches has been a goal of the USFWS since Refuge establishment (USFWS, 2006). The strategy of the USFWS for hydrologic restoration is to implement controlled drainage practices that have been successfully used elsewhere in the Virginia and North Carolina Coastal Plain on agricultural land and managed forests. Adjustable-elevation WCSs were installed in ditches to reduce and slow drainage and to set desired ditch water levels (Dukes and others, 2003; Evans and others, 2007). Forty-nine structures were installed on the Refuge between 1974 and 2015, and more structures are planned. The effectiveness of this approach for restoring peatland hydrology is uncertain because, until recently, there has been little long-term hydrologic monitoring on the Refuge and therefore limited understanding among Refuge staff of hydrologic response to WCS management (USFWS, 2006). Ongoing studies are increasing knowledge of hydraulic characteristics of the Swamp's peat, the connection between the ditches and groundwater, and the hydrologic budget of the Swamp. In spite of this and other continuing research, significant gaps in our knowledge of the Great Dismal Swamp's hydrology remain.

Successful wetland restoration often hinges on an understanding of the hydrologic processes that control a wetland's structure and function. The National Research Council (2001) concluded many wetland mitigation projects fail because predisturbance hydrologic conditions are not well understood or could not be recreated at mitigation sites. Middleton (1999) highlights the importance of re-creating a wetland's predisturbance water regime (annual and long-term fluctuations in water levels in wetlands) when designing restoration strategies. In peatlands like the Great Dismal Swamp, restoring a hydrologic regime that supports peat accumulation is considered the most important aspect of a successful restoration project (Chimner and others, 2016). Therefore, to improve the success of wetland restoration projects, many researchers first conduct hydrologic investigations to inform restoration design (for example, Cooper and others, 1998; Gorham and Rochefort, 2003; Wilcox and others, 2006; Wosten and others, 2008; Bonsel and Sonneck, 2011).

The importance of investigating groundwater and surface-water interactions at Great Dismal Swamp was first proposed by Lichtler and Walker (1974). They recommended quantifying water-budget parameters in a portion of the Swamp affected by existing drainage ditches. This present report builds on those recommendations and supports ongoing studies by providing a detailed and quantitative description of Swamp hydrology and describing results from simulations of selected WCS management alternatives.

Description of the Study Area

The study area is in southeastern Virginia and northeastern North Carolina and is defined by the boundary of the hydrologic model developed in this study (fig. 2). The boundary of the hydrologic model was chosen to align with surface-water and groundwater features and encompass most of the Refuge and the NCDSSP. The study area extends from the eastern part of the Isle of Wight Plain west of the Suffolk Scarp to the Dismal Swamp Canal to the east and from the CSX railroad and Deep Creek in the north (fig. 1) to highway U.S. Route 158 and the Pasquotank River to the south (fig. 2).

Topography

Three main, natural, topographic features set the landscape on which other natural and man-made features are superimposed: the Isle of Wight Plain (higher elevation) and the Dismal Swamp terrace (lower elevation) are separated by the Suffolk Scarp (Wentworth, 1930; Oaks and Coch, 1973) (figs. 1 and 2). The Isle of Wight Plain is dissected by streams that drain across the Suffolk Scarp onto the Dismal Swamp terrace. The Dismal Swamp terrace is a relatively flat surface gently sloping to the north, east, and south toward Deep Creek, the Dismal Swamp Canal, and the Pasquotank River drainages, respectively.

Elevations, referenced to the North American Vertical Datum of 1988 (NAVD 88), range from 0 feet (ft) at the tidal Pasquotank River and Deep Creek, at the southeastern and northeastern boundaries of the study area, respectively, to a maximum of about 65 ft on the Isle of Wight Plain to the west of the Suffolk Scarp (scarp) (Oaks and Coch, 1973), which forms the western boundary of the study area (fig. 2). The scarp is a remnant Pleistocene-age, marine shoreline from a past high sea-level stand. Elevations are 40–60 ft at the top of the scarp and about 25 ft along the eastern foot of the scarp where the Swamp begins. The scarp is incised by small streams draining into the Swamp from the west. From the foot of the scarp, land surface generally slopes to the east, north, and south. Local elevation differences within the Swamp are caused by natural hummocks and hollows that create up to about 3 ft of local relief in the peat surface. Hummocks typically form around the roots of trees and shrubs, whereas hollows form between the trees and shrubs.

Man-made local differences in topography include roads and ditches across the study area. Roads were built on spoil material (peat and sand) dug out to construct the ditches and typically deposited on one side of each ditch. In many cases, the land-surface elevation shifts up or down across road and ditch boundaries. This likely is due to water being impounded on the road side of a combined road and ditch boundary, causing peat to accumulate or perhaps degrade more slowly on the road side, whereas water levels on the ditch side are at lower elevations, contributing to peat degradation that decreases the land-surface elevation. Other known human actions that have altered the local topography include the construction of railroads and fire breaks.

Fire can affect swamp topography by burning peat (fig. 3). Fires in 2008 and 2011 lowered surface elevations to the west and southwest of Lake Drummond (fig. 1). Although the amount of peat loss from the 2008 fire could not be determined, the 2011 Lateral West fire burned about 1.5 ft (47 centimeters [cm]) of peat in the Burn Area, as documented by light detection and ranging (lidar) observations (Reddy and others, 2015) and seen in the lower elevation profile (fig. 4).

Climate

The study area has a humid to subtropical climate (Trewartha and Horn, 1980). Average monthly temperatures observed from 1986 to 2015 at a climate station operated by the U.S. Army Corps of Engineers (USACE) on Lake Drummond (WALLACETON LK DRUMND, GHCND: USC00448837) ranged from about 5 degrees Celsius (°C) in January to about 26 °C in July and August (fig. 5). Mean annual precipitation observed at meteorological station USC00448837 from 1931 through 2015 is 50.7 inches (in.). Although average monthly precipitation does not vary much throughout the year, periods of little precipitation occasionally cause very dry conditions, and wet conditions occasionally cause floods. Observed monthly precipitation for 1986 to 2015

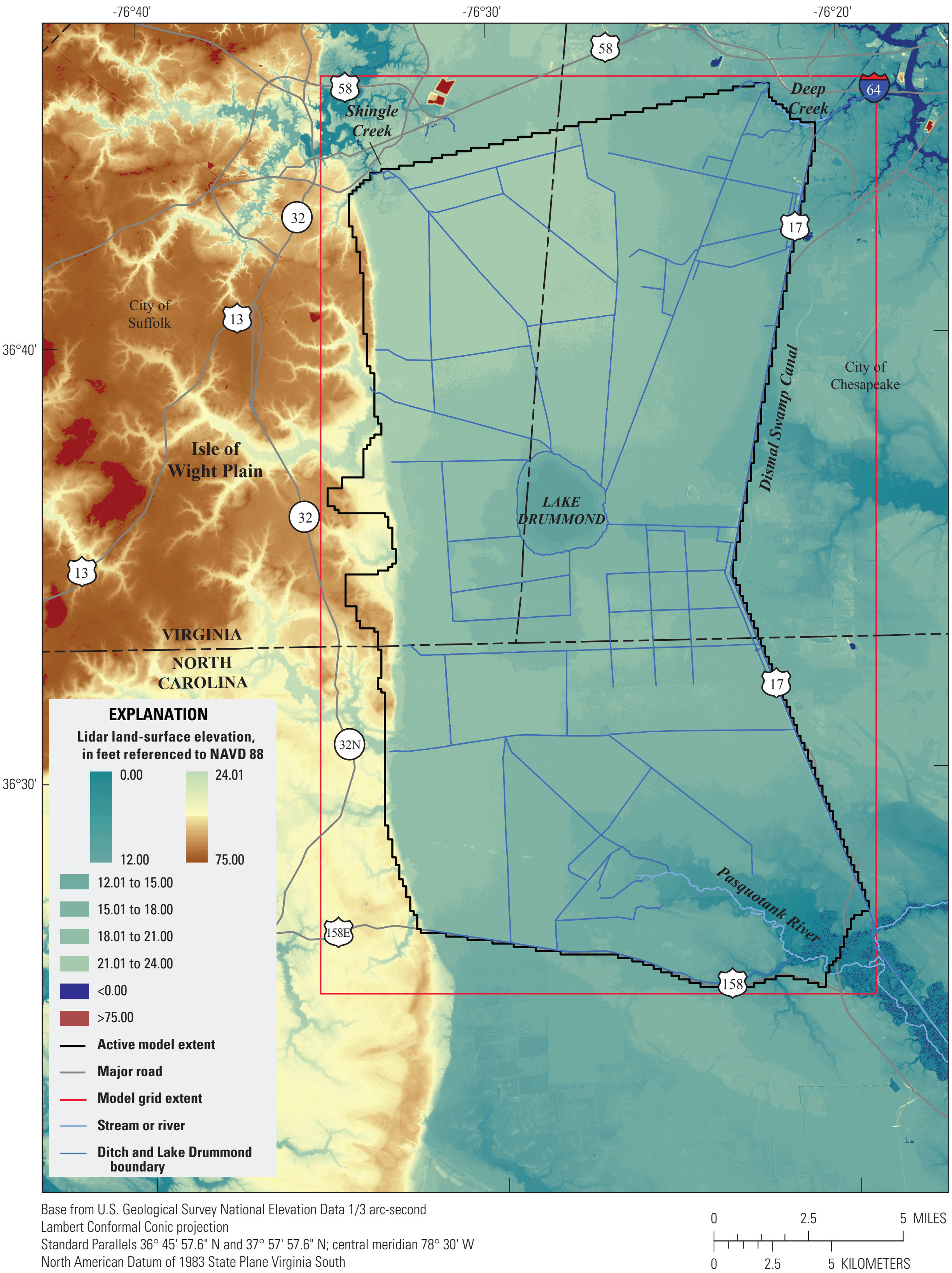


Figure 2. Land-surface elevations based on lidar surveys, Great Dismal Swamp, Virginia and North Carolina.

A

Photo by: U.S. Fish and Wildlife Service, August 2011

B

Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, June 2014

Figure 3. Photographs of the area burned during the 2011 Lateral West fire, Great Dismal Swamp, Virginia and North Carolina: *A*, aerial view, August 2011, and *B*, ground view looking northeast from Corapeake Ditch, June 2014.

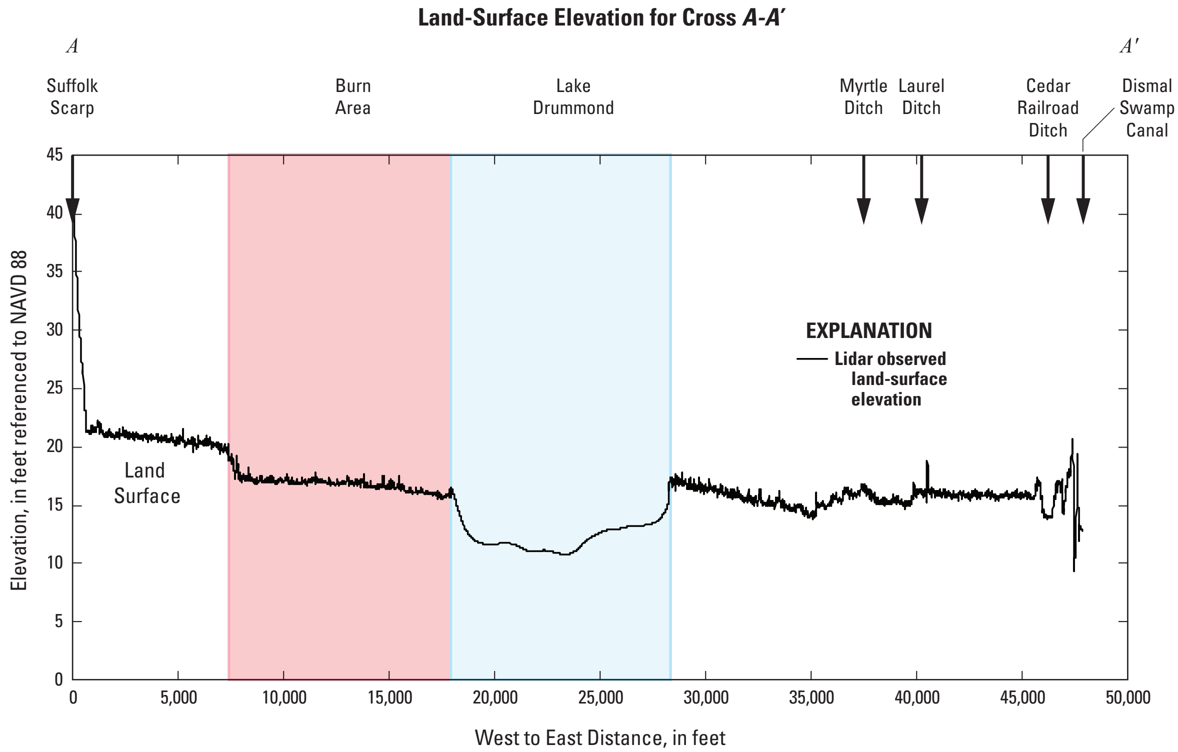


Figure 4. Profile of land-surface elevations observed by using lidar in 2012, across the Lateral West Burn Area, Great Dismal Swamp, Virginia and North Carolina. (Section line shown in figure 1)

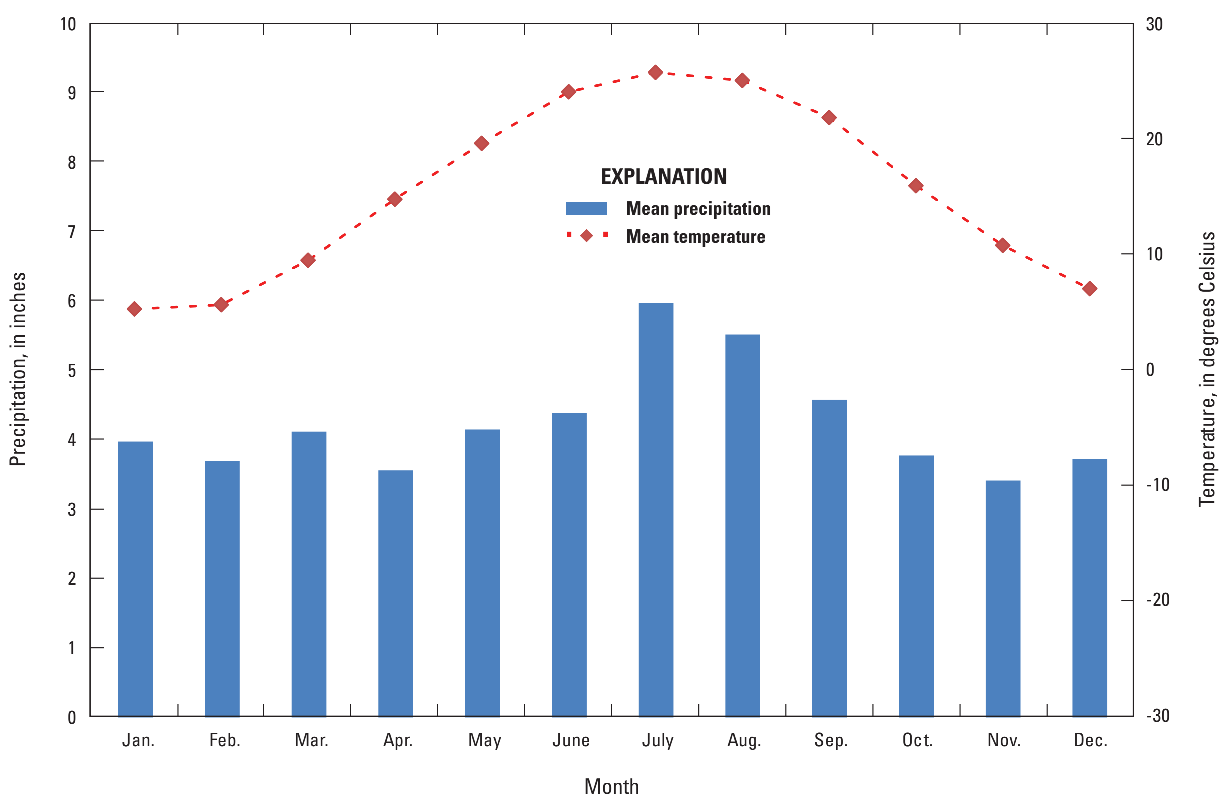


Figure 5. Graph of average monthly precipitation, from 1931 to 2015, and temperature, from 1997 to 2015, at meteorological station USC00448837 operated by the U.S. Army Corps of Engineers on Lake Drummond, Great Dismal Swamp, Virginia and North Carolina. (Location shown in fig. 1)

at station USC00448837 allows characterization of average, typical wet, and typical dry conditions during spring (April, May, and June; fig.6). Observed precipitation totals for spring varied from 7.04 inches (in.) to 20.16 in.

Droughts and floods occur periodically, affecting swamp hydrology and presenting challenges for Refuge managers. Tropical hurricanes, which occur in the summer and fall, have historically caused flooding that raised water levels in the Swamp, damaged WCSs, and inundated populated areas in South Mills, Suffolk, and Chesapeake Counties.

Land Use

Prior to establishment of the Refuge in 1974, human use of land in the study area included forestry, and crop and animal agriculture. Historical land use and the associated canal construction are implicated in the reduction of the species diversity of vegetation in the study area (USFWS, 2006). Since 1974, land use in the study area has changed to conservation of wildlife habitat and restoration of forests. Although most of the study area is uninhabited, people live along the southern, western, and northern edges of the study area.

Vegetation

The Swamp is characterized primarily as a seasonally flooded forested wetland. Vegetation in the Swamp has changed substantially since humans introduced agriculture and timber harvesting in the late 18th century. Agriculture, timber harvesting, altered hydrology, and fires have changed the types of forested-wetland ecosystems from the predominantly *Taxodium distichum* (bald cypress), *Pinus serotina Michx* (pocosin pine), and *Chamaecyparis thyoides* (Atlantic white cedar) (Shaler, 1890), for which the Swamp was known, to predominantly *Acer rubrum* (red maple)/*Nyssa sylvatica* (black gum) plant communities. This transition from a diverse forest community of bald cypress, *Nyssa aquatica* (water tupelo), black gum, Atlantic white cedar, and pocosin pine habitat to one dominated by red maple and black gum (Carter and Gammon, 1976; Levy, 1991; USFWS, 2006) is evident from pollen in peat cores (Stevens and Patterson, 1998). Pollen data near Block C1, an area southeast of Lake Drummond (fig. 1), reveal a vegetation history of an Atlantic white cedar swamp until around the time of colonial settlement about 400 years before present. The vegetation then shifted to that characteristic of a pocosin pine community with an increase in pine pollen to 58 percent and red maple pollen to 2 percent, the highest level in the pollen record (Stevens and Patterson, 1998). This time coincides with a major increase in the charcoal content of the peat, indicating an increase in the occurrence of fire.

The South Atlantic Coastal Plain of the United States is home to extensive forested wetlands on peat soils known as pocosins (Richardson, 1991). Also described as evergreen (or southeastern) shrub bogs, the pocosin vegetation community consists of an open-pine canopy underlain by a dense shrub layer. Pocosins are found chiefly on peatlands with low topographic relief, near the edge of estuarine wetlands, or in

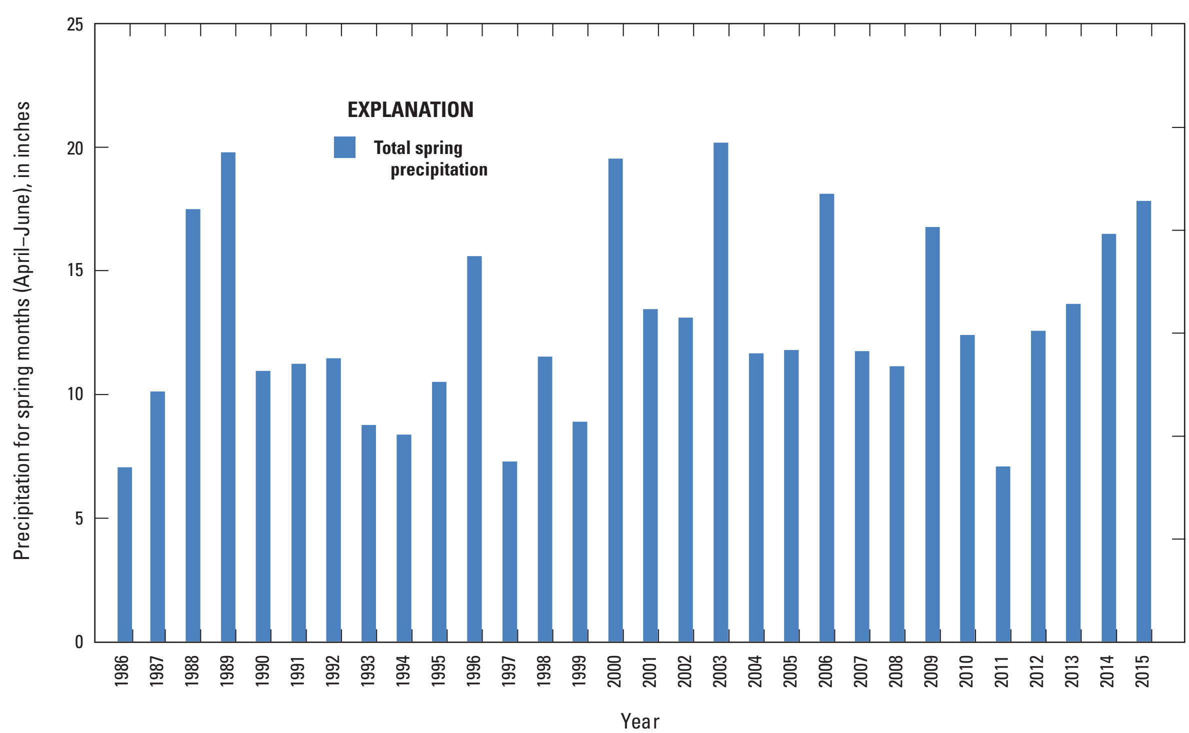


Figure 6. Graph showing spring (April–June) precipitation for the years 1986 to 2015 at meteorological station USC00448837 on Lake Drummond, Virginia, operated by the U.S. Army Corps of Engineers. (Location shown in fig. 1)

depressions with poor drainage (Brinson, 1991). Pocosins are found on the South Atlantic Coastal Plain from Virginia to Florida; the highest concentration is in coastal North Carolina (Richardson, 1991). Pocosins are at the northern extent of their range in the Swamp (USFWS, 2006).

Peat

The land surface across most of the Swamp is covered by leaf litter and an underlying root mat. In the root mat and below, peat forms the surface soil type across most of the Swamp (Oaks and Coch, 1973). The peat is composed of partially decomposed material from woody plants and has little mineral content. Peat in the Swamp can be divided into two horizons, the upper peat and lower peat, on the basis of textural characteristics observed in the field. It is common to encounter layers of buried trees, branches, and roots at varying depths below land surface. Maximum total peat thickness exceeds 10 ft in places but is typically 3–5 ft over much of the Swamp (Oaks and Coch, 1973). Further description of peat thickness is given in the "Geospatial Analysis of Peat Thickness" section below.

Total peat thickness shows spatial patterns corresponding to dendritic erosion patterns in the underlying sand, silt, and clay of the Tabb and Yorktown Formations (Oaks and Coch, 1973, fig. 33; Peebles and others, 1984). A convincing description of the formation of these spatial patterns in the peat thickness is given by Heath (1975, p. 16–19). In summary, peat accumulated over the past 9,000 years in low-lying areas, shallow depressions, and stream channels (Harrison and others, 1965, p. 217–221). Peat accumulated preferentially in stream courses where wet conditions prevailed. As peat accumulated in low-lying areas, it obstructed streams, causing wet conditions to spread and the peat to form over wider areas, expanding across valleys and covering uplands. Therefore, the greatest modern-day peat thickness is found aligned with former stream channels, which can be seen in stratigraphic contours of the top of a sand unit (Oaks and Coch, 1973)

Peat in the Great Dismal Swamp does not appear to have a true acrotelm and catotelm, on the basis of peat composition as described by Ingram (1978) for boreal peatlands. Instead, the composition of the peat is more characteristic of Ingram's catotelm throughout its depth but with variations in structure near the land surface. On the basis of field observations, the upper peat is very porous and highly decomposed, as is the lower peat. The lower peat likely has lower permeability and specific yield than the upper peat because of its finer texture and cohesive, clay-like consistency described as "mucky" (Henry, 1970). The upper peat transitions gradually downward to the lower peat. Various sizes of decomposing tree and shrub parts are present throughout most peat in the study area, and large branches and trunks are not uncommon. In some areas, a laterally discontinuous and thin layer of sticky clay separates the peat from the underlying sand.

Fire

Small fires occur frequently in the Swamp during dry periods as a result of lightning strikes and, in some instances, human activity. These small fires typically have minimal effect and are less common during wet periods. Large wildfires are less frequent, but can have extensive effects, and are known to have occurred in 1806, 1839, 1923–6, 1930, 1941–42, 1955, 1967, 2008, and 2011 (Simpson, 1990; USFWS, 2006; Stevens and Patterson, 1998). Such wildfire, which is required for the existence of some habitats in the Great Dismal Swamp, can alter other habitats, burn deeply into the peat releasing large amounts of carbon dioxide (a greenhouse gas contributing to climate change), change inundation patterns (fig. 3), cause health problems, be expensive to fight, and cause economic loss across the area (USFWS, 2006).

Fire is considered one of the most important controls on vegetation distribution, contributing to the existence of pocosins, a type of pine and shrub peatland (Richardson, 1991). Drainage caused by installed ditches tends to increase the frequency and severity of ground fires in peatlands (Turetsky and others, 2015). Fire suppression techniques developed for pocosin focus on attempting to douse ground fire by flooding the burning area because dousing is more effective than spraying when peat is smoldering below the land surface.

The wildfires of 2008 and 2011 are good examples of the difficulty of fighting peat fires and avoiding their effects. The fires occurred during dry summer periods in an area being prepared for regeneration of a cedar forest. Because groundwater and ditch water levels were low, water was pumped from low-elevation sources through the ditch network to extinguish the peat fires at higher elevations. Temporary dams were coupled with the existing network of WCSs to raise and direct water to the burning areas. Because groundwater levels were low and conditions were dry, the fire burned deeply into the peat and continued to smolder for more than 3 months. An average peat thickness of 1.5 ft and 1.10 teragrams of carbon were lost to the atmosphere in the 2011 Lateral West fire (Reddy and others, 2015). Collectively, these fires cost about $25 million to fight. A large part of the previously forested area remains open water and marsh (fig.3).

Water Use

Human withdrawal of groundwater and surface water, and discharge of wastewater, have the potential to affect Swamp hydrology. Although the study area is sparsely populated, water use occurs on all sides of the study area. Small areas along the northern, western, and southeastern boundaries of the study area are served with publicly supplied water. Wastewater from these small areas is collected and piped out of the study area for treatment in the cities north of the study area. Elsewhere in the study area, wastewater is disposed via private septic systems that drain to groundwater. Because developed areas in the southeast, northeast, and northwest are at lower elevations than the rest of the study area and receive groundwater and surface-water discharge from the Swamp, water use in these areas is unlikely to have much effect on groundwater and surface water within the Swamp. Because areas to the west drain to the Swamp, withdrawal in these areas can reduce the flow of water to the Swamp.

Withdrawals

Water supplies for the approximately 500 households in South Mills in the southeastern part of the study area (fig. 1) are withdrawn from wells by the South Mills Water Association (SMWA). On the basis of records from the North Carolina Department of Environment and Natural Resources (NCDENR) obtained from the online North Carolina Ground Water Data Map Interface (available through http://www.ncwater.org/), SMWA has two wells (South Mills wells 9 and 10) within the study area, both of which withdraw groundwater from screened intervals at 40–60 ft depths. In 2014, annual withdrawals from wells 9 and 10 totaled 0.05 million gallons per day (6,684 cubic feet per day [ft^3/d]). Well 9 was used only part of the year, whereas well 10 was reserved for emergency use and had no withdrawals. Although the SMWA wells are screened in, and therefore withdraw from, the shallow surficial aquifer, they are unlikely to have much effect on groundwater within the Refuge boundaries because the Pasquotank River and Dismal Swamp Canal provide fixed head boundaries less than 1 mi away, and most of the pumped water is likely returned nearby to the aquifer via septic discharge. No groundwater-level monitoring data for that part of the study area were available to this study, so the effects of withdrawals from SMWA supply wells on groundwater levels is unknown.

An estimated 1,050 households are within the northwestern part of the study area in the City of Suffolk, whereas an estimated 1,750 households are within the northeastern part of the study area within the City of Chesapeake. These households are served with public water that is not withdrawn from within the study area. Although a small amount of pumping of groundwater for lawn irrigation and landscaping likely occurs in these areas, no groundwater withdrawal records for such use were available for this study. Records obtained from the Virginia Department of Environmental Quality (VADEQ; Curt Thomas, VADEQ, written commun., April 2016) indicate that there were no permitted groundwater withdrawals in the Virginia portion of the study area from 2005 to 2015.

Wastewater

Only developed areas in the northeastern and northwestern parts of the study area have public wastewater collection, which is provided by the City of Chesapeake and the City of Suffolk, respectively. Wastewater is routed to the regional collection system operated by Hampton Roads Sanitation District and treated outside the study area. Elsewhere in the study area, households discharge wastewater to septic systems that drain to the underlying water table.

Hydrogeology

Groundwater is present throughout the study area, usually just a few feet or less below the land surface. During wet periods, the water table rises above the land surface, inundating much of the study area (fig. 7). Groundwater likely discharges to ditches over most of the study area most of the time and, during drought or seasonal dry conditions, is the only source of water to the ditches.

Aquifers

At the land surface, most of the study area is covered with a thin layer of peat, as described in the “Geospatial Analysis of Land-Surface Elevations and Peat Thickness” section. In some parts of the Swamp, the peat is underlain by a sticky clay layer up to 3 ft thick. Below the lower peat and sticky clay is mineral sediment consisting of fine-grained sand, silt, and clay (Oaks and Coch, 1973; Oaks, 1965). The mineral sediments are part of the Yorktown-Eastover confining unit and the underlying upper portion of the Yorktown-Eastover aquifer (McFarland and Bruce, 2006). Immediately underlying the Yorktown-Eastover aquifer is the Saint Marys confining unit, a low-permeability clay and silt layer found at a depth of about 130 ft below land surface in the study area. Overall, the study area is underlain by about 2,000 feet of layered sediments that are part of the regional North Atlantic Coastal Plain aquifer system, a major water-supply source for residents of the Coastal Plain in Virginia and North Carolina (Masterson and others, 2016a). The aquifers beneath the study area include the Potomac, Virginia Beach, Aquia, and Piney Point found at depths of about 600, 450, 350, and 300 ft, respectively (McFarland and Bruce, 2006, Attachment 1, boreholes 58A 75 and 58A76).

Pumping in these deeper aquifers of the North Atlantic Coastal Plain aquifer system, especially the Potomac, has caused groundwater-level drawdowns across the Coastal Plain, including underneath the study area. However, the shallow aquifer system in the study area appears to be hydraulically isolated from, and therefore not much affected by, the deeper water-supply aquifers. The apparent hydraulic separation is caused by the Saint Marys confining unit, a fine-grained unit with very low hydraulic conductivity (K) that is about 120 ft thick in the study area and lies below the Yorktown-Eastover aquifer (McFarland and Bruce, 2006, Attachment 1, boreholes 58A 75 and 58A76).

Aquifer Properties

The most important aquifer property controlling groundwater flows and levels that is considered in this study is hydraulic conductivity (K). Because only steady-state

Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, June 2014

Figure 7. Photograph of water overtopping Weyerhauser Ditch road after wet weather, June 2014, Great Dismal Swamp, North Carolina.

conditions are considered in this study, storage coefficients are not used as model parameters. The steady-state analysis was designed to ignore the effects of storage change in this system; therefore, the ability for the Swamp to accumulate and release water from storage was not considered in this study. Hydraulic conductivity is an empirically derived value expressing the ease with which water can move through an aquifer or other porous material under the presence of a hydraulic pressure gradient.

No measurements of hydraulic conductivity in the study area were available for this study. Hydraulic conductivity of the upper peat layer is thought to be very high because it is a coarsely textured highly porous material. Hydraulic conductivity of the underlying lower peat and clay layer is expected to be lower. Hydraulic conductivity of the underlying sand of the Yorktown-Eastover aquifer likely varies within the study area depending on the relative percentages of clay, silt, and sand making up the aquifer material. Verry and others (2011) summarize relations between hydraulic conductivity and peat physical properties, such as fiber content, bulk density, and degree of decomposition. In general, peat hydraulic conductivity is higher near the land surface where peat density tends to be lower and organic material is less decomposed compared to deeper peat. Hydraulic conductivity in peat near the land surface can be 2–3 orders of magnitude greater than hydraulic conductivity of the deeper, highly decomposed peat (Verry and others, 2011). Other researchers have noted similar patterns in peatlands in Indonesia (Wosten and others, 2008; Dommain and others, 2010), the United Kingdom (Ramchunder and others, 2009), and Canada (Landry and Rochefort, 2012).

Values of horizontal K for the Yorktown-Eastover aquifer reported in other studies range from 1 to 100 feet per day (ft/d) (Smith, 2003; Heywood and Pope, 2009). As described later in the “Model Development” section, horizontal K values for the upper peat, lower peat, and sand layers are 13,200; 24; and 10 ft/d, respectively.

Groundwater Levels and Flow Patterns

Groundwater-level observations were compiled from a variety of sources for this study and are the foundation for understanding patterns of groundwater levels and inferred directions of flow. The compiled dataset includes periodic observations collected and provided by Refuge staff plus periodic and continuous observations collected by the USGS and downloaded from the USGS National Water Information System (NWIS) online database (http://nwis.usgs.gov). Groundwater-level observations known to have high uncertainties were removed from the dataset. The complete set of 1,999 groundwater-level observations from 131 wells spans

1987 through 2016. Water-level data were collected during all months of the year and over a wide range of hydroclimatic conditions. April, May, and June are the target period for this study, as described in the "Model Development" section, and further description of water levels in this report focuses on those months. Hydrologic conditions during spring were identified by Refuge staff as critical to water management in the Refuge because most tree growth occurs then and is sensitive to water-table elevations. Dry conditions in the spring usually precede increased fire risk during the summer. To describe average spring conditions, water levels observed in the spring between April 1, 2005, and June 30, 2015, were averaged for each monitoring location.

With few exceptions, groundwater-flow rates and directions cannot be directly observed and must instead be inferred from groundwater-level and surface-water-level observations. Groundwater discharge to the land surface can be observed in some locations at the bottom of the scarp along the western side of the study area, where it is expected that groundwater flows eastward from the scarp.

Precipitation and Evapotranspiration

Precipitation and evapotranspiration (ET) make up a large fraction of the total water budget of the Swamp. A portion of precipitation falling on the Swamp percolates down to the water table and recharges the groundwater system. ET is the flux of groundwater, soil water, and surface water to the atmosphere either by evaporation or by plant transpiration. Both precipitation and ET occur everywhere in the study area. Because the water table is within a few feet or less below the land surface in most locations, groundwater is widely available to plants for transpiration, and the water table responds rapidly to precipitation and ET. Where the water table is above land surface, water can evaporate directly to the atmosphere.

Water-table responses in well 59 A39 (USGS station identifier 363320076261101) to 11 different precipitation events that occurred from November 2009 to September 2011 (fig. 8*A*) demonstrate that the first 0.39–0.79 in. (10–20 millimeters [mm]) of precipitation during a rainfall event is intercepted by vegetation or wets unsaturated peat and does not cause a measurable rise in the water table. But nearly all additional precipitation during a rainfall event percolates to the water table. The water-table response to precipitation varies depending on the water-table position relative to the land surface. Water-table response to a storm event, which occurred from August 26 to 28, 2011 and had total precipitation of 12 in. (0.3 m), shows that porosity or specific yield (*Sy*) increases from about 7 percent below a depth of 2.3 ft (0.70 meter [m]) to about 60 percent above a depth of about 1.5 ft (0.45 m) (fig. 8*B*). For example, 1 in. of recharge will raise the water table by 1.7 in. when the water table is near land surface and *Sy* is 60 percent but by as much as 14 in. when the water table is below 2.3 ft and *Sy* is 7 percent.

Potential evapotranspiration (PET) rates were calculated for April–June from observed mean monthly temperature data at the Lake Drummond meteorological station (USC00448837) by using Thornthwaite's equation (eq. 1–3). Calculated spring PET ranges from 9.7 to 13.0 in. for the years 2005 through 2015 (fig. 9) with the average PET rate for that period equaling 11.0 in., or 44.2 inches per year (in/yr) when converted to an annual rate. For the years 2011 and 2015, which are used to define dry and wet climatic conditions in the model scenarios discussed in the "Simulated Hydrology and Water Management" section of this report, spring PETs are calculated to be 11.2 in. (45.1 in/yr) and 11.7 in. (47.1 in/yr), respectively.

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_a}{I}\right)^{\alpha} \quad (1)$$

$$a = \left(6.75\text{x}10^{-7}\right)I^3 - \left(7.71\text{x}10^{-5}\right)I^2 + \left(1.792\text{x}10^{-2}\right)I + 0.49239 \quad (2)$$

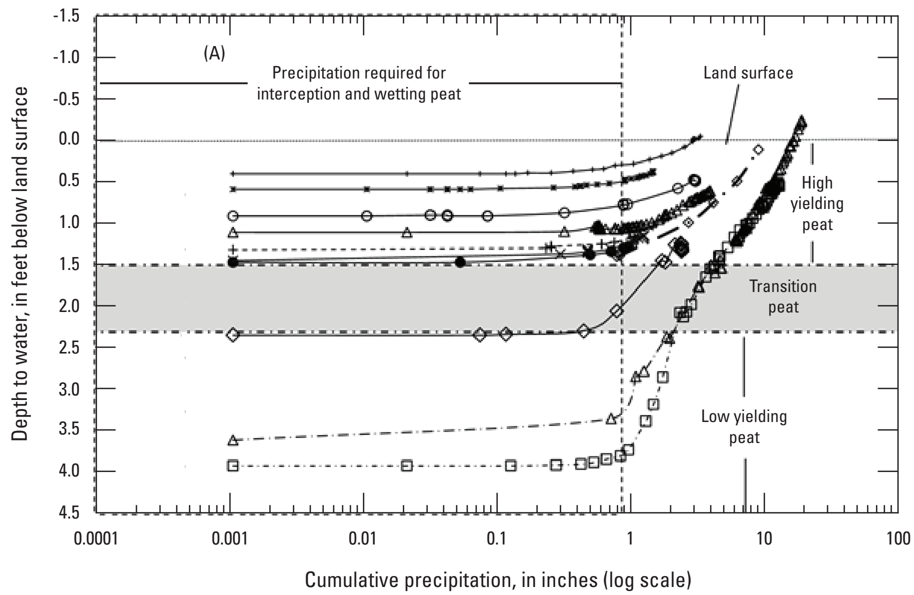
$$I = \sum_{i=1}^{12}\left(\frac{T_{ai}}{5}\right)^{1.514} \quad (3)$$

where

- PET is estimated potential evaporation (mm/month),
- L is mean day length (hours) of the month being calculated,
- N is the number of days in month being calculated,
- T_a is mean daily temperature in degrees Celsius of the month being calculated,
- α is an empirical exponent coefficient that varies with location, and
- I is the heat index dependent on the 12 monthly mean temperatures.

Other data are available to describe ET. The MODIS-MOD16 dataset (Mu and others, 2011) provides calculated actual ET at 3,218-ft (1-kilometer [km]) grid spacing for the years 2000–14. Monthly actual ET values are based on the Penman-Monteith equation using daily meteorological reanalysis data and 8-day remotely sensed vegetation property dynamics from MODIS satellite (hereafter MODIS) as inputs. The MODIS ET values give a mean rate of 50.7 in. (0.01158 ft/d) for April, May, and June from 2005 through 2014. Gridded ET estimates at the 3,281-ft (1-km) scale for the years 1971–2000 are also available from Sanford and Selnick (2013), who used a water-balance method combined with a climate and land-cover regression equation. Average ET rates from the Sanford and Selnick (2013) dataset for the study area show a mean annual ET rate of 27.6 in/yr (0.0062 ft/d).

A



B

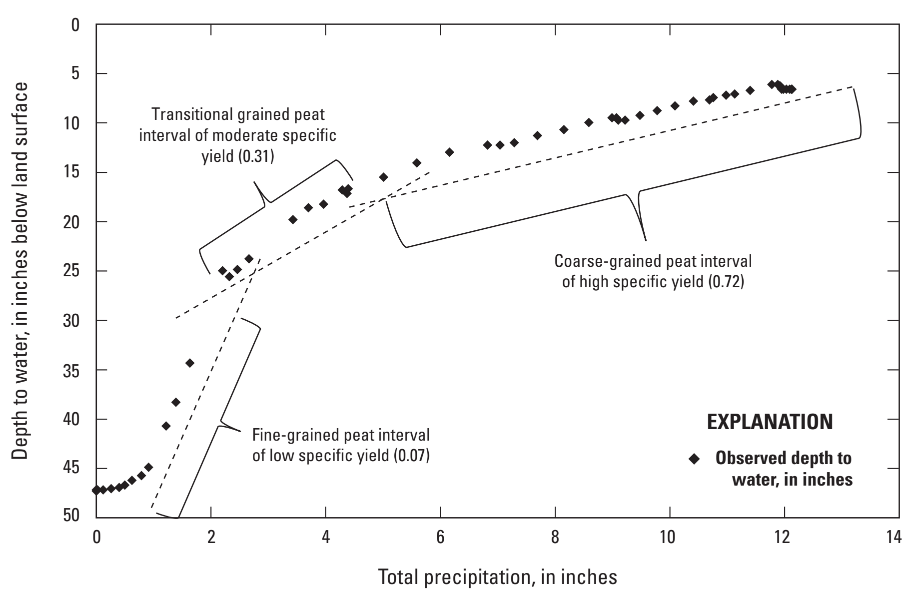


Figure 8. Graphs showing response of the water table in well 59A 39 to precipitation, *A* water-level response to selected precipitation events, *B* water-level response to 12 inches of precipitation from August 26 to 28, 2011, Great Dismal Swamp National Wildlife Refuge, Virginia and North Carolina.

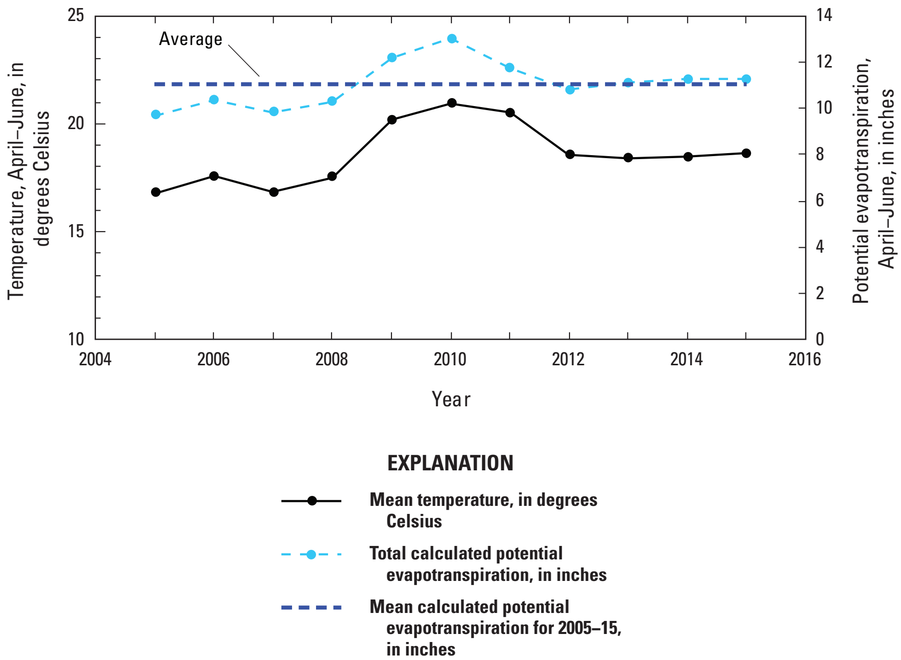


Figure 9. Graph showing mean observed temperature at meteorological station USC00448837 on Lake Drummond operated by the U.S. Army Corps of Engineers, total calculated potential evapotranspiration (PET), and mean calculated PET, determined by using Thornthwaite's equation for April, May, and June, 2005 through 2015, Great Dismal Swamp, Virginia and North Carolina. (Location of station USC00448837 shown in fig. 1)

These various ET rates are calculated by using different methods and data collected at different times, so the ET rates are examples of possible values rather than a defined single rate. These values are used as comparison for ET rates calculated by the model, as discussed in the "Calibration Approach" and "Calibration Results" sections.

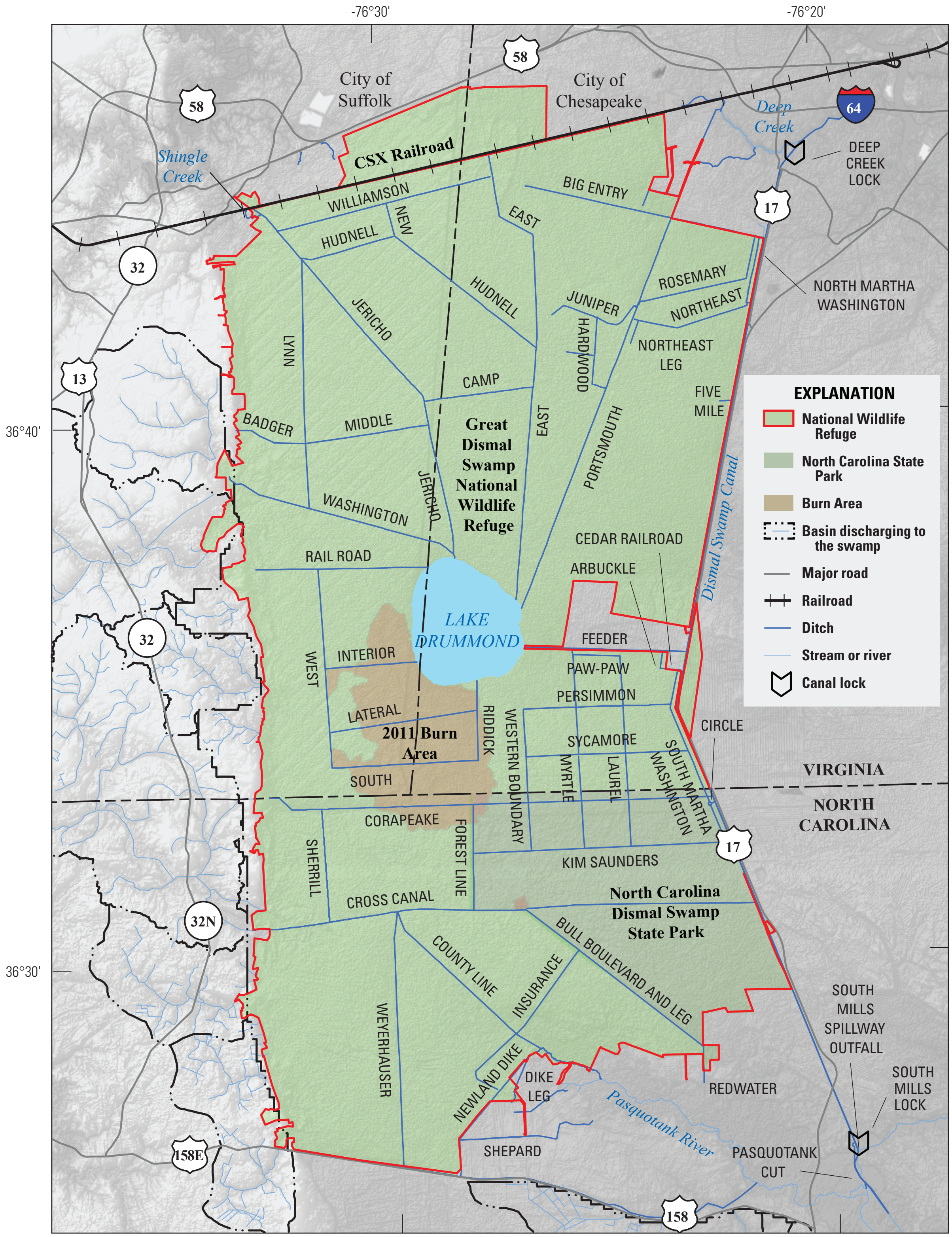
Surface-Water Hydrology

Surface water is present across the study area as standing water on the land surface during both wet and dry conditions and as surface-water bodies with defined banks. The surface-water bodies include streams draining across the scarp and into the Swamp, streams and ditches within the Swamp, the Dismal Swamp Canal, and Lake Drummond (fig. 1). Lake Drummond is a 3,108-acre shallow lake near the center of the Swamp (USFWS, 2006) that, although originally naturally occurring, has been impounded since at least 1830 (Shaler, 1890; Trout, 1998). The maximum depth of the lake is about 6 ft, and mean depth is about 4.5 ft, based on bathymetry data (USACE, 1970). The observed mean daily water-level elevation is 15.92 ft for January 1, 2005, through June 30, 2015, recorded by the USACE. The Lake Drummond Spillway keeps water in Lake Drummond about 5 ft higher than in the Feeder Ditch and passes flow from the lake into the Feeder Ditch. The USACE manages the dam, Feeder Ditch, and Dismal Swamp Canal to provide navigation for watercraft between the Chesapeake Bay and Albemarle Sound. Other surface-water bodies in the study area include natural freshwater drainages flowing across the Suffolk Scarp into the Swamp and streams at the boundaries including the freshwater Shingle Creek at the northwest corner and the tidal Deep Creek and Pasquotank River at the northeast and southwest corners, respectively. The most widely occurring surface-water features are ditches that have been dug throughout the Swamp.

Most ditches have a predominant flow direction, but because of the very flat topographic gradients, flow directions can reverse temporarily in some ditches under changing climatic and hydrologic conditions, or under changed weir level settings. Clogging of culverts and construction of beaver dams can also change flow directions and rates.

Ditches and Roads

Ditches were dug historically to lower water levels, provide fill for road construction, and carry water and goods from the interior of the Swamp to waterways to the north, east, and south. Although an unknown number of ditches have been abandoned and filled, many currently (2017) continue to act as primary discharge pathways for surface water flowing out of the Swamp. Actively flowing ditches are described and mapped (fig. 10) on the basis of data provided by Refuge staff.



Base from U.S. Geological Survey National Elevation Data 1/3 arc-second
Lambert Conformal Conic projection
Standard Parallels 36° 45' 57.6" N and 37° 57' 57.6" N; central meridian 78° 30' W
North American Datum of 1983 State Plane Virginia South

0 2.5 5 MILES

0 2.5 5 KILOMETERS

Figure 10. Ditches and roads in the Great Dismal Swamp, Virginia and North Carolina.

Roads built on top of spoil piles parallel most ditches (fig. 11). Spoil-bank roads are a barrier to surface-water flow because, unless water is higher than the road surface, water must divert to a culvert or pipe before flowing around or underneath the road. Roads are also barriers to groundwater flow because roads compact peat and reduce its hydraulic conductivity. However in a few locations, groundwater flows through roadbeds of corduroy construction. Corduroy construction is the creation of a roadbed base from tree trunks lain side-by-side across the width of the road. Dirt, sand, or gravel is then spread over the tree trunks. The tree trunk layer can provide a relatively low-resistance path for water to flow through the roadbed, particularly as the wood rots or degrades. Geospatial data describing road locations were provided by Refuge staff.

Water Control Structures

The strategy of the USFWS for hydrologic restoration of the Swamp centers on installation of engineered structures with weirs to control ditch water levels and flows (figs. 12 and 13, table 1). WCSs and their management follow the techniques of controlled drainage practices used on agricultural land in southeast Virginia and northeast North Carolina (Dukes and others, 2003; Evans and others, 2007). The Refuge manages smaller structures on interior ditches, termed "WCSs," which in this report describes all engineered structures controlling surface water in the Swamp. The most common WCS type is made of corrugated aluminum culvert material (fig. 13*B*) and consists of a horizontal culvert (typically 4–6 ft diameter) with a one-half section of culvert material welded vertically to the upstream end. Two or three structures are installed at some sites to provide extra flow capacity. Structures are typically placed in ditches at road crossings using heavy excavating equipment. Headwalls of aluminum, stone, and wood on the upstream and downstream faces of structures were installed to reduce erosion. Once a structure is in place, 0.5-ft stop-logs are added to the riser section to control water-surface elevations. The stop-logs function as rectangular weirs, and Refuge staff control ditch water levels by adjusting the elevation of weirs at 49 WCSs (fig. 12) (Wurster and others, 2016). Depending on the position of a WCS within the ditch network and elevation relative to the surrounding peat surface, a single WCS can affect water levels in several miles of adjacent ditches. WCSs that are currently (2017) actively managed to control water levels were installed starting in the mid-1980s (table 1).

The USACE manages water levels in the Dismal Swamp Canal, Feeder Ditch, and Lake Drummond (fig. 12). Water levels in Lake Drummond are controlled by the spillway on the Feeder Ditch (#28 on fig. 12), whereas water levels in the Dismal Swamp Canal are controlled by navigational locks and associated spillways and weirs at South Mills, N.C., and Deep Creek, Va. (#70 and #1 in fig. 12). These control structures are managed as described in the "Water Management" section.

Most head loss in the surface-water flow network occurs at structures, rather than as friction loss along the ditches. This can be seen in the mean observed surface-water levels of Corapeake Ditch from April 2013 to June 2015 (fig. 14). Data show that 4.3 ft of the total head drop of 6.3 ft, or 69 percent, occurred at the three WCSs (Western Boundary Ditch , 0.6 ft; Laurel Ditch, 1.5 ft; and Weir 1, 2.2 ft), whereas the remaining 2.0 ft, or 31 percent, occurred as frictional head loss along the length of Corapeake Ditch.

Surface-Water Inflows and Outflows

Surface water flows into the Swamp from the west and south. From the west, small streams drain into the Swamp through channels eroded across the Suffolk Scarp. From the south, constructed channels drain water from forested and agricultural land through culverts under Route 158 into the drainage ditch on the north side of Route 158, which carries flow east to the Pasquotank River. Rates of inflow to the Swamp (table 2) were estimated (eq. 4) on the basis of the inflowing streams' contributing drainage areas, and observed precipitation and calculated evapotranspiration for the periods representing wet, dry, and average climatic conditions. As described in the "Model Development" section, the inflows were later assigned as input to the model. Precipitation totals during the spring (April–June) for the wet, dry, and average climatic conditions are 17.81, 7.06, and 12.86 in., whereas evaporation totals are 11.75, 11.24, 11.03 in., also described in the "Model Development" section. Although a small area to the east of Route U.S. 17 drains to the Dismal Swamp Canal through culverts, this inflow is not expected to be significant and is not included in the model.

$$\text{Inflow} = \text{Drainage area} \times (\text{Precipitation} - \text{Potential evapotranspiration}) \quad (4)$$

At the foot of the scarp, water from streams flowing into the Swamp from the west spreads out and moves as diffuse groundwater or surface drainage until captured by drainage ditches in the interior of the Swamp. Exceptions to this are streams in Taylor Swamp and Pocosin Swamp, which after entering the Swamp are intercepted by Cross Canal and Washington Ditch, respectively (fig. 10). On the basis of field observations, groundwater is expected to discharge mostly to land surface at the toe of scarp and into ditches running parallel to the scarp, such as Lynn Ditch, West Ditch, and Sherrill Ditch (fig. 10).

Outflows from the Swamp are to Shingle Creek from Jericho Ditch at the northwestern corner of the study area; to Deep Creek from Portsmouth Ditch and from the Dismal Swamp Canal at the northeastern corner; and to the Pasquotank River from various ditches and the Dismal Swamp Canal at the southeastern corner (fig. 10). Some of these outflows are monitored (table 3). The USGS has operated a streamflow gaging station (0204382800 Pasquotank River near South Mills, N.C.) in the southeast corner of the study area since

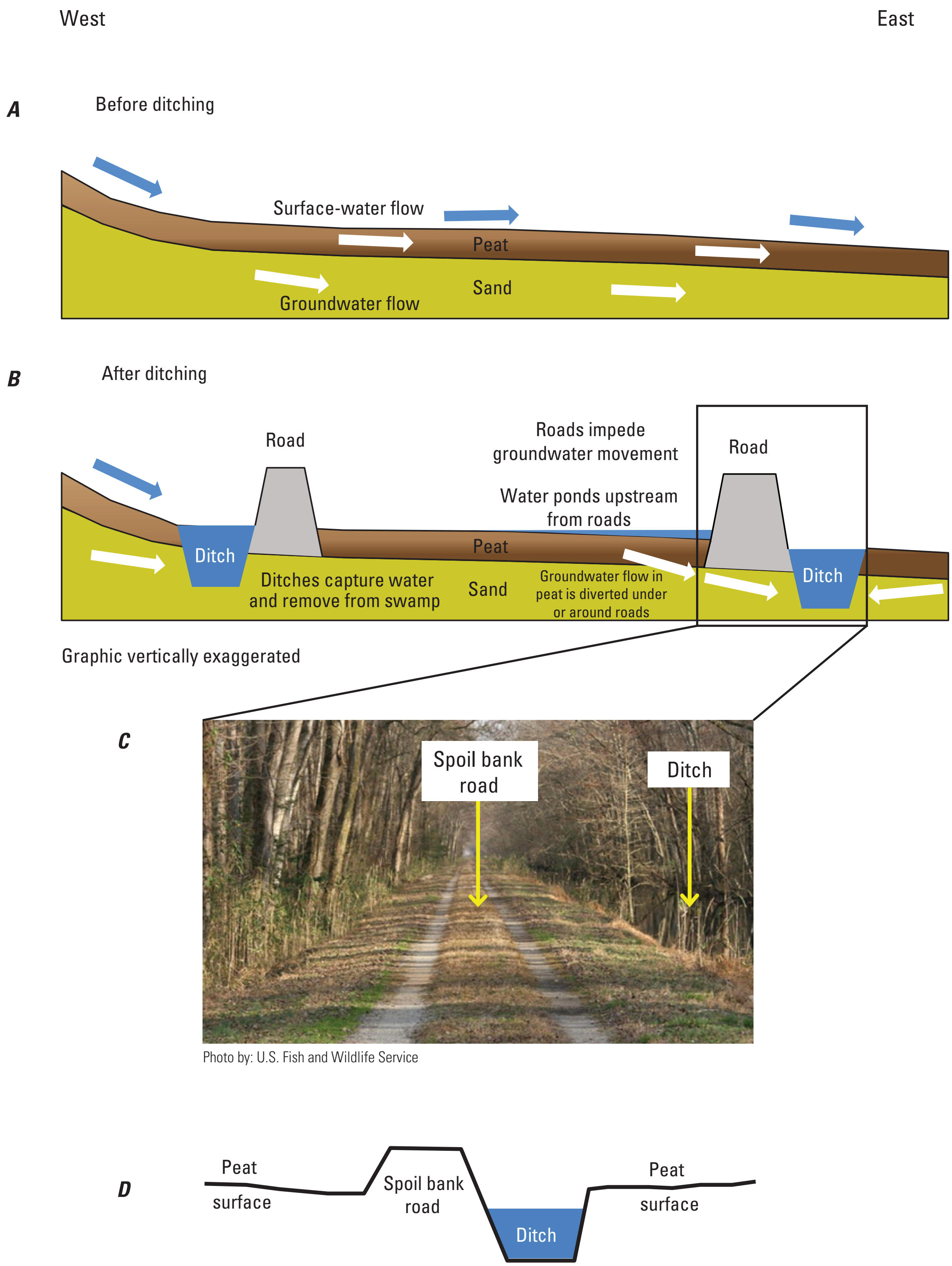


Figure 11. Cross-sectional diagrams of groundwater and surface-water flow *A*, before ditching and *B*, after ditching, *C*, photo of road and ditch in Great Dismal Swamp, Virginia and North Carolina, and *D*, diagram of road and ditch.

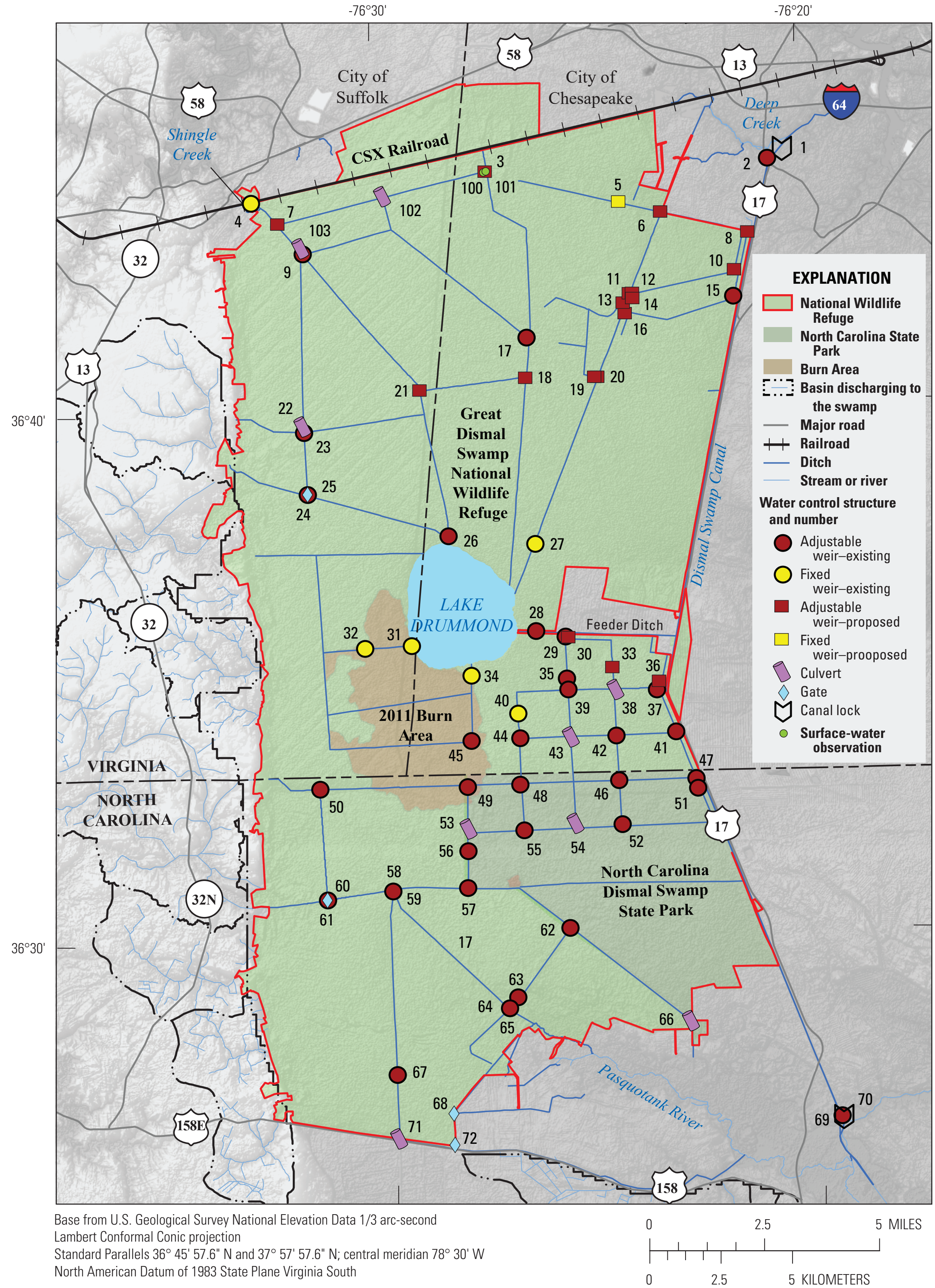


Figure 12. Locations of water control structures in the Great Dismal Swamp, Virginia and North Carolina. (Structure information listed in table 1)

Table 1. Description of water control structures in the Great Dismal Swamp, Virginia and North Carolina.

[Locations of sites are shown in figure 12. WCS, water control structure; NA, not applicable; NE, Northeast; N, North; E, East; NW, Northwest; S, South; W, West; SE, Southeast]

Structure name	Site map number	Site in model	Structure type	Typical flow direction	Year installed	Gage	Weir invert elevation, in feet, according to model scenario				
							1, 2 Baseline, wet	3 Dry	4 Future WCS added	5, 6 Flood the swamp (wet, dry)	7, 8 Drain the swamp (wet, dry)
Deep Creek Locks	1	Yes	Canal Lock	NE	1941	Yes	7.9	7.9	7.9	7.9	7.9
Deep Creek Spillway	2	Yes	Adjustable Weir	N	1941	Yes	7.9	7.9	7.9	7.9	7.9
Williamson/East	3	Yes, proposed	Adjustable Weir	E	Proposed	NA	None	None	20.5	22.0	16.0
Jericho North	4	Yes	Fixed Weir	NW	2009	Yes	19.0	19.0	19.0	19.5	16.5
Big Entry Fixed Weir 2	5	Yes, proposed	Fixed Weir	NA	Proposed	NA	None	None	14.0	14.0	14.0
Portsmouth/Big Entry	6	Yes, proposed	Adjustable Weir	NE	1994/Proposed	NA	7.4	7.4	12.0	13.6	7.4
Jericho @ Williamson	7	Yes, proposed	Adjustable Weir	NW	NA/Proposed	No	18.0	18.0	20.0	23.0	15.0
Rosemary/Big Entry	8	Yes, proposed	Adjustable Weir	NA	Proposed	NA	None	None	11.0	14.5	6.5
Lynn/Jericho	9	Yes	Adjustable Weir	N	1984	Yes	16.2	16.2	16.2	22.0	16.2
Rosemary @ Road	10	Yes, proposed	Adjustable Weir	NA	Proposed	NA	None	None	12.0	15.5	9.0
Rosemary @ Portsmouth	11	Yes, proposed	Adjustable Weir	NE	1984	Yes	16.1	16.1	14.5	16.7	11.2
Portsmouth @ Rosemary	12	Yes, proposed	Adjustable Weir	E	Proposed	NA	14.3	14.3	14.3	17.0	12.0
Juniper @ Road	13	Yes, proposed	Adjustable Weir	N	Proposed	NA	None	None	15.0	17.0	13.0
Portsmouth @ Juniper	14	Yes, proposed	Adjustable Weir	NE	Proposed	NA	None	None	15.5	17.0	12.0
Northeast	15	Yes	Adjustable Weir	NE	1984	Yes	13.5	13.5	13.5	15.0	9.0
Portsmouth/Northeast	16	Yes, proposed	Adjustable Weir	NA	Proposed	NA	16.1	16.1	15.0	16.5	11.1
Hudnell/East	17	Yes	Adjustable Weir	E	2012	Yes	17.6	17.6	17.6	21.3	15.5
Camp/East	18	Yes, proposed	Adjustable Weir	NA	NA/Proposed	NA	17.3	17.3	20.0	21.0	16.0
Portsmouth/Hardwood	19	Yes, proposed	Adjustable Weir	W	NA/Proposed	NA	14.0	14.0	16.5	18.5	14.5
Portsmouth Dam	20	Yes, proposed	Adjustable Weir	N	Proposed	NA	9.0	9.0	16.5	18.5	14.5
Jericho/Camp	21	Yes, proposed	Adjustable Weir	E	1990/Proposed	NA	17.0	17.0	20.0	20.0	16.0
Lynn @ Badger	22	Yes	Culvert	S	NA	No	19.0	19.0	19.0	19.0	19.0
Lynn/Middle	23	Yes	Adjustable Weir	E or W	1984	Yes	18.6	18.6	18.6	24.0	18.6
Lynn South	24	Yes	Gate	N or S	1984	Yes	17.0	17.0	17.0	17.0	17.0
Washington/Lynn	25	Yes	Adjustable Weir	SE	1984	Yes	21.0	21.0	21.0	24.0	18.0
Washington/Jericho	26	Yes	Adjustable Weir	S	1977	Yes	17.2	17.2	17.2	18.3	14.0
Porstmouth Unknown	27	Yes	Fixed Weir	NA	NA	NA	17.7	17.7	17.7	17.7	17.7
Lake Drummond Spillway	28	Yes	Adjustable Weir	E	1935	Yes	15.1	15.1	15.1	15.1	15.1

Table 1. Description of water control structures in the Great Dismal Swamp, Virginia and North Carolina.—Continued

[Locations of sites are shown in figure 12. WCS, water control structure; NA, not applicable; NE, Northeast; N, North; E, East; NW, Northwest; S, South; W, West; SE, Southeast]

Structure name	Site map number	Site in model	Structure type	Typical flow direction	Year installed	Gage	Weir invert elevation, in feet, according to model scenario				
							1, 2 Baseline, wet	3 Dry	4 Future WCS added	5, 6 Flood the swamp (wet, dry)	7, 8 Drain the swamp (wet, dry)
Myrtle North	29	Yes	Adjustable Weir	N	2006	Yes	12.8	13.3	12.8	15.5	11.4
Paw Paw/Myrtle	30	Yes, proposed	Adjustable Weir	W	Proposed	No	16.0	16.0	13.0	16.0	11.0
Interior to Drummond	31	Yes	Fixed Weir	E	2011	NA	16.2	16.2	16.2	16.2	16.2
Interior @ mid point	32	Yes	Fixed Weir	NA	2011	NA	17.1	17.1	17.1	17.1	17.1
Laurel Weir @ Persimmon	33	Yes, proposed	Adjustable Weir	N	Proposed	No	None	None	14.5	17.0	13.0
Riddick Plug	34	Yes	Fixed Weir	N	2011	No	19.3	19.3	19.3	19.3	19.3
Myrtle South	35	Yes	Adjustable Weir	N	2012	Yes	14.0	14.5	14.0	17.5	12.0
S. Martha Weir @ Persimmon	36	Yes, proposed	Adjustable Weir	N	2015	No	None	None	14.5	17.0	13.3
S. Martha/Persimmon	37	Yes	Adjustable Weir	N	2012	Yes	14.8	14.8	14.8	17.3	13.3
Persimmon/Laurel	38	Yes	Culvert	W	NA	No	10.0	10.0	10.0	10.0	10.0
Myrtle/Persimmon	39	Yes	Adjustable Weir	E or W	1984	Yes	14.5	14.5	14.5	18.7	10.7
Rock Weir	40	Yes	Fixed Weir	N	1990	No	17.1	17.1	17.1	17.1	17.1
Sycamore/South Martha Washington	41	Yes	Adjustable Weir	S	1984	Yes	14.9	15.3	14.9	18.6	10.0
Sycamore/Laurel	42	Yes	Adjustable Weir	E	2013	Yes	15.3	15.7	15.3	18.7	13.8
Sycamore/Myrtle	43	Yes	Culvert	E	NA	No	12.5	12.5	12.5	12.5	12.5
Sycamore/West	44	Yes	Adjustable Weir	E	2012	Yes	16.0	16.5	16.0	19.5	14.3
South/Riddick	45	Yes	Adjustable Weir	E	1990	Yes	17.6	17.6	17.6	17.7	13.0
Corapeake/Laurel	46	Yes	Adjustable Weir	E	1985	Yes	15.0	15.5	15.0	18.5	12.0
Weir 1	47	Yes	Adjustable Weir	S	2012	Yes	13.5	14.5	13.5	21.0	8.5
Corapeake/West Bndry	48	Yes	Adjustable Weir	E	1995	Yes	16.0	16.0	16.0	18.3	12.3
Forestline North	49	Yes	Adjustable Weir	N or S	1994	Yes	18.2	18.2	18.2	21.0	16.3
Sherrill North	50	Yes	Adjustable Weir	N	1984	Yes	17.0	17.5	17.0	19.5	15.0
Weir 2	51	Yes	Adjustable Weir	N	2013	No	13.8	13.8	13.8	16.8	9.5
Kim Saunders/Laurel	52	Yes	Adjustable Weir	E	2015	Yes	13.3	14.0	13.3	18.0	13.0
Forestline Culvert North	53	Yes	Culvert	S	NA	No	14.7	14.7	14.7	14.7	14.7
Kim Saunders/Myrtle	54	Yes	Culvert	E	NA	No	10.5	10.5	10.5	10.5	10.5
Kim Saunders/Western Boundary	55	Yes	Adjustable Weir	E	2015	Yes	13.0	14.0	13.0	18.0	13.0
Forestline 2	56	Yes	Adjustable Weir	S	2014	No	15.7	15.7	15.7	21.0	15.7

Table 1. Description of water control structures in the Great Dismal Swamp, Virginia and North Carolina.—Continued

[Locations of sites are shown in figure 12. WCS, water control structure; NA, not applicable; NE, Northeast; N, North; E, East; NW, Northwest; S, South; W, West; SE, Southeast]

Structure name	Site map number	Site in model	Structure type	Typical flow direction	Year installed	Gage	Weir invert elevation, in feet, according to model scenario				
							1, 2 Baseline, wet	3 Dry	4 Future WCS added	5, 6 Flood the swamp (wet, dry)	7, 8 Drain the swamp (wet, dry)
Forestline South	57	Yes	Adjustable Weir	S	1984	Yes	16.6	17.0	16.6	22.0	14.8
Cross Canal/Weyerhauser	58	Yes	Adjustable Weir	E	1994	Yes	15.0	15.5	15.0	20.0	13.5
County Line/Weyerhauser	59	Yes	Adjustable Weir	SE	1994	Yes	15.0	15.5	15.0	20.0	12.5
Sherrill South	60	Yes	Gate	N	1985	Yes	15.0	15.0	15.0	15.0	15.0
Cross Canal/Sherrill	61	Yes	Adjustable Weir	E	1985	Yes	18.0	18.0	18.0	21.0	15.0
Bull Boulevard/Insurance	62	Yes	Adjustable Weir	SE	1995	Yes	14.3	14.3	14.3	17.5	10.5
Head of River 1	63	Yes	Adjustable Weir	SE	NA	Yes	12.0	13.0	12.0	16.5	10.8
Insurance/Countyline	64	Yes	Adjustable Weir	NE	1995	Yes	7.7	7.7	7.7	15.0	7.7
County Line/Insurance	65	Yes	Adjustable Weir	SE	1995	Yes	12.4	12.8	12.4	15.0	8.7
Bull Boulevard South	66	Yes	Culvert	S	NA	No	5.8	5.8	5.8	5.8	5.8
Weyerhauser	67	Yes	Adjustable Weir	S	1984	Yes	16.8	16.8	16.8	18.8	14.0
Newland Slide Gate	68	Yes	Gate	E	NA	No	13.0	13.0	13.0	13.0	13.0
South Mills Spillway	69	Yes	Adjustable Weir	W	1941	Yes	7.9	7.9	7.9	7.9	7.9
South Mill Locks	70	Yes	Canal Lock	S	1941	Yes	7.9	7.9	7.9	7.9	7.9
Weyerhauser 158 culverts	71	Yes	Culvert	E	NA	Yes	10.0	10.0	10.0	10.0	10.0
Newland Dike Screwgate	72	Yes	Gate	E	NA	No	12.0	12.0	12.0	12.0	12.0
Williamson/East - Williamson	100	No	Observation	NA	NA	No	NA	NA	NA	NA	NA
Williamson/East - East	101	No	Observation	NA	NA	Yes	NA	NA	NA	NA	NA
Williamson/New	102	No	Culvert	NW	NA	Yes	NA	NA	NA	NA	NA
Jericho/Hudnell	103	No	Culvert	NW	NA	Yes	NA	NA	NA	NA	NA

A

Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, April 2011

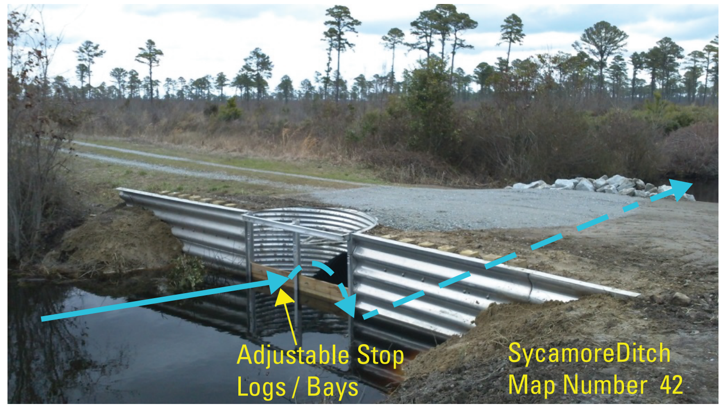


Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, March 2013

Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, January 2014

B

Photo by: Frederic Wurster, U.S. Fish and Wildlife Service, November 2012

Figure 13. Photographs of representative water control structures managed by the Great Dismal Swamp National Wildlife Refuge, Virginia and North Carolina: *A*, installed structures and *B*, a new combined culvert and riser on route to installation.

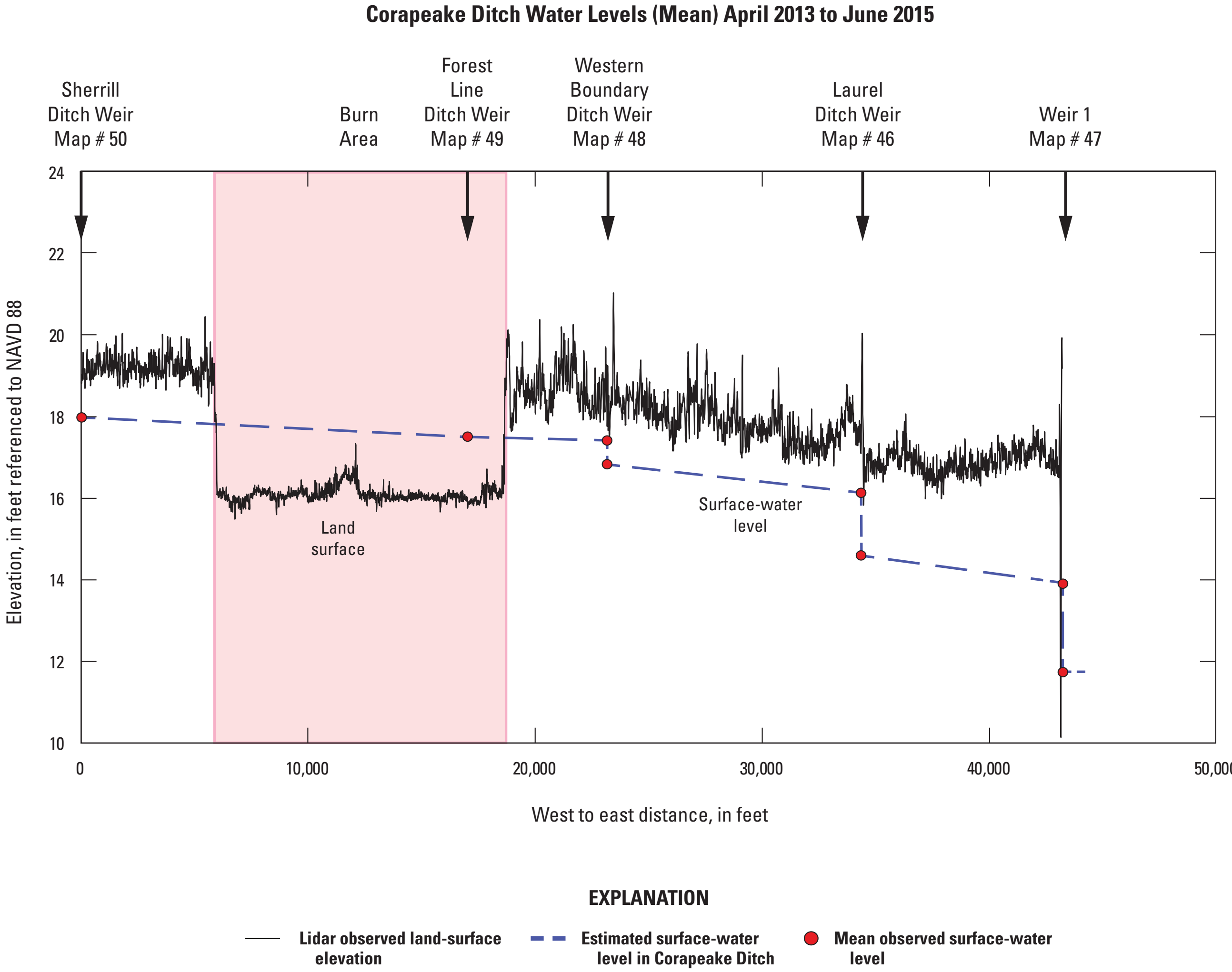


Figure 14. Mean observed surface-water levels along Corapeake Ditch, Great Dismal Swamp, Virginia and North Carolina, April 2013–June 2015.

Table 2. Estimated surface-water inflows to the Great Dismal Swamp, Virginia and North Carolina.

[mi^2, square miles; ft^3/s, cubic feet per second]

Inflow area	Total area (mi^2)	Estimated inflow (ft^3/s)		
		Dry	Wet	Average
Cypress Swamp	30.0	0	53.7	16.3
Daniels Road Swamp	22.8	0	40.8	12.3
Folly Swamp	6.5	0	11.6	3.5
Goose Creek/Acorn Hill	7.2	0	12.9	3.9
South of Rt. 158	13.0	0	23.2	7.0
Moss Swamp	5.0	0	8.9	2.7
Pocosin Swamp	8.8	0	15.7	4.8

Table 3. Observed surface-water outflows from the Great Dismal Swamp, Virginia and North Carolina.

[USACE, U.S. Army Corps of Engineers; USFWS, U.S. Fish and Wildlife Service; USGS, U.S. Geological Survey; WCS, water control structure; fig., figure; ft^3/s, cubic feet per second; --, no data; Avg, average]

Station	Data source	Location	Condition and average period flow rate, in ft^3/s		
			Dry: April–June 2011	Wet: April–June 2015	Avg: April–June, 2005–15
South Mills	USACE	WCS map numbers 73 and 74 in fig. 12	55.0	154.7	131.3
Deep Creek	USACE	WCS map numbers 1 and 2 in fig. 12	56.4	158.6	113.8
Jericho	USFWS	WCS map number 4 in fig. 12	4.7	11.8	8.5
Pasquotank	USGS	USGS station 0204382800 in fig. 1	56.8	127.8	105.3
Portsmouth	None	No structure	--	--	--
Shingle Creek	None	No structure	--	--	--
Total Outflow			[1]172.9 +	[1]452.9 +	[1]361.4 +

[1]Sum of measured flow is less than total flow.

1994 (fig. 1). The USACE has recorded daily water levels since 1923 and flows since 1953 at the Lake Drummond spillway (#28 in fig. 12) and, for this study, provided daily records of levels and flows for 2010 through 2015 at the Deep Creek and South Mills locks (#1 and #70 on fig. 12). At the northwestern corner of the study area, Jericho Ditch and other smaller unnamed ditches and drainages discharge to Shingle Creek (fig. 10). Flow is not observed in Shingle Creek, but Refuge staff make periodic flow observations at the last WCS on Jericho Ditch, which on the basis of field observations constitutes most of the outflow to Shingle Creek.

Water Management

Water management by the USFWS has focused on “restoring” the hydrology of the Swamp (USFWS, 2006) and has the additional operational goal of maintaining water levels for fire suppression (Wurster and others, 2016). By installing WCSs across canals and ditches, Refuge managers are able to re-wet drained peat areas and raise or lower water-table elevations to encourage the growth of particular tree species and ecologies and to mitigate peat loss.

The USACE manages the Feeder Ditch and Dismal Swamp Canal to maintain water at levels that can support boat traffic, while also managing occasional floods. In addition, the USACE works with the Refuge to honor an informal agreement with the USFWS, in place since 1977, to manage the Dismal Swamp Canal so as to not adversely affect the Refuge (USFWS, 2006). The USACE manages the dam between Lake Drummond and Feeder Ditch, and the locks at Deep Creek and South Mills (J. Scussel, USACE, oral commun., 2016), according to the following operational goals:

- Maintain water levels in Lake Drummond at 15.98 ft,
- Maintain water levels in the Dismal Swamp Canal at Deep Creek at 8.41 ft,
- Maintain water levels in the Dismal Swamp Canal at South Mills at 8.33 ft,
- Reduce the number of boat lockings when the Lake Drummond water level is less than 15.28 ft and dropping, and
- Stop boat lockings when Lake Drummond water levels fall to 14.38 ft or below.

Drought and dry summer conditions can make it difficult to maintain water levels in the lake and canal. As a result of drought, the canal has been closed to boat traffic for as much as several months in recent years. On the basis of USACE data, the mean daily water-level elevation at Lake Drummond from January 1, 2005, to June 30, 2015, was 15.92.

Several other agencies manage water in the study area. The Newland Drainage District manages dikes and WCSs to facilitate farming on land southeast of the Swamp near the Pasquotank River. The City of Suffolk and the City of Chesapeake both manage stormwater drainage networks in populated areas in the northern part of the study area.

Inundation

Water inundates the land surface in many areas of the Swamp, particularly during wet periods. Because access is difficult in many areas of the Swamp, remote sensing can be an effective tool for identifying the extent of inundation. Two different remote sensing products were used in the study as indicators of inundation:

1. Dynamic Surface Water Extent (DSWE) (Jones, 2015; http://remotesensing.usgs.gov/ecv/SWE_pp.php) and

2. Interferometric Synthetic Aperture Radar (InSAR) coherence and Synthetic Aperture Radar (SAR) double-bounce backscatter analysis (Kim and others, 2015).

The DSWE product is derived from Landsat satellite imagery and shows areas of standing water. DSWE is well suited for analysis of the Dismal Swamp because it is effective in areas that have tree cover and are occasionally inundated and relatively inaccessible on the ground. The DSWE product comes in raster format with spatial resolution of 98 ft (30 m). Relatively clear skies at the time of satellite overpass are needed to collect data that can be used to successfully generate the DSWE product. DSWE methods were used to estimate the percent of time a given location was inundated using LANDSAT data scenes covering the Great Dismal Swamp (path 14, row 35) during April, May, and June 2005 through 2015.

The other remote sensing product used is derived from InSAR coherence and SAR double-bounce backscattering (Kim and others, 2015). The SAR/InSAR data product indicates whether a land area is inundated at the time of satellite flyover. For this study the inundation estimate was developed from L-band data from the ALOS PALSAR mission (Rosenqvist and others, 2004) and acquired on April 1, 2010, and May 17, 2010. The SAR/InSAR product is a binary raster describing inundation or lack of inundation, with a spatial resolution of about 75 ft (23 m) in the study area.

Both inundation observation values, the spatially averaged DSWE and SAR/InSAR inundation measures, were scaled up to the model grid cell size of 500 ft for use in calibrating the model, as described in the section “Observations and Weighting” subsection “Inundation Observations.” The approximately 45 SAR/InSAR raster values within each model cell were averaged to produce a measure of percent area inundated for the April–May 2010 period, and for the active model area, the values averaged 4.7 percent inundated. The approximately 26 DSWE raster values within each model cell were averaged to produce a measure of percent area inundated, and for the active model area, the values averaged 2.5 percent inundated. Because these DSWE raster values are already averaged temporally, giving for each raster the percent time inundated during April–June 2005 through 2015, the resulting observed DSWE value for each model cell was averaged over space and time. Both the inundation observation values, the spatially averaged DSWE and SAR/InSAR inundation measures, ranged smoothly from 0 to 100 percent, with most values close to 0 (fig. 15).

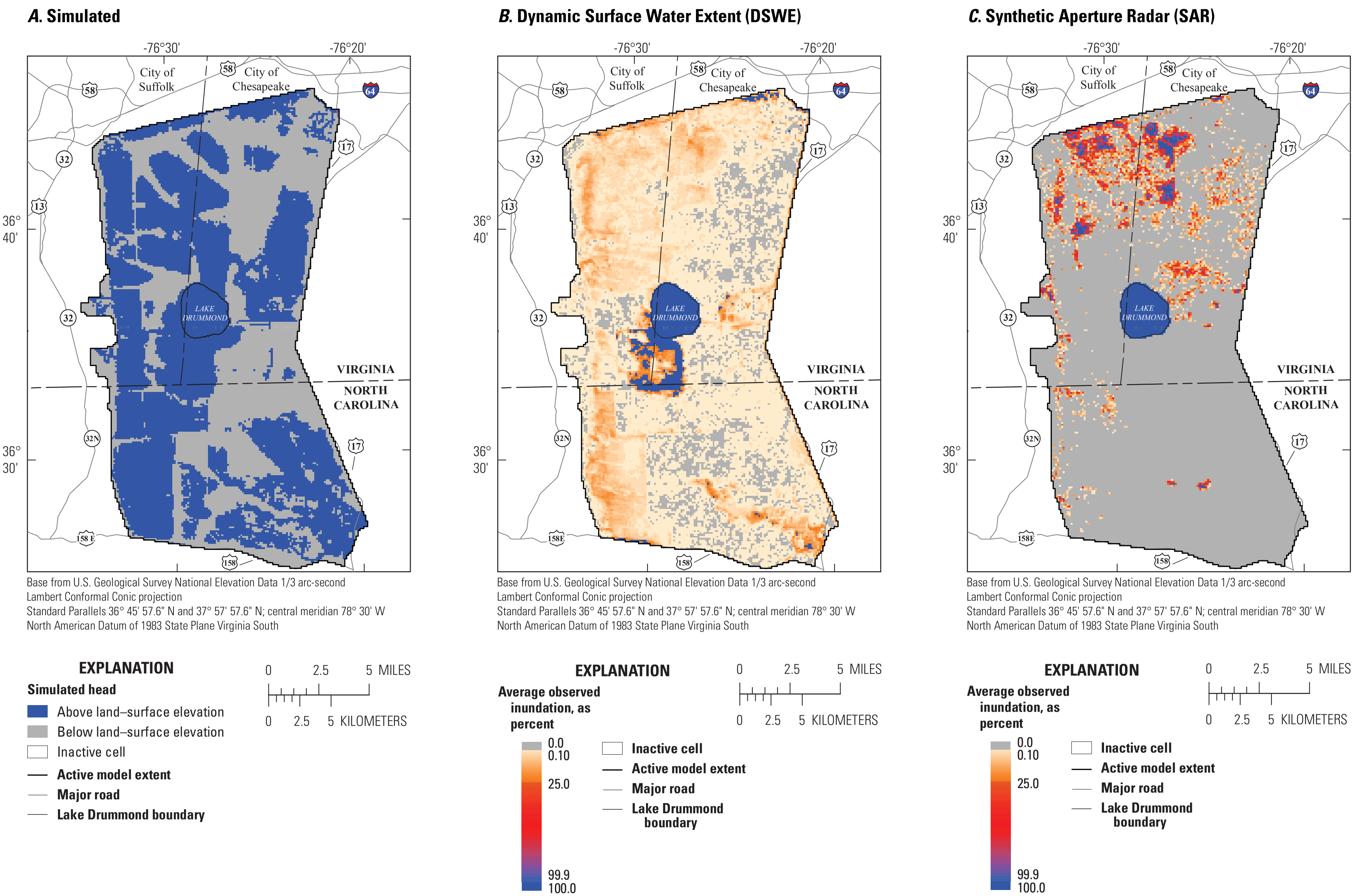


Figure 15. Inundated land areas in the Great Dismal Swamp, Virginia and North Carolina, determined by *A*, simulated water levels above land surface from model Scenario 1, *B*, Dynamic Surface Water Extent (Jones, 2015), and *C*, Synthetic Aperture Radar backscatter analysis (Kim and others, 2015).

Geospatial Analysis of Land-Surface Elevations and Peat Thickness

Because land-surface topography and peat stratigraphy are important to swamp hydrology, geospatial analysis was used to determine land-surface elevations and peat thickness as accurately as possible. Land-surface elevations were derived from multiple lidar datasets. Peat thickness was determined for the entire active model area by spatial interpolation of point values and subsequent processing with spatial filters. These peat thickness values were then used to assign layering in the groundwater model ("Model Development" section).

Land-Surface Elevation Observations by Lidar

Three lidar datasets describing land-surface elevations in the study area and one bathymetric dataset describing elevations of the bottom of Lake Drummond were compiled into a 6.6-ft (2-m) raster grid, digital-elevation model (DEM). The DEM was then used as the basis for vertical layering in the model and for describing topography of the study area. In 2010, lidar data were collected for the Great Dismal Swamp NWR and NCDSSP. The 2010 data were combined in a mosaic with a 2006 lidar dataset covering the City of Chesapeake, a 2012 lidar dataset covering the area burned during the Lateral West Fire, and a bathymetric DEM of the bottom of Lake Drummond. The Lake Drummond DEM was developed by digitizing lake-bottom-elevation data from a bathymetric map (USACE, 1970) and interpolating the elevations across a 6.6-ft (2-m) grid covering the lake (fig. 2). The mosaic DEM was then tested for error.

The vertical accuracy of the mosaicked DEM was tested by comparing DEM elevation values to ground survey point elevations collected by Courtney and Associates in 2013, by Woolpert Inc. in 2010 and 2012, and by USFWS staff in 2010 (Wurster, 2014). Survey points that were located on sloped road embankments were removed from the dataset following vertical checkpoint standards (American Society for Photogrammetry and Remote Sensing, 2015). Root mean square error (RMSE) values for the difference between surveyed elevations and lidar values were then calculated (table 4). The RMSE for the elevation dataset was 0.55 ft (16.7 cm) with a 95-percent confidence interval of 1.1 ft (37.7 cm), which meets the standard for the National Elevation Dataset at Quality Level 3 (Heidemann, 2014)

The mapped lidar elevation surface (fig. 2) reveals both natural and man-made topographic features. A low-relief dendritic drainage pattern shows a natural pattern of flow from Isle of Wight Plain eastward into the Swamp, from the interior of the Swamp towards Lake Drummond, towards the Pasquotank River in the southeast, towards Shingle Creek and Deep Creek in the north, and towards the Dismal Swamp Canal on the eastern boundary.

Table 4. Ground survey control elevation datasets and error analysis of lidar-derived elevations and interpolated top of sand elevation values.

[USFWS, U.S. Fish and Wildlife Service; IDW, inverse distance weighted; RMSE, root mean square error; ft, foot]

Dataset	Number of points	Mean error (ft)	Mean percent error	RMSE (ft)
Lidar				
Woolpert	25	0.01	1.34	0.10
USFWS	48	0.00	2.85	0.27
Courtney	20	0.27	7.24	0.51
All	93	0.06	3.39	0.31
Top of sand[1]				
Topo to Raster	294	−0.03	0.03	0.43
IDW	294	0.00	0.46	0.56
Kriging	292	0.28	4.27	1.59

[1]Data were checked against measured points, where the elevation was surveyed or estimated from lidar.

Peat Thickness

Because peat is important to Swamp hydrology, total peat thickness was estimated for the entire study area. Observations of peat depth and thickness were compiled from a variety of data sources from January 1973 through October 2015. These data provide good coverage in the northern two-thirds of the study area but generally sparse coverage in the southern one-third of the study area (fig. 16). Thickness of the upper peat layer, a portion of total peat thickness, was recorded in 60 locations by the USFWS and USGS. The mean upper peat thickness from these 60 values is 1.47 ft. Additional data were compiled from previous studies (Oaks and Coch, 1973; USACE, 1970), which had greater uncertainty associated with the horizontal locations.

Estimated peat thickness values were added to improve interpolation in areas where observed values were not available. Estimated point values, based on field reconnaissance, were added along the western side of the study area (Suffolk Scarp) and in the south of the study area near the Pasquotank River. Estimated point values were also used to limit the extent of peat in areas where peat is known to be absent, in which case they were assigned a thickness of 0. In total, 2,494 estimated point values were used in the interpolation (fig. 16 and table 5).

Because peat thickness changes over time, sometimes rapidly as seen for the 2008 and 2011 fires (Reddy and others, 2015), the resulting interpolated peat thicknesses represent general conditions between 1973 and 2015 rather than conditions during any particular year. Some observations of peat thickness gave minimum peat thickness rather than absolute thickness because peat was thicker than the probe length or

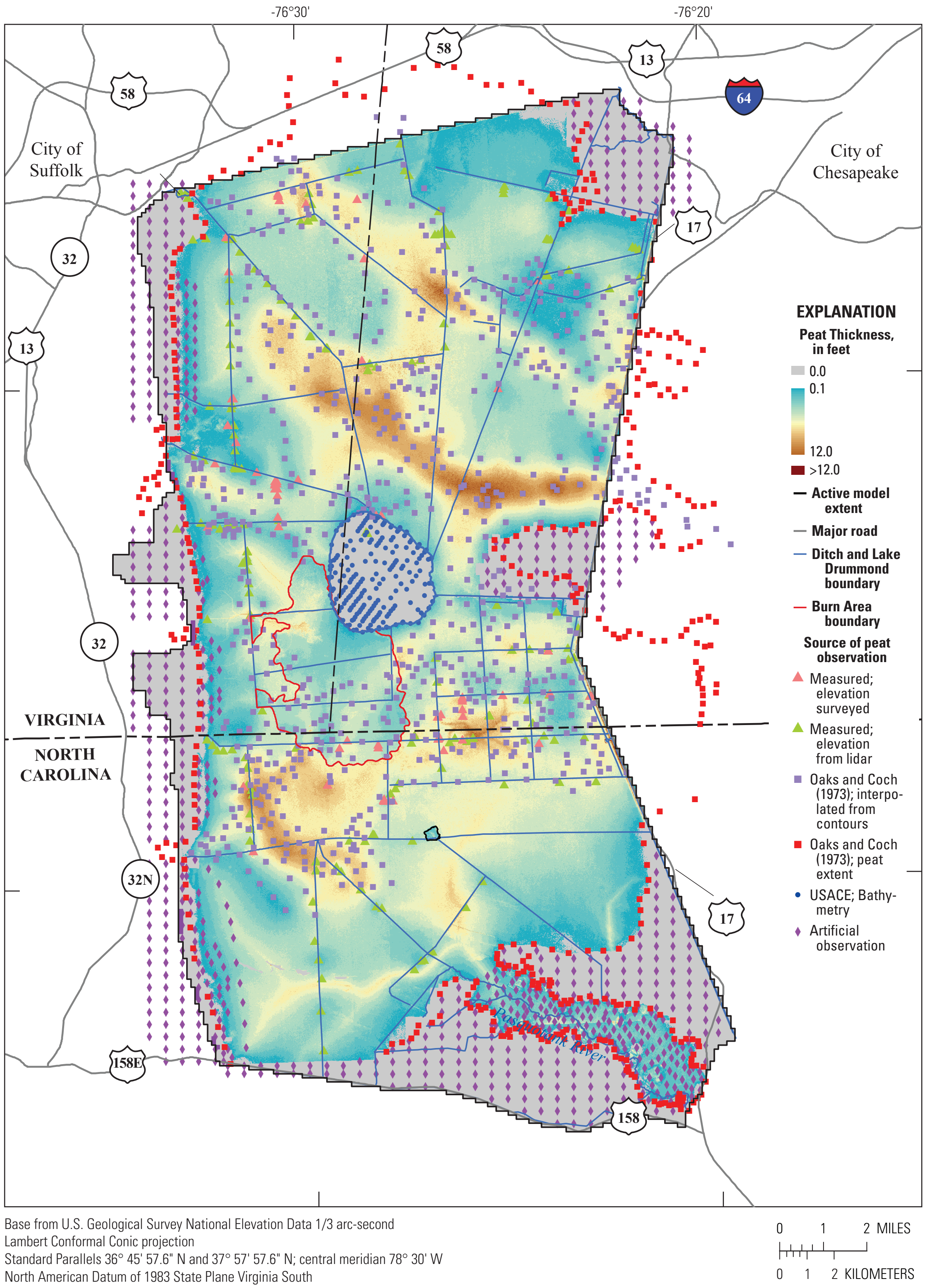


Figure 16. Interpolated peat thickness and locations of elevation observation points, Great Dismal Swamp, Virginia and North Carolina. (USACE, U.S. Army Corps of Engineers)

Table 5. Observation frequency, by decade, of elevation and peat extent observations used for interpolating peat thickness over the entire study area.

[USACE, U.S. Army Corps of Engineers]

Source of peat observation	Observation frequency per decade					Total per source
	1970s	1980s	1990s	2000s	2010s	
Measured; elevation surveyed	47	0	0	8	10	65
Measured; elevation from lidar	15	0	0	0	222	237
Oaks and Coch (1973); interpolated from contours	742	0	0	0	0	742
Oaks and Coch (1973); peat extent	419	0	0	0	0	419
USACE; Bathymetry	204	0	0	0	0	204
Artificial observation	0	0	0	0	827	827
Total per decade	1,427	0	0	8	1,059	2,494

borehole depth. In such cases, the observation was not used as a basis for interpolation but was instead used as an error check.

Point values of peat thickness were interpolated using the Topo to Raster tool in ESRI ArcMap, which applies spline methods adapted for terrain modeling (Hutchinson and others, 2011). Different interpolation methods were tested, but Topo to Raster yielded the smallest percent error at locations that had an associated observed value. The resulting 6.6-ft (2-m) resolution raster was clipped to a known peat extent (Oaks and Coch, 1973), excluding areas where there is no peat (such as Lake Drummond and developed areas). The resulting map (fig. 16) shows some interpolation artifacts but honors the observed point values well and was used successfully as input to the hydrologic simulation model.

Peat thickness was used to calculate top-of-sand elevations by subtracting peat thickness from lidar land-surface-elevation values. In parts of the study area where peat was absent, lidar land-surface elevations were used to generate a continuous top of sand elevation raster for the model area.

Conceptual Hydrologic Model

A conceptual model of swamp hydrology can be developed from previous studies and observations. Although water budgets for neither groundwater nor surface water have been previously quantified in much detail, major water exchanges in the Swamp are generally known. Groundwater and surface-water hydrology are closely linked throughout the study area, so much so that understanding the water budget for one component requires a full understanding of the water budget for other component. Groundwater discharges to ditches, streams, and the land surface at the foot of the western scarp. During wet periods, the water table rises and inundates land surface in many areas. Although most surface-water bodies are expected to receive groundwater discharge, surface water likely recharges the underlying aquifer in areas where surface water is ponded behind roads or WCSs. On the basis of expected high porosity and permeability of the upper peat layer, there likely is low resistance to lateral groundwater flow in the upper peat.

The primary water input to the Swamp is precipitation, which upon entering the Swamp gets divided between surface water, evapotranspiration, and groundwater infiltration. A second major input of water to the Swamp is flow from streams and drainages to the west and south. Although these surface inflows are generally unmonitored, the area of contributing watershed is about 39 percent of the area of the Swamp. The third known water input to the Swamp is groundwater discharge that originates along the scarp and areas west of the Swamp, then flows eastward to discharge at the bottom of the scarp slope near the western boundary.

A major outflow (or loss) of water from the Swamp is evapotranspiration, discussed in more detail in the "Recharge and Evapotranspiration" section. The other major outflow of water from the Swamp is surface-water discharge from ditches and the Dismal Swamp Canal to tidal water bodies. Surface water flows from the study area to the Pasquotank River outflow in the southeast, to Shingle Creek in the northwest, and to Deep Creek in the northeast, as well as from both ends of the Dismal Swamp Canal at South Mills and Deep Creek (fig. 1). Although groundwater almost certainly discharges to the tidal water bodies bordering the Swamp, such as Deep Creek or Shingle Creek to the north or the Pasquotank River to the south, these presumed groundwater discharges have not been previously observed or modeled.

The active groundwater system of the Swamp is probably limited to the shallow subsurface. Although the shallow groundwater system of the Swamp includes the upper part of the Yorktown-Eastover aquifer, little groundwater exchange with deeper parts of the formation is expected because, as discussed in the "Hydrogeology" section, the Saint Marys confining unit that underlies the Yorktown-Eastover aquifer likely isolates the Swamp hydrologic system from deeper aquifers of the Coastal Plain.

Numerical Model Development

Numerical simulation models were developed to simulate water levels and flows in the study area. The first model is a preliminary 2-D, cross-sectional, steady-state model of Block C1 (fig. 17) that simulates groundwater levels and flows between Corapeake Ditch and Sycamore Ditch. The second model is a 3-D steady-state model of the entire study area that simulates groundwater and surface water. The 2-D model was used to conceptualize vertical layering, assess likely flow patterns, develop experience applying the modeling software to the study area, and develop initial hydraulic parameter values for use in the 3-D model. Because the 3-D model simulates both groundwater and surface-water levels and flows within the study area, it can be used to answer questions about management of WCSs and their effect on water levels. This report section first describes the 2-D model, then describes the 3-D model. Where the term "model" is used by itself, it refers to the 3-D model (fig. 17). The input, output, and execution files for the numerical model, as well as documentation on use of the model, are publicly available (Eggleston and others, 2018).

The 2-D and 3-D models use the hydrologic modeling software package MODFLOW-NWT (Niswonger and others, 2011), which is based on simulation of groundwater but has many add-on capabilities including simulation of surface water. MODFLOW-NWT is a finite-difference groundwater model that uses a Newton-Raphson formulation to improve the solution of unconfined groundwater flow problems. From the multiple MODFLOW packages capable of simulating surface water, the Surface-Water Routing (SWR1) Process (Hughes and others, 2012) was selected for its simulation capabilities, previous success simulating flooded environments (Hughes and White, 2016), and available technical support. The SWR1 Process is well suited to simulate Swamp hydrology because of its capability to simulate surface-water features as boundary conditions for the groundwater system and to simulate complex surface-water features, including dynamic surface flows, flow in both directions within a reach, and detailed control structure and weir management options.

The 2-D and 3-D models were used only for steady-state simulations to simplify model development and reduce model run times. In steady-state simulations, hydrologic conditions remain constant over time and changes in storage are not accounted for. A steady-state model does not have the capability to simulate transient events such as individual storms or changing hydrologic conditions; a transient model is needed for that. Construction of a transient SWR1 model was beyond the scope of this project. The steady-state model still has significant value because it can simulate average water balances, flow directions, and rates. The steady-state models were developed and calibrated so that in future studies they can be readily modified to simulate transient conditions.

Three climatic scenarios were developed to represent three different steady-state, hydrologic conditions: (1) average spring conditions, which is the baseline scenario; (2) dry spring conditions; and (3) wet spring conditions. Spring (April, May, and June) conditions were simulated because these months are critical in the Great Dismal Swamp for water-management decisions. Low water levels resulting from particularly dry periods result in increased fire risk, whereas high levels following particularly wet periods negatively affect vegetation growth rates and can lead to forest stress and mortality. April–June is the most active period of WCS management as Refuge staff adjust weir levels to strike a balance between preventing wildfires and avoiding tree stress.

Groundwater flow paths were simulated by using MODPATH version 6 software (Pollock, 2012) to illustrate the groundwater flow field and determine watershed boundaries within the study area. Using MODPATH, a tracking particle was placed in every other active model cell, and the path of each particle from its origin to its model exit point was simulated. Simulated groundwater particles can leave the groundwater system by evapotranspiration, by discharge to head dependent boundaries (SWR1 reaches) representing surface water, or by discharge to specified-head boundaries (general head boundary [GHB] cells) representing tidal boundary waters.

Block C1 Preliminary Model

As a first step towards building a model of the entire study area, a 2-D preliminary flow model of Block C1 (fig. 17) was constructed. The Block C1 model aided development of the full-scale 3-D model by improving hydrogeologic understanding, testing the use of the SWR1 Process and assignment of boundary conditions, and improving assignment of hydraulic parameter values in the 3-D model. The Block C1 area was chosen for preliminary modeling because it has relatively simple hydrologic boundaries and a relatively high density of groundwater-level observations.

Cross-Sectional Block C1 Model

A 2-D cross-sectional model was developed to quantify local-scale groundwater discharge patterns along a transect from Corapeake Ditch (south) to Sycamore Ditch (north) (fig. 17). The axis of the model is aligned north-south, parallel to Myrtle and Western Boundary Ditches and perpendicular to Corapeake and Sycamore Ditches. Vertically the model is divided into three layers: the lowest layer is sand of uniform thickness of 21 ft, overlain by a 4-ft thick, low-permeability layer, overlain by a 3-ft thick high-permeability peat layer that extends to the land surface/water table (fig. 18*A*). Horizontal discretization varies from 20 to 200 ft.

In the Block C1 model, Corapeake and Sycamore Ditches are represented by GHB conditions, with stages set to average observed levels (14.74 ft for Sycamore Ditch and 16.88 ft for Corapeake Ditch). Average water levels are the mean of periodic observations collected approximately monthly from June 2009 to March 2011. During this period, water levels in Sycamore Ditch were about 2 ft lower than those in Corapeake

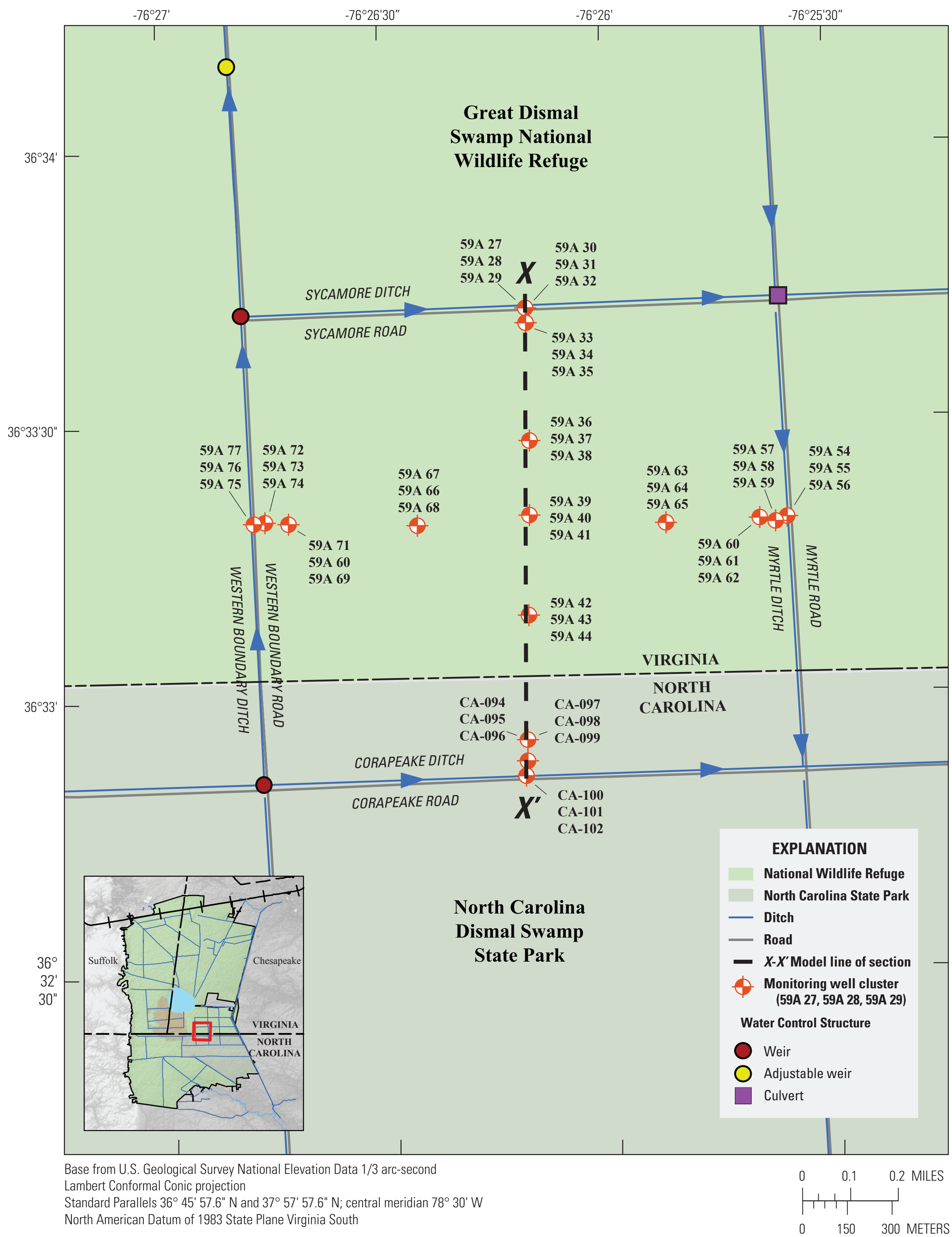


Figure 17. Block C1 with line of section *X–X′*, Great Dismal Swamp, Virginia and North Carolina. (Cross sections shown in figures 18*A–C*)

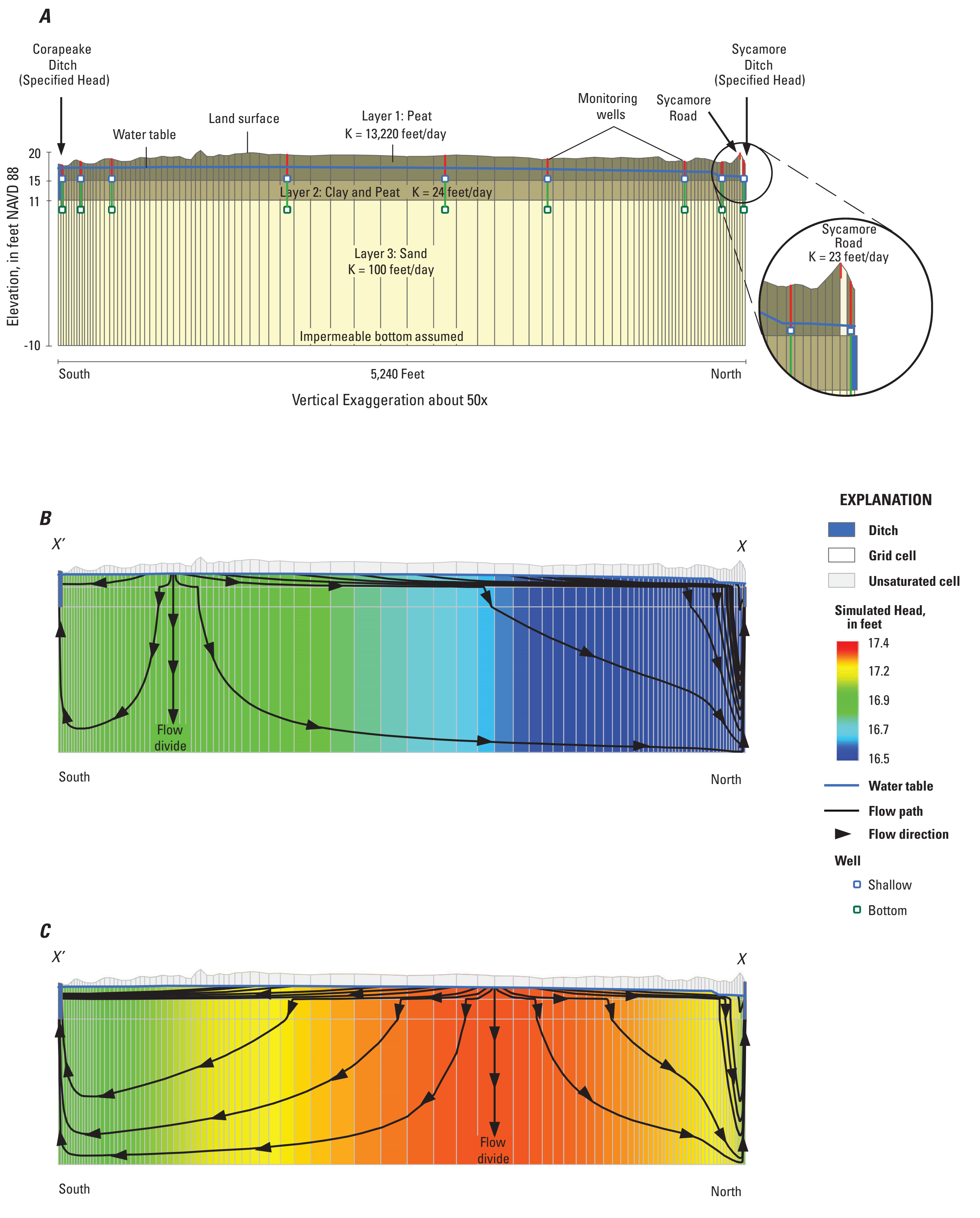


Figure 18. Cross-sectional views of the Block C1 model showing *A*, grid spacing and boundary conditions *B*, simulated heads and flow paths under baseline average conditions, and *C*, simulated heads and flow paths when water levels in Sycamore Ditch are raised by 2 feet. (Line of section *X–X′* shown in fig. 17. K, hydraulic conductivity)

Ditch because surface-water flow between the two ditches was limited by WCSs. The bottom of the model was assigned a no-flow boundary, and the water-table surface was calculated during model simulations. Recharge of 0.89 foot per year (ft/yr) was assigned on the basis of long-term average annual precipitation of 4.22 ft/yr recorded at the Lake Drummond meteorological station for 1931 through 2015, minus average annual evapotranspiration from MODIS-MOD16 dataset (Mu and others, 2011), averaging 3.33 ft/yr over the study area for 2003 through 2013.

Hydraulic conductivity is the only assigned hydraulic property in the Block C1 model. Four hydraulic conductivity values were assigned, 1 for each of the 3 layers and 1 for cells representing Sycamore Road (table 6). Horizontal to vertical anisotropy was initially set at 10:1 for all units but was allowed to vary during sensitivity analysis.

Sycamore Road, lying between Block C1 and Sycamore Ditch, impedes groundwater flow as a result of compaction of the upper high-permeability peat layer. In the model, Sycamore Road is represented by lower permeability assigned to the upper two layers, which represent peat. Corapeake Road is on the far side of Corapeake Ditch from Block C1 and is not represented in the model.

The Block C1 model was manually calibrated to groundwater levels at monitoring wells located near the model transect (fig. 17). Target groundwater levels were assigned equal to average annual present conditions. Hydraulic conductivity parameter values for Layers 1, 2, and 3 and for the road bed were adjusted to improve the fit between simulated and observed groundwater-level values. The mean absolute error between 18 observed and simulated head values is 0.25 ft or about 10 percent of the head difference between the two ditches (2.14 ft).

Table 6. Calibrated parameters of the Block C1 cross-sectional model.

[Horizontal to vertical anisotropy fixed at 10:1 for all units. Kh, horizontal hydraulic conductivity; ft/d, foot per day; in/yr, inch per year]

Parameter	Value	Calibration method
Peat Kh	13,220 ft/d	Least squares minimization
Sand Kh	100 ft/d	Least squares minimization
Clay Kh	24 ft/d	Least squares minimization
Road Kh	23 ft/d	Least squares minimization
Precipitation/recharge rate	44.24 in/yr	Assigned

Block C1 Model Sensitivity Analysis

A sensitivity analysis was performed to evaluate the effects of the different aquifer parameters and boundary conditions on the simulated groundwater levels. For each sensitivity run, a single parameter or boundary condition was manually adjusted from the values used in the calibrated baseline model. Parameters were then qualitatively assigned either a small, moderate, or large effect on the basis of magnitude of changes in the simulated heads. In addition, groups of parameters were identified that are highly correlated and potentially result in an equally matched comparison of simulated and observed targets (table 7). Highly correlated parameter pairs with horizontal hydraulic conductivity (Kh) are peat Kh/recharge, peat Kh/road Kh, and road Kh/recharge.

Table 7. Results of parameter sensitivity analysis for the Block C1, Great Dismal Swamp, Virginia and North Carolina, cross-sectional model.

[Kh, horizontal hydraulic conductivity]

Parameter	Composite scaled sensitivity	Ratio to maximum	Qualitative effect
Peat Kh	1.35E−01	3.91E−01	Moderate
Road Kh	2.77E−02	8.00E−02	Small
Clay Kh	1.99E−02	5.75E−02	Small
Sand Kh	1.03E−01	2.96E−01	Moderate
Precipitation/recharge rate	3.46E−01	1.00E+00	Large

Block C1 Model Simulation Results

Results from the Block C1 baseline model show that 84 percent of groundwater outflow discharges to Sycamore Ditch; the remaining 16 percent discharges to Corapeake Ditch. Most of the recharge to the water table traveled laterally through the upper peat nearly to the road before turning downward across the clay and then into the sand to flow under the road and discharge to Sycamore Ditch. Correspondingly, the groundwater flow divide is located 84 percent of the cross-sectional distance towards Corapeake Ditch (fig. 18*B*). Most of the flow travels to Sycamore Ditch even though the low-permeability road and compacted peat beneath the road act as a barrier for flow towards Sycamore Ditch. This result demonstrates the importance of ditch water levels in controlling groundwater flow.

To further assess the effect of ditch stage control on groundwater flow patterns, an additional model scenario was simulated in which the water-level in Sycamore Ditch was raised by 2 ft, from 14.74 to 16.74 ft, whereas the 16.88-ft water level in Corapeake Ditch was unchanged. The higher assigned ditch stage caused the water table to rise over the whole cross section and the groundwater divide to shift to the north closer to Sycamore Ditch. Despite the higher stage in Corapeake Ditch, 63 percent of groundwater flowed to Corapeake Ditch (fig. 18*C*). This is caused by the low permeability of the road bed and underlying compacted peat between Sycamore Ditch and the interior of the block, increasing resistance to flow. These results show that ditch levels and the presence of intervening roads have a strong effect on groundwater levels and groundwater flow directions, and indicate that Refuge staff can affect groundwater levels by managing water levels in ditches.

Water budgets for the baseline and raised ditch-stage scenarios were scaled to percent of total flow (table 8) to provide general insight into the Swamp flow system. The water budget results also show that the water level in Sycamore Ditch strongly affects groundwater flow. Raising the stage in Sycamore Ditch caused the flow divide to shift north (fig. 18*B* and *C*) and the percent of total inflow (recharge) discharging to Sycamore Ditch to decrease from 84 to 37 percent. Raising the stage in Sycamore also caused the percent of recharge penetrating to the bottom sand layer to decrease from 69 to 30 percent of total recharge. This can be attributed to the combined effects of less water flowing to Sycamore Ditch because water was forced to flow beneath Sycamore Road to discharge to Sycamore Ditch, as seen in the flow paths (fig 18*B* and *C*).

Table 8. Simulated water budgets from the Block C1 model for the steady-state baseline scenario and for the Sycamore Ditch raised water level scenario, Great Dismal Swamp, Virginia and North Carolina.

[Values shown are flow as a percent of recharge]

	Model boundary conditions	
	Baseline case	**Raised stage**
Outflow destination	Percent of total flow	Percent of total flow
Corapeake Ditch	16	63
Sycamore Ditch	84	37
Percent flow through aquifer materials	Percent of total flow	Percent of total flow
Peat	100	100
Clay	80	75
Road	23	14
Sand	69	30

Spatial Discretization of the Three-Dimensional Model

For the 3-D model (model), the study area was divided into a rectilinear grid of 500-ft by 500-ft square cells (fig. 19) with axes oriented east-west and north-south. Horizontal spacing of 500 ft was chosen as a compromise between a cell size small enough to simulate hydrologic conditions at a useful scale for Refuge managers and a cell size large enough to allow reasonable model run times. The model grid has 154 columns and 256 rows for a total of 39,424 cells per layer, of which 26,391 are active in Layer 1. Groundwater conditions and hydrogeologic properties are uniform within each model cell, so the model does not simulate differences in groundwater levels or flows over horizontal distances of less than 500 ft.

Land surface, as represented by the lidar elevation dataset described previously, is the reference elevation for vertical layering in the model. Because lidar elevations are in a 6.6-ft raster grid, and the model has a 500-ft grid, land-surface elevations were scaled up for the model, with about 5,800 lidar raster cells in each model grid cell. The land-surface elevation for each model cell was assigned a value equal to the mean minus one standard deviation of the lidar elevation values falling within that model cell. This approach sets land-surface elevations in the model to relatively low values so that hummocks and local elevation high points have less effect on land-surface elevation in the model, and therefore less effect on simulated ET from the water table. In contrast, lower lidar elevations in depressions and shallow channels would have a greater effect on model land-surface elevations and simulated ET from the water table. Under the assumption that lidar elevations are normally distributed, this assigns the local 16 percent land-surface elevation value to each model cell.

Vertically the model is divided into four layers (fig. 20 and table 9) that allow hydrologic conditions and hydraulic properties to vary with depth. Layer 1 holds water that inundates the land surface. Layer 2 represents the upper, more permeable and porous peat, whereas Layer 3 represents the underlying less permeable peat. Layer 4 represents the sand of the Yorktown-Eastover aquifer underlying the peat.

Layer 1 contains water above the land surface under inundated conditions. The choice was made to use a high-K Layer 1 to allow water on the land surface to move laterally with little resistance, rather than routing the water flow through SWR1 reaches, to improve model stability and reduce model run times. Hydraulic conductivity of Layer 1 is set to a high value to establish rapid lateral flow, as described in the “Calibration Approach” section. The top of Layer 1 for each cell is assigned an elevation equal to the land-surface elevation plus 20 ft; the bottom elevation represents the land surface and is based on the lidar DEM as described above.

Layer 2 has variable thickness and, because it represents the coarse upper peat, is assigned a relatively high hydraulic conductivity value. The elevation of the top of Layer 2 for each cell is the land-surface elevation. The thickness of Layer 2 is assigned cell by cell, with values between 1.0 and

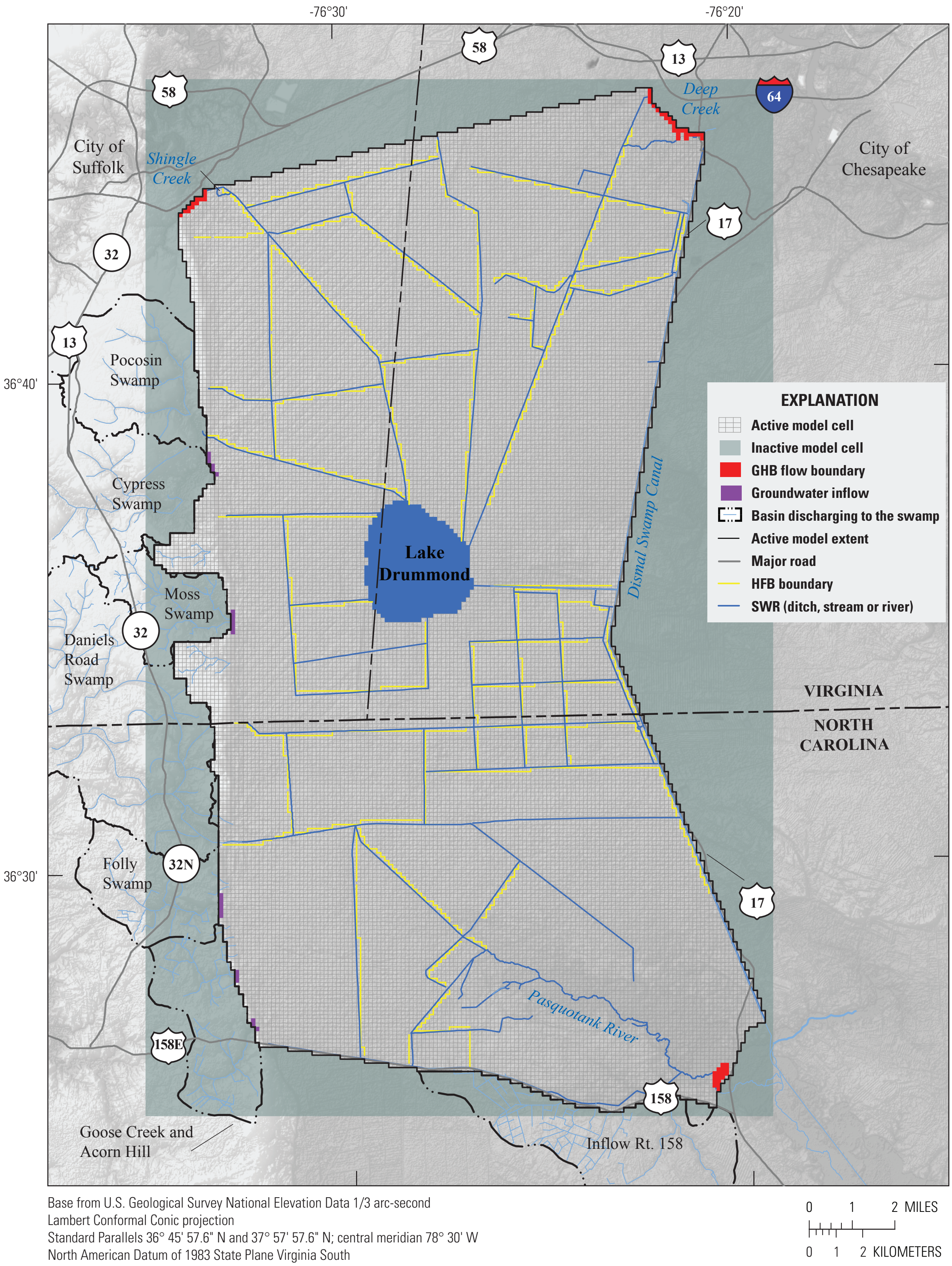


Figure 19. Hydrologic model grid and boundary conditions for the Great Dismal Swamp, Virginia and North Carolina. (GHB, general head boundary; SWR, surface-water feature simulated with the MODFLOW-SWR1 Process; HFB, Hydraulic Flow Boundary)

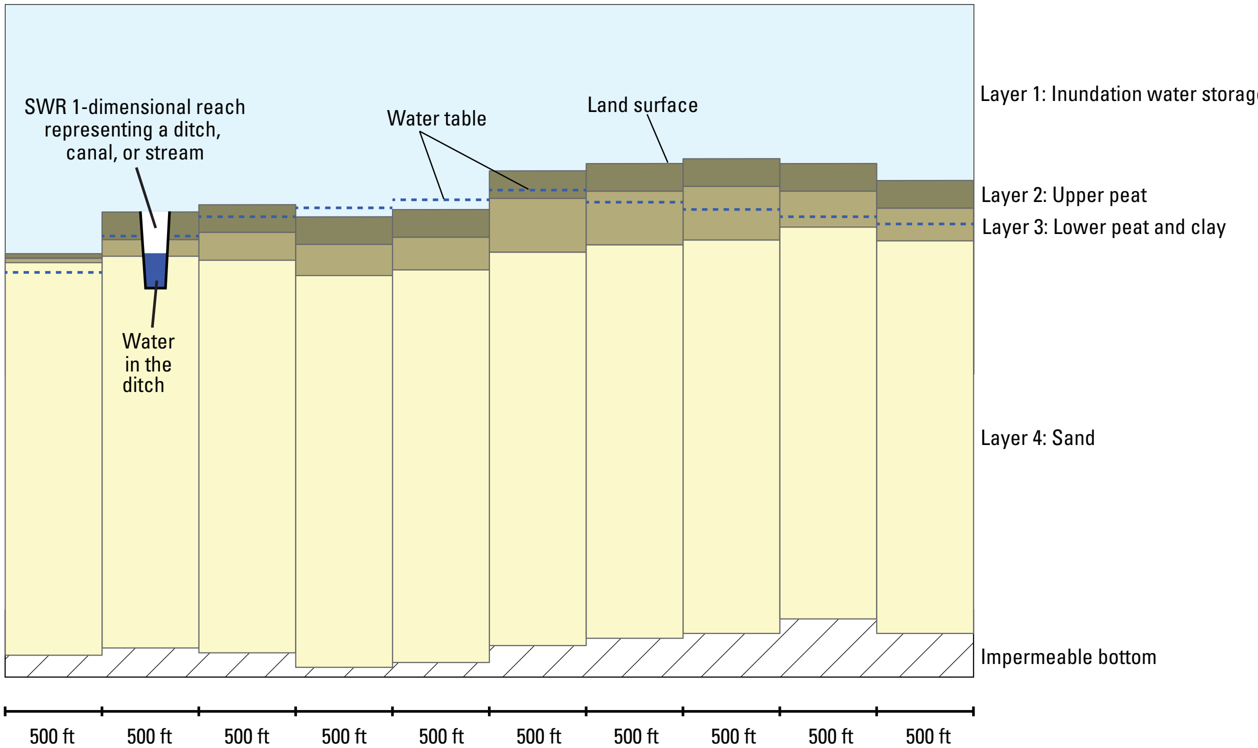


Figure 20. Representative cross-sectional view of a ditch and water-table elevations in the 3-dimensional hydrologic simulation model of the Great Dismal Swamp, Virginia and North Carolina. (ft, feet; SWR, surface-water reach simulated with the MODFLOW-SWR1 Process)

Table 9. Thickness and hydraulic properties of Layers 2 and 3 of the three-dimensional hydrologic simulation model of the Great Dismal Swamp, Virginia and North Carolina.

[ft, feet; <, less than; >, greater than]

Model layer		Total peat thickness in swamp (ft)					
		Thickness of layers in model (ft)					
Number	**Description**	**0–0.5**	**>0.5–1.0**	**>1.0–1.5**	**>1.5–2.0**	**>2.0–2.5**	**>2.5**
2	Upper peat	1	1	Total peat thickness	1.5	1.5	1.5
3	Lower peat	1	1	1	1	1	Layer 2 Bottom elevation - Total Peat thickness + 1.5

Property assignment
Upper peat
Lower peat
Sand

Thickness rules
Minimum thickness for all layers is 1 ft
Maximum thickness for Layer 2 is 1.5 ft
Where peat is < 0.5 ft, properties of the underlying sand are assigned

1.5 ft (table 9) that are based on land-surface elevations and peat thicknesses described in the “Peat Thickness” section (fig. 16). Peat thickness for each model cell was assigned as the mean of all peat thickness elevations from the lidar DEM that fall within the model cell. In parts of the study area where total peat thickness is less than 1.0 ft, Layer 2 is assigned a minimum thickness of 1 ft to prevent numerical instabilities in the model (table 9). In areas where total peat thickness is between 1.0 and 1.5 ft, Layer 2 is assigned a thickness equal to the total peat thickness. In areas where total peat thickness is greater than 1.5 feet, Layer 2 is assigned a thickness of 1.5 feet. The bottom elevation of Layer 2 is determined by subtracting the assigned Layer 2 thickness from the land-surface elevation.

Layer 3 has variable thickness and represents the lower peat, which has relatively lower porosity and permeability than the upper peat (table 9). The top elevation of Layer 3 is equal to the bottom elevation of Layer 2. In areas of the Swamp where total peat thickness is less than 2.5 feet, Layer 3 is assigned a minimum thickness of 1 ft. Where total peat thickness is greater than 2.5 feet, Layer 2 is assigned a thickness equal to total peat thickness minus 1.5 ft. The bottom elevation of Layer 3 is determined by subtracting the assigned Layer 3 thickness from the Layer 2 bottom elevation.

Layer 4 has variable thickness and represents the relatively permeable sand layer underlying the peat. The top elevation of Layer 4 is equal to the bottom elevation of Layer 3. The bottom elevation of Layer 4 is constrained to have a maximum elevation value of 0 ft to prevent problems with layer discontinuity. Layer 4 is assigned a thickness of 21 ft everywhere, except along the western side of the model where the combination of higher surface elevations and the Layer 4 maximum bottom elevation of 0 ft causes the thickness of some Layer 4 cells to be greater than 21 ft. The bottom elevation for each Layer 4 cell is determined by subtracting the thickness from the elevation of the top of Layer 4.

Time Periods Represented by Simulations

The model is steady-state, so simulated conditions do not change over time. Three periods were selected to represent baseline, wet, and dry climatic conditions. The baseline simulation represents average climatic and hydrologic conditions during the spring growing months of April, May, and June for 2005 through 2015. Observations collected during this period are used to determine average conditions, which were used to assign boundary conditions (table 10) and calibrate the baseline model. The period representing dry conditions is spring (April, May, and June) 2011, which had a total rainfall of 7.06 in. The representative wet period is spring 2015, which had a total rainfall of 17.81 in. Because the model is steady-state rather than transient, the simulations do not represent hydrologic conditions in the spring of 2011 and 2015, but rather are a generic representation of dry and wet conditions.

Table 10. Climatic conditions and representative time periods for model scenarios for the three-dimensional hydrologic simulation model of the Great Dismal Swamp, Virginia and North Carolina.

Condition	Range	Representative period	
		Start	End
Dry	Average conditions Spring 2011	April 1, 2011	June 30, 2011
Wet	Average conditions Spring 2015	April 1, 2015	June 30, 2015
Baseline	11-year average, April, May, and June only	April 1, 2005	June 30, 2015

Boundary Conditions

Head or flow conditions are assigned to all external model boundaries (top, bottom, and sides). Assignments of boundary conditions in the baseline model include precipitation/recharge rates, evapotranspiration rates, lateral inflows, and specified head boundaries, which are based on average observed values during the spring of 2005 through 2015 (tables 10 and 11). For simulations of wet and dry climatic conditions, different boundary conditions are assigned to describe the representative periods (tables 2 and 11). The bottom of the model is assigned as a no-flow boundary.

Table 11. Assigned boundary conditions for representative climatic conditions in the three-dimensional model for Great Dismal Swamp, Virginia and North Carolina.

[ET, evapotranspiration]

Assigned boundary condition	Unit	Climatic conditions		
		Average	Wet	Dry
Surface inflows, total	inches/year	2.42	4.97	0
Groundwater inflow, total	inches/year	1.48	4.89	1.48
Recharge	inches/year	51.61	71.44	28.32
Maximum ET rate	inches/year	44.24	47.13	45.08

Recharge is assigned equal to observed precipitation rates under the three climatic scenarios simulated (table 11). Recharge is not readjusted during calibration of the baseline model. Steady-state recharge rates for the three scenarios are assigned equal to observed precipitation rates during the spring months of 2011, 2015, and 2005–15: 7.06, 17.81, and 12.86 in. (0.00647, 0.01631, and 0.01178 ft/d) for the dry, wet, and average conditions, respectively (table 11). Unlike other groundwater modeling studies in which ET is subtracted from precipitation prior to assignment of recharge (for example, Masterson and others, 2016b), 100 percent of precipitation is assigned as recharge to the water table. Water is then removed from the water table by evapotranspiration as described in the "Evapotranspiration" and "Surface Water" sections. Simulated ET rates are determined by the model during simulation on the basis of assigned calibrated parameter values. Recharge to Lake Drummond is assigned as an inflow in the SWR1 Process.

Lateral Inflows

Lateral inflows to the model for each scenario simulated (table 2) are assigned along the western and southern boundaries to represent groundwater and surface-water flows into the Swamp (fig. 1). Inflows from Daniels Road Swamp and Pocosin Swamp discharge primarily to Cross Canal Ditch and Washington Ditch (fig. 19), respectively, so those two inflows are assigned as specified flow to the most upstream SWR1 reaches representing those ditches. The other five inflows from Cypress Swamp, Folly Swamp, Goose Creek/Acorn Hill, South of Route 158, and Moss Swamp disperse diffusely into the Swamp, so these inflows are assigned as groundwater inflows to Layer 4 in the model (fig. 19) using the MODFLOW well package (WEL) (Harbaugh and others, 2000). These inflow rates (table 2) were estimated as described above in the "Surface-Water Inflows and Outflows" section.

Specified Head Boundaries

Specified heads are assigned to model boundaries formed by Deep Creek, Shingle Creek, and the Pasquotank River (fig. 19). Model cells are assigned a specified head of 2 ft along Deep Creek and Shingle Creek and a specified head of 1 ft along the Pasquotank River.

Evapotranspiration

ET occurs over the entire active model area and is simulated with the MODFLOW EVT package (Harbaugh and others, 2000). Simulated evapotranspiration for a given cell depends on three parameters and on the simulated water-table elevation. The three parameters specified to control ET rates are (1) ET surface elevation, (2) maximum ET rate, and (3) extinction depth. All three parameters are assigned initial values that are based on likely assumptions, then adjusted during model calibration. The ET surface elevation for each cell is assigned an initial value equal to the land-surface elevation minus 4.76 ft. The maximum ET rate is assigned an initial value of 44.2 in/yr, as calculated with the Thornthwaite equation and described previously in the "Precipitation and Evapotranspiration" section. The extinction depth is the depth below the ET surface where the ET rate is zero and is assigned an initial value of 3 ft (McDonald and Harbaugh, 1988). The simulated water-table elevation is calculated by the model.

Given the assigned parameter values, ET is calculated by the model according to equations 4a–c. Paraphrasing from McDonald and Harbaugh (1988), the groundwater ET from a given model cell equals the maximum ET rate (*ETmax*) when the water-table elevation (*Hwt*) is at or above the ET surface (*Hes*). When the depth of the water table below *Hes* (*D*) is greater than the extinction depth (*Dex*), then *ET* equals zero. When *Hwt* is below *Hes* but not down as far as *Dex*, *ET* decreases linearly with depth between zero and *ETmax* (eq. 4)

$$ET = ET\,max \qquad Hwt > Hes \tag{4a}$$

$$ET = 0 \qquad Hwt < Hes - Dex \tag{4b}$$

$$ET = ETmax \times (Dex - D) / Dex \qquad Hes - Dex <= Hwt <= Hes \tag{4c}$$

The initial assigned values of *Hes* and *Dex* were assigned on the basis of results obtained by Shah and others (2007) and by numerically simulating the ET process with the one-dimensional (1-D) Richards' equation for different soil and land cover types. Results show that for forested land cover, the full PET was removed from the soil until groundwater levels fell below a range of depths from 1.28 to 6.10 ft beneath the land surface, depending on soil type. On the basis of these results, a *Hes* value of 4.76 ft for a sandy clay soil type was chosen to represent the soil of the Great Dismal Swamp for all modeling scenarios.

Shah and others (2007) fit an exponential decay function to observation data and calculate the ratio of *ET* to *ETmax* for groundwater levels below *Hes*. In MODFLOW EVT a linear function is used to scale the *ET* rate, so parameter values are chosen that would roughly match the results of Shah and others (2007). Extinction depth is assigned to result in similar numerically integrated values of the ratio of ET to PET for the range of depths (fig. 21). For a forested land cover type over sandy clay soils, this extinction depth value was calculated to be 8.86 ft from the surface elevation. The extinction depth used within the EVT package is entered as the depth below the *ET* surface, which is 4.76 ft below land surface, and corresponds to a value of 4.1 ft, which is used for all model scenarios.

Because recharge values in the model are assigned equal to 100 percent of precipitation, simulated ET from the water table is intended to include all types of ET, including ET of

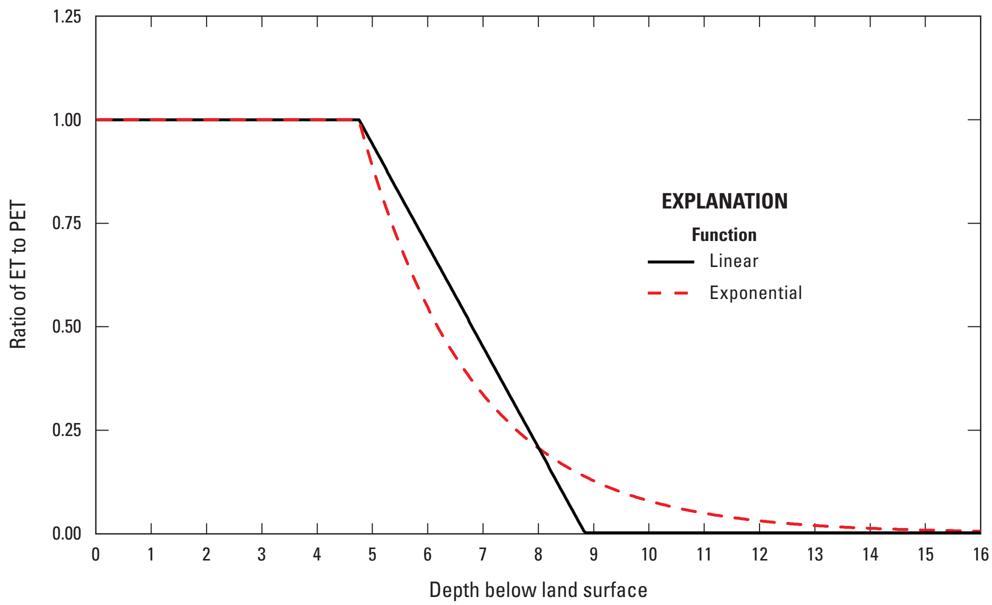


Figure 21. The ratio of actual evapotranspiration (ET) to potential evapotranspiration (PET) for a forested land type over sandy clay soils using exponential and linear functions.

water intercepted by vegetation or stored on the land surface. This approach to simulation of recharge and ET was chosen because, in many parts of the swamp, the water table is above land surface and because actual ET rates vary spatially and are poorly constrained by observation values. Simulated ET can occur anywhere in the study area that the simulated water table is within 8.86 ft of the land surface. Of the 131 wells with groundwater-level observations, only 2 wells have any observations showing depth to water table of more than 8.86 ft, and both of these wells are at locations with relatively high elevations. One well is on the western scarp, and the other is at a spoils pile next to the Great Dismal Swamp Canal. In these areas, assigned model recharge rates equal to 100 percent of precipitation will be greater than actual net recharge rates (Precipitation-Evapotranspiration-Runoff), which are discussed further in the “Limitations” section.

Roads

The Hydraulic Flow Boundary (HFB) package (Harbaugh and others, 2000; Hsieh and Freckleton, 1993) of MODFLOW is used to represent the effects of roads on groundwater flow in the Swamp. The HFB package reduces conductance between pairs of model cells to simulate barriers to flow. Because roads in the Swamp are known to compact underlying peat, HFB barriers are placed in the model coincident with roads to represent peat compaction and reduce horizontal conductance between cells in Layers 2 and 3. On the basis of geospatial data processing that identified 5,499 cell pairs containing roads, HFB boundaries are assigned to reduce conductance between the cell pairs. The HFB package requires assignment of a hydraulic characteristic of the flow barrier, which in this model is equal to K of material beneath the road divided by the width of the road. Initial values for the hydraulic characteristic were set to 1.53, calculated as the estimated K of the roadbed material from the cross-sectional model (23 ft/d) divided by a representative road width of 15 ft. The hydraulic characteristic value was then modified during calibration of the model.

Surface Water

Surface water in ditches, streams, canals, and Lake Drummond is simulated using the SWR1 process of MODFLOW (Hughes and others, 2012). SWR1 features are simulated as boundary conditions that interact with aquifer cells; however, SWR1 features also interact with each other, with WCS, and with external boundaries (fig. 20). Spatial discretization and time steps for the SWR1 component of the model are specified separately from the groundwater component of the model. Canals, ditches, and streams are represented by 1-D “reaches” with assigned cross-sectional geometry and hydraulic characteristics; Lake Drummond is represented with a 2-D reach. To reduce model run times, SWR1 was not used to simulate overland surface runoff from the interiors of the blocks to the ditches. Instead this overland flow was simulated as groundwater flow through Layer 1, as described previously, using a high hydraulic conductivity value to permit water to move laterally with little resistance.

Because ditches are dug down through the peat layer and into the underlying sand (fig. 20), SWR1 reaches representing ditches and canals in the model are assigned to penetrate the entire thickness of model Layers 2 and 3 and a portion of model Layer 4. SWR1 reaches that represent ditches exchange water with all layers and all adjacent SWR1 reaches. To reduce model run times, each reach cell is assigned to a level-pool reach group, which constrains water levels to be the same for every reach in the group. This assignment is considered to be realistic because most head loss occurs at WCSs rather than along ditches, as discussed previously in the "Water Control Structures" section (fig. 14). All reaches are assigned to have rectangular cross-sections. Ditch bottom widths are assigned on the basis of data provided by the Refuge, with most ditches having a bottom width of 25 ft and larger ditches having greater widths (for example 50 ft for the Feeder Ditch and 100 ft for the Dismal Swamp Canal; Lake Drummond SWR1 reaches have assigned widths of 500 ft, equal to cell widths).

Weirs and Culverts

All weirs, culverts, and other WCSs in the Swamp that are known to affect flow (fig. 12) are explicitly simulated in the model as SWR1 structures. Weir invert elevations must be assigned in the SWR1 Process, so for each model scenario, elevations were assigned that are based on survey data provided by Refuge staff (table 1). Any culvert or weir classified as "failed" in the geospatial data provided by the Refuge was not included in the model.

Fixed-crest weirs specified in the SWR1 Process represent WCSs at Deep Creek, South Mills, and the spillway from Lake Drummond to the Feeder Ditch. Weir widths are set equal to 48 ft for Deep Creek and South Mills and to 30 ft for the Lake Drummond Spillway, following data provided by the USACE (J. Scussel, oral commun., 2015). Weir invert elevations were assigned separately for both Deep Creek and South Mills structures and were adjusted during model calibration to match simulated upstream stages with mean observed values. Mean upstream stage observations for average January–April are 8.50 and 8.49 ft (NAVD 88) for Deep Creek and South Mills, respectively. An invert elevation of 7.88 ft resulted in simulated upstream stages of 8.50 and 8.50 for Deep Creek and South Mills, respectively, and was used for all simulations. The invert elevation specified for the Lake Drummond Spillway weir was adjusted so that simulated lake stage matched the mean observed lake stage of 15.95 ft (NAVD 88). An invert elevation of 15.11 ft resulted in a lake stage of 15.95 ft and was used for all subsequent simulations.

Weir elevations at WCSs change over time as Refuge staff add or remove boards. Weir elevations can also change for unintended reasons such as debris accumulation and failure of WCS components including boards, which occasionally cause flow to bypass a WCS. Weir elevations used in the model are equivalent to board elevations, which were observed regularly by Refuge staff at most active WCSs from 2010 to 2015 but were mostly unobserved from 2005 to 2010.

Table 12. Parameters used in model calibration and composite normalized parameter sensitivities.

[ET, evapotranspiration; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; HFB, Hydrologic Flow Boundary; ft/d, foot per day; ft, foot; $s/m^{1/3}$, second per meter$^{1/3}$]

Parameter	Description	Parameter group	Units	Lower bounds	Upper bounds	Calibrated value	Sensitivity
etratemax	Maximum ET rate	etrate	ft/d	0.005	0.012	0.007	35,354,150
etextdepth	ET extinction depth (below ET surface)	et	ft	1	5	3.19	5,511.95
etsurfdepth	ET surface depth	et	ft	1	6	3.50	5,109
hk2	Kh of Layer 2	aquiferk	ft/d	1,000	1,000,000	13,224	0.64
hk3	Kh of Layer 3	aquiferk	ft/d	10	1,000	24	99.81
hk4	Kh of Layer 4	aquiferk	ft/d	10	1,000	100	114.99
vk2	Kv anisotropy of Layer 2	aquiferk	unitless	1	10	1	5,113
vk3	Kv anisotropy of Layer 3	aquiferk	unitless	0.10	1	0.224	585
vk4	Kv anisotropy of Layer 4	aquiferk	unitless	0.10	1	0.504	2,954
leaktypical	Leakance of ditches	swrleak	1/day	1	10	5.05	3,292
leakcanal	Leakance of Dismal Swamp Canal	swrleak	1/day	1	10	4.94	2,712
leakpasquo	Leakance of Pasquotank River	swrleak	1/day	1	10	4.97	1,129.53
manngtypical	Manning's n for a typical ditch	swrmnng	$s/m^{1/3}$	0.02	0.05	0.05	249,830
manngcanal	Manning's n for the Dismal Swamp Canal	swrmnng	$s/m^{1/3}$	0.02	0.05	0.05	248,994
manngpasquo	Manning's n for the Pasquotank River	swrmnng	$s/m^{1/3}$	0.02	0.05	0.05	72,163
hfbcond	Hydraulic characteristic of HFB boundaries	hfb	1/d	0.10	10	1.58	2,465
inqmult	Multiplier for lateral surface inflow	inqgroup	unitless	0.50	2	1.11	16,765

Board and invert elevation values for each WCS, provided by Refuge staff, were then averaged to match the period of each model scenario (table 10).

Calibration Approach

The model was calibrated so that it would accurately simulate water levels and flows. To calibrate the model, parameter values were adjusted as described below until simulated water level and flow values adequately matched observed values. Initial calibration was performed manually to produce a model that was stable and gave a first approximation of hydrologic conditions. Final calibration was automated, using parameter estimation (PEST) software (Doherty, 2010) to fine tune the model, improve accuracy by optimizing parameters, and determine sensitivity of model results to various parameters. Parameter sensitivity was evaluated simultaneously with optimization of parameter values.

Model Parameterization

Model parameters were assigned on the basis of best available field data, prior studies, and results from the cross-sectional 2-D model. Some model parameters were then adjusted during calibration (table 12). Boundary conditions that are well constrained by observational data, such as precipitation rates, were assigned fixed values and were not calibrated. Other boundary conditions that are less well constrained by observational data, such as lateral surface-water inflows and ET, were adjusted during calibration. Hydraulic conductivity and conductance of the ditch bottoms are not well known, so values were adjusted during calibration (table 12), except for horizontal hydraulic conductivity of Layer 1, which was fixed at 1,000,000 ft/d. Hydraulic parameters for the aquifer are assigned by layer and are not subdivided laterally into smaller zones because available data do not indicate clear zonation across the study area. A closer model fit between observed and simulated water levels and flows could be obtained; however, locally adjusting parameters within smaller zones to match observations without a supporting conceptual basis does not improve the understanding of hydrologic processes and may not result in a model that accurately represents the hydrologic system.

Observations and Weighting

Values used to calibrate the model are observations of groundwater levels in wells; surface-water levels in ditches, the Dismal Swamp Canal, and Lake Drummond; observations of surface-water flows at WCSs and at a few open channel flow sites, such as in the Pasquotank River; and remote-sensing-derived observations of land-surface inundation (table 13). Observations were filtered so that only those made during the months of April, May, and June from 2005 through 2015 were used for calibration of the baseline model. All groundwater and surface-water monitoring sites have multiple observations made over time. To calibrate the steady-state model, mean values for each site were calculated and used as the observation target values.

An additional date filter was applied to groundwater-level- and surface-water-level observations made in the Blocks area, roughly that area bordered on the west by Western Boundary Ditch, on the east by South Martha Washington Ditch, on the north by Persimmon Ditch, and on the south by Kim Saunders Ditch (fig. 10). In the Blocks area, groundwater levels were affected by a number of WCSs installed between 2011 and 2013 that caused ditch water levels to rise. Because of this disturbance, observations made in the Blocks area were used for model calibration only if they were made in spring 2014 or 2015.

Each observation target was assigned a weight, and weighted observations were used in calculating the objective function value (Φ) that is minimized during automated calibration. Weights serve several purposes during calibration:

- emphasize observation types that are most important to match,
- scale observations of different magnitudes, for example, scaling values of flow (ft^3/d) relative to values of water level (ft) to account for magnitude differences, and
- emphasize observations with lower observation error or uncertainty.

Table 13. Observation group weight multiplier and contributions to the total objective function (Φ) at the end of calibration of the three-dimensional model.

[Percentages do not sum to 100 as a result of rounding. %, percent; Φ, objective function]

Type of observation	Group weight multiplier	Number of observations in group	Φ contribution in calibrated model
Inundation	200	2	21%
Surface-water outflow	1.3	5	15%
Surface-water internal flow	1	11	28%
Groundwater level	400,000	42	10%
Surface-water level upstream from structure	500,000	36	24%
Surface-water level downstream from structure	200,000	19	3%

Group weights were assigned (table 13) to emphasize observation types containing the most important information for steering the model towards correct simulation of water flows, and groundwater and surface-water level patterns, at the Refuge scale. Inundation observations, were assigned a relatively high group weight because they were the only hydrologic observations with complete spatial coverage of the entire study area. Surface-water flow observations received a moderate relative weight because, although matching total water balances was important, there were no observations for flow out of Portsmouth Ditch, and flows for Pasquotank River were uncertain owing to the tidal nature of the station. In addition, the best known outflows, at Deep Creek and South Mills locks, were extremely sensitive to the invert elevation of the SWR1 weirs representing the locks. For example, lowering the weir elevation at Deep Creek by 0.074 ft, less than 1in., caused Deep Creek outflow to increase by 5 percent (from 111 to 116 ft^3/s). Therefore, the parameters adjusted during the calibration process were relatively less important to outflows at Deep Creek and South Mills than some assigned parameters. Internal flow observations were given high relative weights because they had wide spatial coverage and were important for accurately simulating the catchment areas for individual WCSs. Groundwater-level observations were given relatively low weight because they do not have wide spatial coverage. Surface-water-level observations collected upstream from WCSs were given relatively high weights because they had good spatial coverage, accurate simulation of water levels in ditches is important, and ditch levels are expected to have strong control over groundwater levels. Surface-water-level observations made downstream from WCSs were given relatively low weight because these levels are often affected by debris and by turbulence when water free falls over the WCS.

To de-emphasize observations with high error, the weight of an observation is typically determined by its variance, which includes observation error. All observations are assumed to represent steady-state conditions, which is a simplifying assumption for numerical representation because average observation values represent different sample sizes of observations collected at different times. With an accurate numerical representation of evenly distributed observations, the assigned weights would be based on observation variance and observation error (Hill and Tiedeman, 2007). However, other factors, such as representing time-varying water levels at a well or WCS with a single average value and representing land elevations within a 250,000-square foot (ft^2) model cell with a single elevation, likely introduce more error into an observation than observation error itself. Therefore, the weights assigned to each observation group may be somewhat subjective and can be used to reflect existing knowledge of the hydrogeologic system. However, parameter values are generally not very sensitive to moderate changes in the weights used (Hill, 1998), and observation may be weighted as a group on the basis of relative magnitudes.

Groundwater-Level Observations

Average spring groundwater levels for 42 wells in the Swamp (fig. 22), described previously in the “Groundwater Levels and Flow Patterns” section, were used for calibration. Criteria for inclusion of a well in the groundwater observation calibration dataset were (1) land-surface elevation accuracy of 0.5 ft or less, (2) sample size of two or more, and (3) well depth reported.

Inundation Observations

Inundation observations, described previously in the “Inundation” section, were included as targets during model calibration. For comparison to the remotely sensed inundation, a model cell is considered inundated if the simulated water table was above land surface. Simulated inundation for each active cell in Layer 1, not including Lake Drummond cells, was therefore assigned a value of 1 (inundated) if the simulated water table was in Layer 1; otherwise it was assigned a value of 0 (not inundated).

Whereas simulated inundation has binary values 0 or 1, observed inundation values for each model cell, the spatially averaged DSWE and SAR/InSAR inundation measures, had values ranging continuously from 0 to 1, with most values close to 0. For use in calibration, a sum of square error values was calculated for the entire active model area from observed and simulated inundation values and separately for DSWE and SAR inundation observations (eq. 5–6).

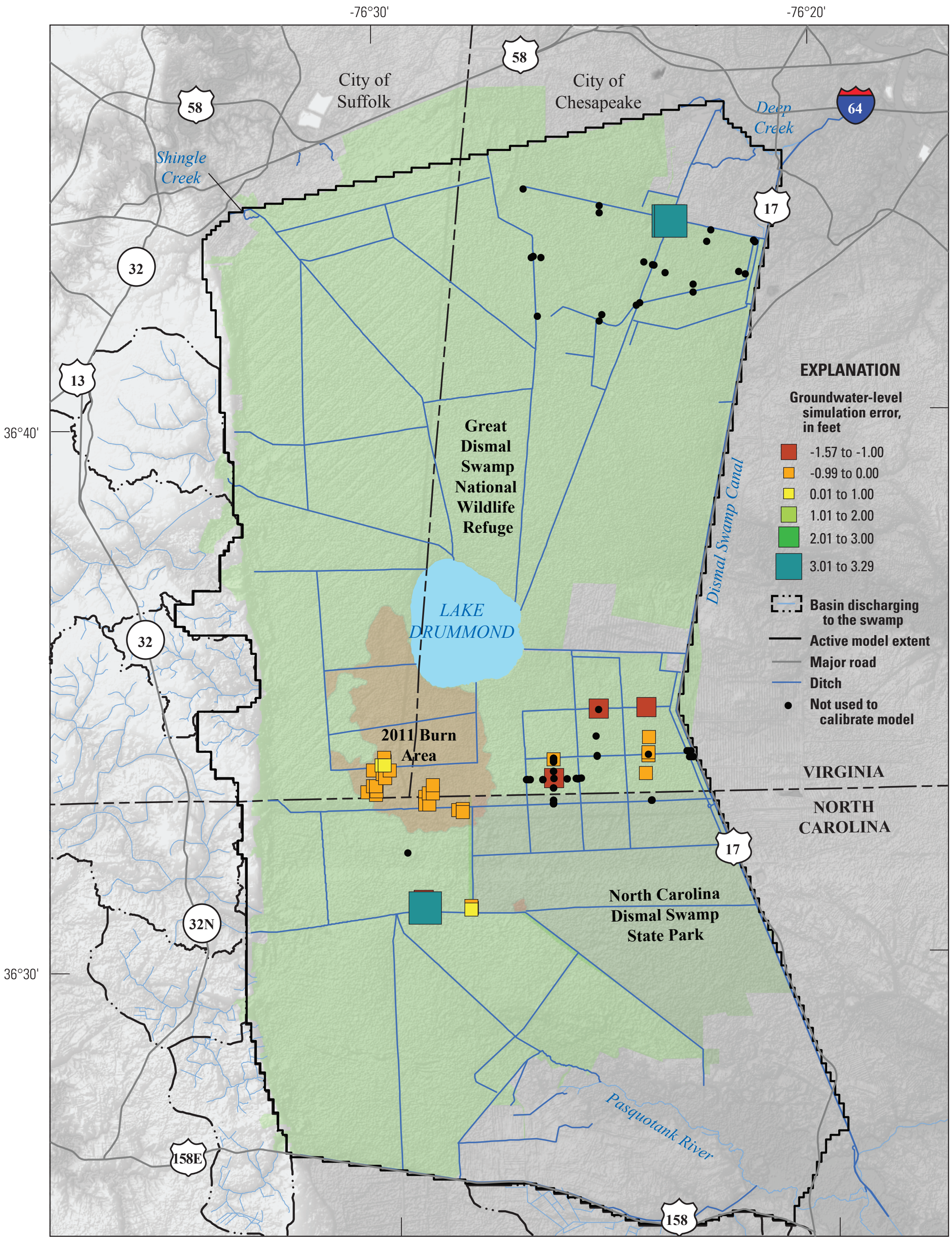
$$\textit{DSWE Inundation Error Sum of Squares} = \sum_{i=1}^{\textit{Number of active Layer 1 Cells}} \left[\textit{Simulated DSWE Inundation}_i - \textit{Observed Inundation}_i\right]^2 \tag{5}$$

$$\textit{SAR Inundation Error Sum of Squares} = \sum_{i=1}^{\textit{Number of active Layer 1 Cells}} \left[\textit{Simulated SAR Inundation}_i - \textit{Observed Inundation}_i\right]^2 \tag{6}$$

Surface-Water Level and Flow Observations

Surface-water-level observations made at 37 sites (WCSs) were used to calibrate the model, and at 18 of these sites, observations were made just upstream and just downstream from the WCS. Therefore, a total of 55 mean surface-water-level values was used to calibrate the model. Because more observations give averaged values more certainty, sites with less than 5 surface-water-level observations were excluded as calibration targets; 55 stations met this requirement (fig. 23 and table 14).

Flow-monitoring stations were required to have at least three flow observations. Sixteen stations met this criteria, and



Base from U.S. Geological Survey National Elevation Data 1/3 arc-second
Lambert Conformal Conic projection
Standard Parallels 36° 45' 57.6" N and 37° 57' 57.6" N; central meridian 78° 30' W
North American Datum of 1983 State Plane Virginia South

Figure 22. Groundwater-level observation sites in the Great Dismal Swamp, Virginia and North Carolina, and simulation errors.

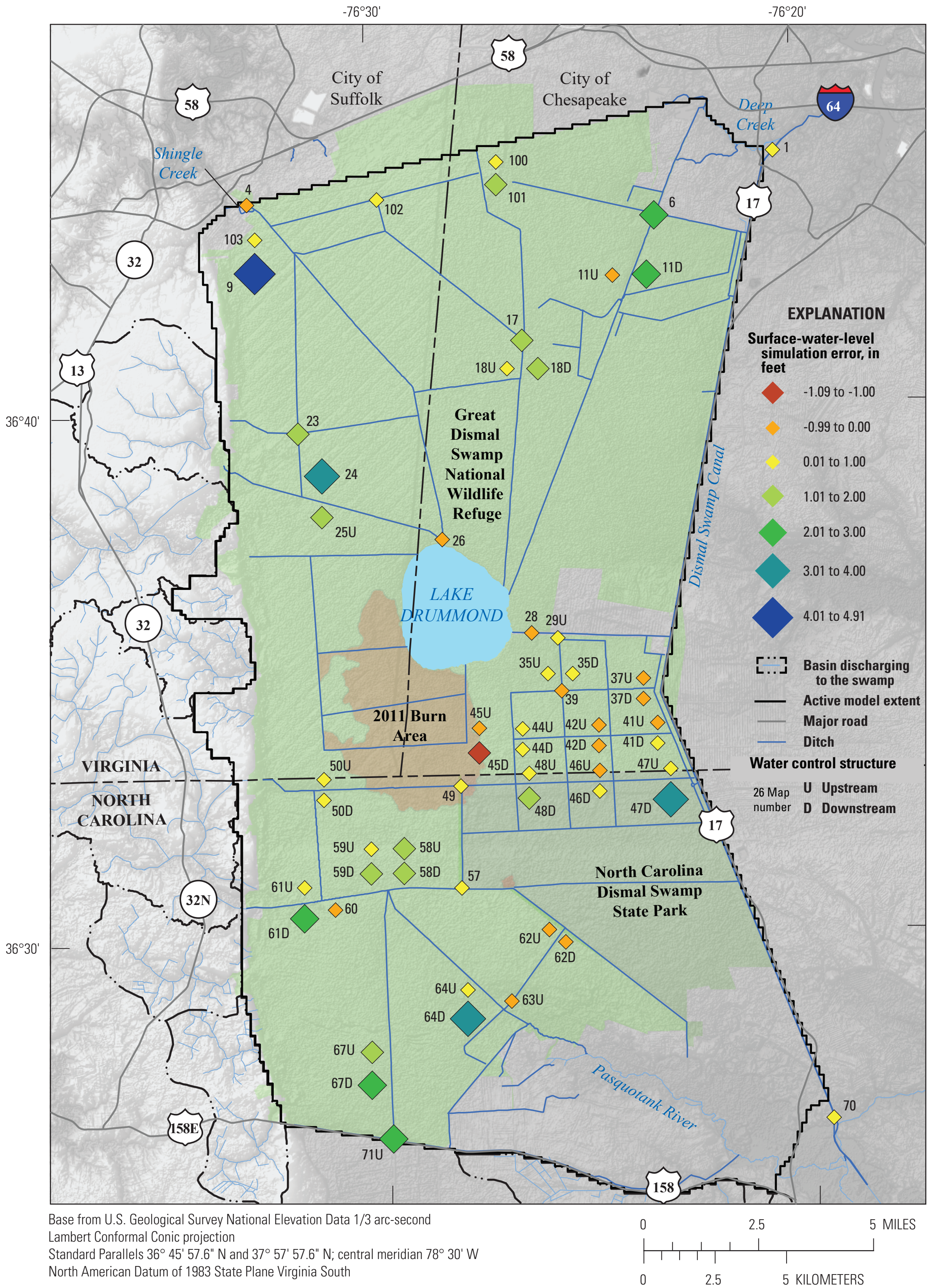


Figure 23. Surface-water-level observation sites at water control structures and simulation errors, Great Dismal Swamp, Virginia and North Carolina.

Table 14. Average observed surface-water levels during 2005–15 and surface-water levels during 2015 wet conditions and 2011 dry conditions at 55 observation sites in the Great Dismal Swamp, Virginia and North Carolina, used to calibrate the three-dimensional model.

[NA, not available]

Water control structure		Water level (feet)					
		Climate scenario—spring growing conditions					
		Dry observed		Wet observed		Average	
Name	Water control structure number[1]	April–June, 2011	Number of observations	April–June, 2015	Number of observations	April–June, 2005–15	Number of observations
Camp/East Upstream	18	NA	0	19.61	4	19.69	15
Camp/East Downstream	18	NA	0	19.42	4	19.45	15
County Line/Weyerhauser Upstream	59	16.71	6	16.07	9	16.37	96
County Line/Weyerhauser Downstream	59	14.04	6	14.41	9	14.85	35
Portsmouth/Rosemary Upstream	11	14.58	5	14.50	9	14.31	45
Portsmouth/Rosemary DownStream	11	NA	0	13.69	7	13.87	11
Sherrill North Upstream	50	17.82	6	17.79	11	18.09	58
Sherrill South	60	17.34	4	NA	0	18.08	21
Cross Canal/Sherrill Upstream	61	17.93	5	18.33	4	18.15	70
Cross Canal/Sherrill Downstream	61	18.22	2	17.47	3	17.88	24
Cross Canal/Weyerhauser Upstream	58	16.71	6	16.09	7	16.71	50
Cross Canal/Weyerhauser Downstream	58	14.52	3	14.94	6	15.58	33
County Line/Insurance Upstream	64	12.58	4	13.38	5	13.34	24
County Line/Insurance Downstream	64	10.74	2	11.69	3	11.39	13
Head of River 1 Upstream	63	12.26	3	12.99	2	12.82	14
Weyerhauser 158 culverts Upstream	71	14.04	3	NA	0	15.55	12
Bull Boulevard/Insurance Upstream	62	12.62	3	13.66	2	13.41	15
Bull Boulevard/Insurance Downstream	62	12.07	1	NA	0	12.27	9
Weyerhauser Upstream	67	16.85	3	16.44	4	16.40	53
Weyerhauser South Downstream	67	14.02	2	15.38	3	15.70	16
Forestline South	57	17.47	8	17.06	11	17.07	100
Forestline North	49	17.59	6	17.44	15	17.50	68
Corapeake/West Boundary Upstream	48	16.77	2	17.08	12	17.41	39
Sycamore/West Upstream	44	NA	0	16.79	9	17.15	34
Sycamore/West Downstream	44	NA	0	16.57	6	16.69	23
Sycamore/Laurel Upstream	42	NA	0	15.71	16	16.03	45
Sycamore/Laurel Downstream	42	NA	0	15.45	9	15.38	33
Corapeake/Laurel Upstream	46	16.49	5	15.66	15	16.24	80
Corapeake/Laurel Downstream	46	11.04	2	14.81	8	14.33	20

Table 14. Average observed surface-water levels during 2005–15 and surface-water levels during 2015 wet conditions and 2011 dry conditions at 55 observation sites in the Great Dismal Swamp, Virginia and North Carolina, used to calibrate the three-dimensional model.—Continued

[NA, not available]

Water control structure		Water level (feet)					
		Climate scenario—spring growing conditions					
		Dry observed		Wet observed		Average	
Name	Water control structure number[1]	April–June, 2011	Number of observations	April–June, 2015	Number of observations	April–June, 2005–15	Number of observations
Weir 1 Upstream	47	NA	0	14.00	10	14.56	17
Weir 1 Downstream	47	NA	0	11.52	3	11.54	8
Sycamore/South Martha Washington Upstream	41	13.86	2	15.30	11	15.09	32
Sycamore/South Martha Washington Downstream	41	10.16	2	14.91	6	13.95	18
S. Martha/Persimmon Upstream	37	NA	0	15.10	5	15.29	18
Myrtle/Persimmon	43	13.68	2	13.92	11	14.34	38
Myrtle South Upstream	35	NA	0	13.80	8	14.49	25
Myrtle South Downstream	35	NA	0	13.34	8	13.59	21
Myrtle North Upstream	29	13.89	3	13.29	4	13.81	47
Lynn/Middle	23	21.20	3	20.69	2	21.53	21
Washington/Lynn Upstream	25	21.21	3	20.62	4	21.50	79
Lynn South	24	20.35	2	NA	0	20.98	17
Washington/Jericho	26	17.04	2	17.62	1	17.39	36
Jericho North	4	19.36	3	19.14	4	18.95	22
Jericho/Hudnell	103	19.76	1	20.72	3	21.03	12
Lynn/Jericho	9	20.27	2	20.78	3	21.11	48
Hudnell/East	17	NA	0	19.75	3	19.82	13
Williamson/East - Williamson[2]	100	19.57	1	NA	0	20.70	10
Williamson/East - East[2]	101	18.57	1	19.06	3	19.11	13
Williamson/New	102	NA	0	20.66	2	20.97	10
Portsmouth/Big Entry	6	10.50	4	11.55	9	11.19	31
South/Riddick Upstream	45	17.43	3	17.72	2	17.65	13
Lake Drummond Spillway	28	12.59	91	12.65	91	12.55	987
South Mills Lock	70	8.47	91	8.56	91	8.44	987
Deep Creek Lock	1	8.41	91	8.58	91	8.45	987
Pasquotank River (0204382800)[3]	NA	0.69	86	0.79	91	0.70	987

[1]Water control structure number shown in Figure 12.

[2]Surface-water-level observation.

[3]Shown in figure 1.

mean values from these stations were used to calibrate the model. Flow observations made during the simulation periods were averaged to provide mean flow target values for the baseline simulation period.

Calibration and Error-Based Calibration Criteria

The model was calibrated with the automated parameter estimation software (PEST) (Doherty, 2010). Calibration targets included groundwater-level data from 42 monitoring wells (fig. 22), surface-water-level data from 55 sites (fig. 23), surface-water-flow data from 16 WCSs, and surface inundation data from remote sensing (fig. 15). The automated calibration was run in estimation mode, adjusting parameters to minimize the objective function Φ (eq. 7).

$$\Phi = \Sigma(w_i r_i)^2 \quad (7)$$

where

Φ is the objective function to be minimized,

r_i is residual for observation i (simulated value – observed value), and

w_i is weight for observation i.

Calibration Results

Simulated surface-water-level and groundwater-level values match well with observed values at most monitoring sites (table 15 and figs. 22, 23, and 24), indicating that the model provides a reasonable steady-state representation of swamp hydrology. In general, simulated values that are within 2 ft of average observed spring values are considered reasonable. Simulated water-level values that exceed observations by 3 ft are less desirable and are indicative of uncertainties in the model conditions at those locations. Simulated groundwater levels have a mean error (simulated minus observed value) of +0.18 ft, and simulated surface-water levels have mean errors of -0.66 ft and -1.04 ft, upstream and downstream from a WCS respectively.

Table 15. Simulation errors for different observation groups.

[SW, surface water; GW, groundwater]

Observation group	Number of observations	Mean error	Mean absolute error	Mean percent error
Inundation	2	−13,630.32	13,630.30	−100.00
Major SW outflows	5	−117,477.60	8,182,940.00	−1.42
Internal SW flows	11	216,821.18	1,665,354.50	14.97
GW levels	42	0.18	17.10	1.04
SW levels up	36	−0.66	16.40	−3.99
SW levels down	19	−1.04	14.40	−7.21

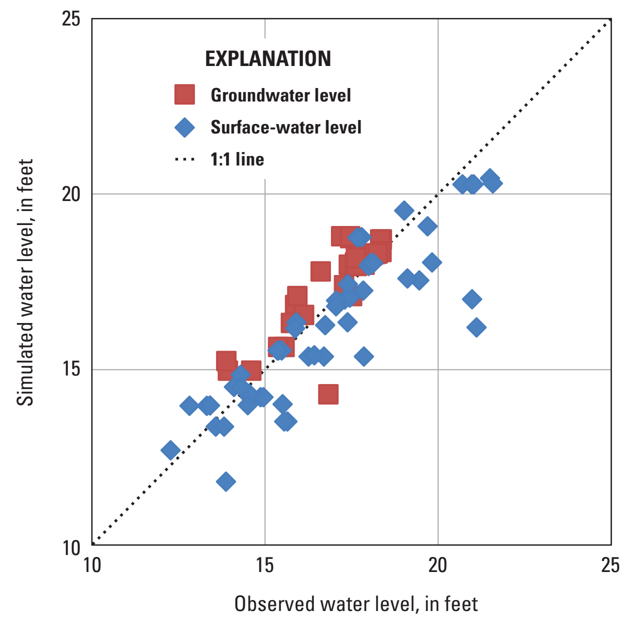


Figure 24. Simulated and observed groundwater and surface-water levels and the ideal 1:1 line.

Simulated flows and levels at the three structures managed by the USACE (Deep Creek Locks, South Mills Locks, and Lake Drummond Spillway) match well with observed mean values for average April–June conditions. The simulated upstream stage and flow at Deep Creek are 8.49 ft and 111.3 ft^3/s, respectively, and mean observed values are 8.50 ft and 113.6 ft^3/s, respectively; the difference in flow is less than 2 percent. The simulated upstream stage and flow at South Mills are 8.49 ft and 111.7 ft^3/s, and mean observed values are 8.49 ft and 131.2 ft^3/s. The simulated upstream lake level at the spillway from Lake Drummond to the Feeder Ditch is 15.95 ft., the same as the mean observed lake level of 15.95 ft. Simulated flow at the spillway from Lake Drummond to the Feeder Ditch is 110.5 ft^3/s, about 2 percent less than observed flow 112.7 ft^3/s. As described previously, the flows at the structures managed by the USACE are very sensitive to SWR1 weir elevation settings, which in the model were manually set to achieve the close match between observed and simulated values.

As judged by the high group error value (table 15), and a fraction of simulated inundated cells (58.1%) that is greater than observed inundated cells (4.7% for SAR/InSAR and 2.5% for DSWE), simulated inundation does not appear to be a good fit with observed inundation (fig. 15). However, visual comparisons indicate that simulated inundation exhibits spatial patterns similar to the DSWE and SAR observed inundations (fig. 15). Simulated and observed images all show areas of inundation to the southwest of Lake Drummond, which corresponds to observed ponding in the 2011 Burn Area. Simulated wet areas generally correspond well to wet areas reported by Refuge staff and include the burned area south of Lake Drummond, the Pasquotank River flood plain, the foot of the western scarp, and the northwestern Swamp. The large mean inundation error is caused partly by the model cell size of 500 ft, which is larger than the observed inundation raster sizes of 98 ft (30 m) for DSWE and 75 ft (23 m) for SAR/InSAR. To have an error of zero for a single cell would require that the approximately 45 SAR/InSAR raster values or 26 DSWE raster values within each model cell be 0 or 1, matching the simulated 0 or 1 inundation value. This is unlikely to happen in areas subject to inundation, except during very wet or dry periods.

Water-budget mass balance errors were -0.4 percent for the groundwater budget and 0.0 percent for the surface-water budget. The relatively low errors indicate that the model has adequate numerical stability.

Sensitivity

Sensitivity describes how much simulated water levels and flows change in response to a change in parameter value. If simulated flows and water levels change a lot when a parameter X is changed, then sensitivity to parameter X is high. A sensitivity analysis of the 17 calibrated parameters in the model (table 12) was performed by using PEST during model calibration. Composite normalized parameter sensitivities, which describe the information content of observations relative to a specific model parameter (Doherty, 2010), were calculated (eq. 8). Comparison of composite parameter sensitivities shows the relative contribution of each parameter or parameter group to the objective function during the automated parameter estimation process. Different observation data, model structure, or parameterization results in different sensitivities. So the best use of the composite normalized parameter sensitivities is to gauge relative sensitivities of parameters within the same model. The composite sensitivity of parameter, *i*, is calculated as (eq. 8)

$$S_i \frac{\left(J^T w^2 J\right)_{ii}^{\frac{1}{2}}}{m} \tag{8}$$

where

- J is the Jacobian (sensitivity) matrix,
- T is the matrix transpose operation,
- w is the diagonal matrix of observation weights, and
- m is the number of observations with nonzero weights.

The most sensitive parameter in the model, by far, is *etratemax*, the maximum evapotranspiration rate, used by MODFLOW to calculate the simulated ET rate for each cell. The sensitivity of etratemax is an order of magnitude greater than all other parameters because it is the primary control on vertical outflow rates from the aquifer. The next most sensitive parameters are the Manning's roughness coefficients, which control the simulated loss of head for flow in the ditches. All three of the Manning's roughness coefficient parameters in the model (manngtypical, manngcanal, manngpasquo) have calibrated values of 0.05, which is the maximum value (PARUBND) assigned during the PEST calibration. The value of 0.05 is at the high range of acceptable values and corresponds to natural channels in poor condition. Most ditches in the study are straight with dense vegetation along the edges and frequent downed trees and brush in the channels. A higher maximum limit of 0.1 was tried in an additional PEST run, which pushed manngtypical and manngpasquo from 0.05 to 0.1 and yielded a marginally better calibration fit. But it was decided that a value of 0.1 was unreasonably high for the ditches in the Swamp, based on reported values for the Manning's roughness coefficient (Chow, 1959). Therefore the Manning's coefficient values in the model should be considered as assigned to upper limits, given understanding of the system, and based on the automated calibration results, rather than assigned as part of the optimization regression.

Simulated Hydrology and Water Management

Results from the model simulations provide new understanding of swamp hydrology and options for water management. The calibrated baseline model, which simulates average spring conditions, provides results that improve our understanding of water balances, levels, and flow directions. Additional model runs, or scenarios (table 16, scenario 1), were developed to simulate hypothetical wet and dry conditions and different WCS management strategies. These alternative climatic conditions and water-management strategies were simulated by changing boundary conditions of the calibrated model. Climatic conditions were assigned (tables 2 and 10) on the basis of averaged observations of precipitation and temperature during spring 2011, when dry conditions prevailed, and spring 2015, when wet conditions prevailed. Water-management actions were simulated by adjusting SWR1 Process weir levels in the model input files.

Additional WCSs proposed for construction by the Refuge were simulated in Scenario 4 (table 16). Scenarios 5 and 6 simulate flooding of the Swamp by raising elevations of all existing active and proposed WCSs to the elevation of nearby land-surface elevations. Scenarios 7 and 8 simulate draining of the Swamp by removing all existing active and proposed WCS.

Table 16. Description of hydrologic simulation scenarios for the three-dimensional model of the Great Dismal Swamp, Virginia and North Carolina.

[WCS, water control structure]

	Scenario	Climatic conditions	Weir level settings	Water control structures included
1	Baseline	Average	Low	Those active in 2015
2	Wet	Wet	Low	Those active in 2015
3	Dry	Dry	High	Those active in 2015
4	Future WCS added	Average	Low	Proposed + active 2015
5	Flood the swamp wet	Wet	Very high	Proposed + active 2015
6	Flood the swamp dry	Dry	Very high	Proposed + active 2015
7	Drain the swamp wet	Wet	Very low	Proposed + active 2015
8	Drain the swamp dry	Dry	Very low	Proposed + active 2015

Average Spring Hydrologic Conditions

The baseline scenario (Scenario 1) simulates average spring hydrologic conditions from 2005 through 2015. A water budget was calculated for the simulated combined (groundwater and surface water) hydrologic system (table 17). Precipitation is the primary source of water to the study area, representing about 900 ft^3/s of the approximately 974 ft^3/s inflow or 92 percent, whereas surface-water and groundwater inflows from the south and west make up the remainder. Surface-water inflows account for 48 ft^3/s or 5 percent of simulated inflows, whereas groundwater inflows account for 26 ft^3/s (3 percent).

Total simulated outflow from the study area is 976.7 ft^3/s, consisting of ET equal to 541.7 ft^3/s (55%), surface outflow of 395.5 ft^3/s (41%), and groundwater discharge of 39.5 ft^3/s (4%) (table 17). These outflow values are exclusive of exchanges within the Swamp between the aquifer and ditches. Simulated spring ET has a rate of 30.4 in/yr, obtained by dividing the volumetric ET rate of 541.7 ft^3/s by the active model area. This calibrated ET rate is less than the estimated annual average rate of 36 in/yr reported by Heath (1975) for the Albemarle-Pamlico region and less than the MODIS average ET rate for spring months during 2005–14 of 50.7 in/yr, which includes the southern part of the study area, but the calibrated ET rate is greater than the average value of 27.6 in/yr for the study area estimated by Sanford and Selnick (2013). ET rates during the calibration period April through June would be expected to increase from relatively low rates in early April when most vegetation has little leaf surface area to maximum rates in May and June when plant growth reaches maximum rates for the year. Simulated ET rates agree with those presented by Heath (1975) and Sanford and Selnick (2013) for the study area. Some confidence in the simulated value comes from noting that the value is derived from the water balance enforced by the model. The MODIS estimated ET rate is likely too high, especially considering that it is equal, apparently by coincidence, to observed mean precipitation at the one meteorological station (USC00448837) in the study area.

As expected for a shallow unconfined aquifer system in a saturated landscape, simulated groundwater levels (fig. 25) show spatial patterns similar to those seen in land-surface elevations (fig. 2). The highest groundwater levels are found along the western scarp boundary, whereas the lowest are in the northwest, northeast, and southeast corners where tidal creeks are represented by specified head boundaries.

Groundwater levels are generally higher away from ditches and lower close to ditches, indicating that groundwater generally discharges to ditches. This is further confirmed by groundwater budget results for groundwater/surface-water exchange (table 17) showing that the groundwater discharge rate to the ditches (455.3 ft^3/s) is greater than the rate of recharge to the aquifer from ditches (106.1 ft^3/s). Simulated vertical head gradients have small magnitudes across the study area, generally from -0.0001 to +0.00001 (fig. 26). Positive

Table 17. Simulated water budget for the calibrated baseline three-dimensional hydrologic model, Scenario 1, of the Great Dismal Swamp, Virginia and North Carolina.

[ET, evapotranspiration; Head dep bounds, head dependent boundaries; SWR, surface-water routing; --, no data]

Hydrologic component	Description	In (cubic feet per second)	Out (cubic feet per second)
Wells	Groundwater inflow from scarp	26.4	--
Lateral flow	Surface-water inflow from scarp	47.6	--
Recharge	Recharging precipitation	899.9	--
ET	Evapotranspiration	--	541.7
Head dep bounds	Groundwater exchange with tidal rivers	--	39.5
Boundary flow	Surface-water outflow to tidal rivers	--	395.5
	TOTAL	973.8	976.7
SWR Leakage[1]	Groundwater/surface-water exchange	106.1	455.3

[1]Internal exchanges between surface water and groundwater are not included as part of the overall water balance of the hydrologic system. “In” is surface inflow to the groundwater system, while “Out” is groundwater discharge to the surface-water system.

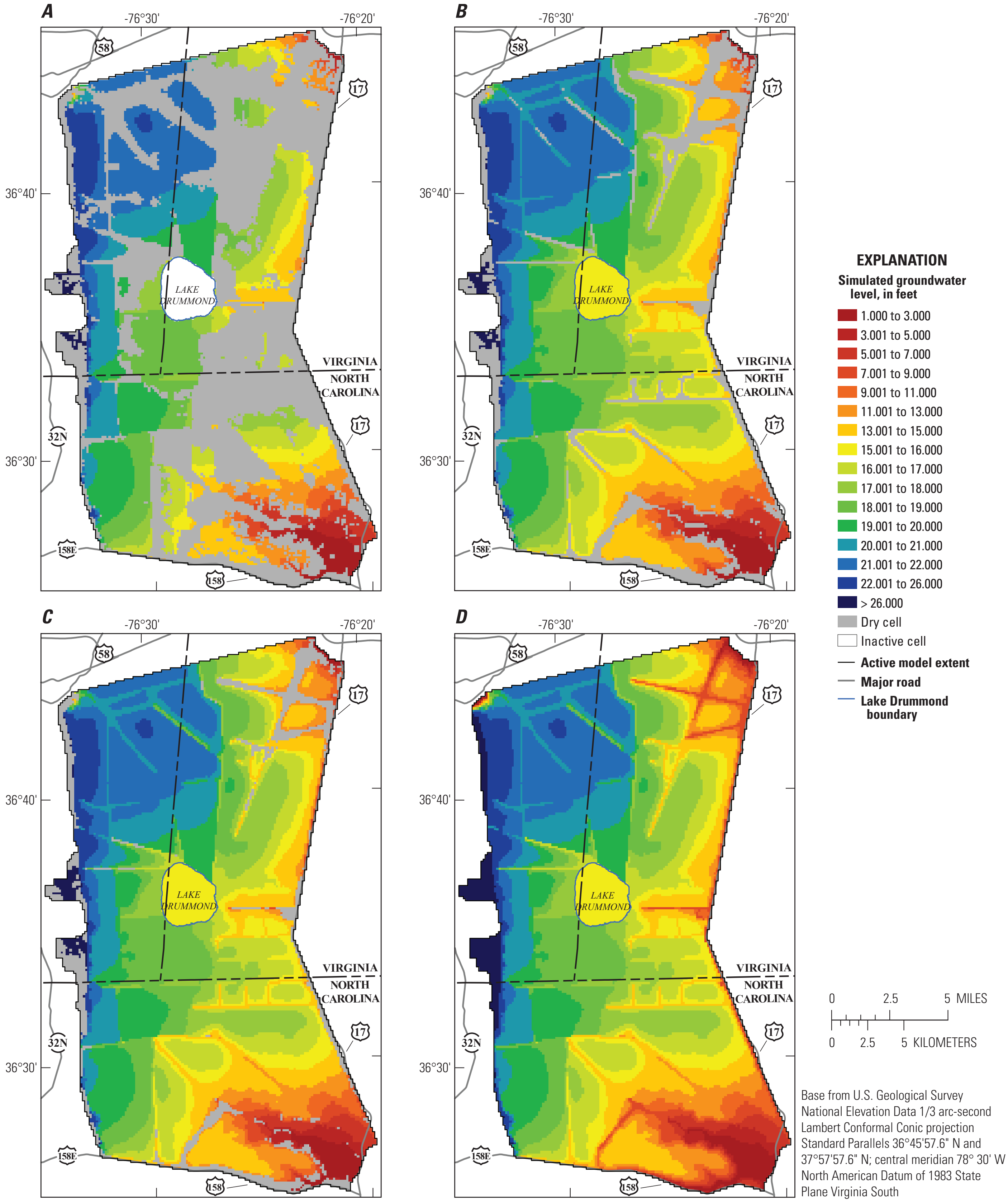


Figure 25. Simulated groundwater levels in the Great Dismal Swamp, Virginia and North Carolina, and dry cells in *A*, Layer 1, *B*, Layer 2, *C*, Layer 3, and *D*, Layer 4.

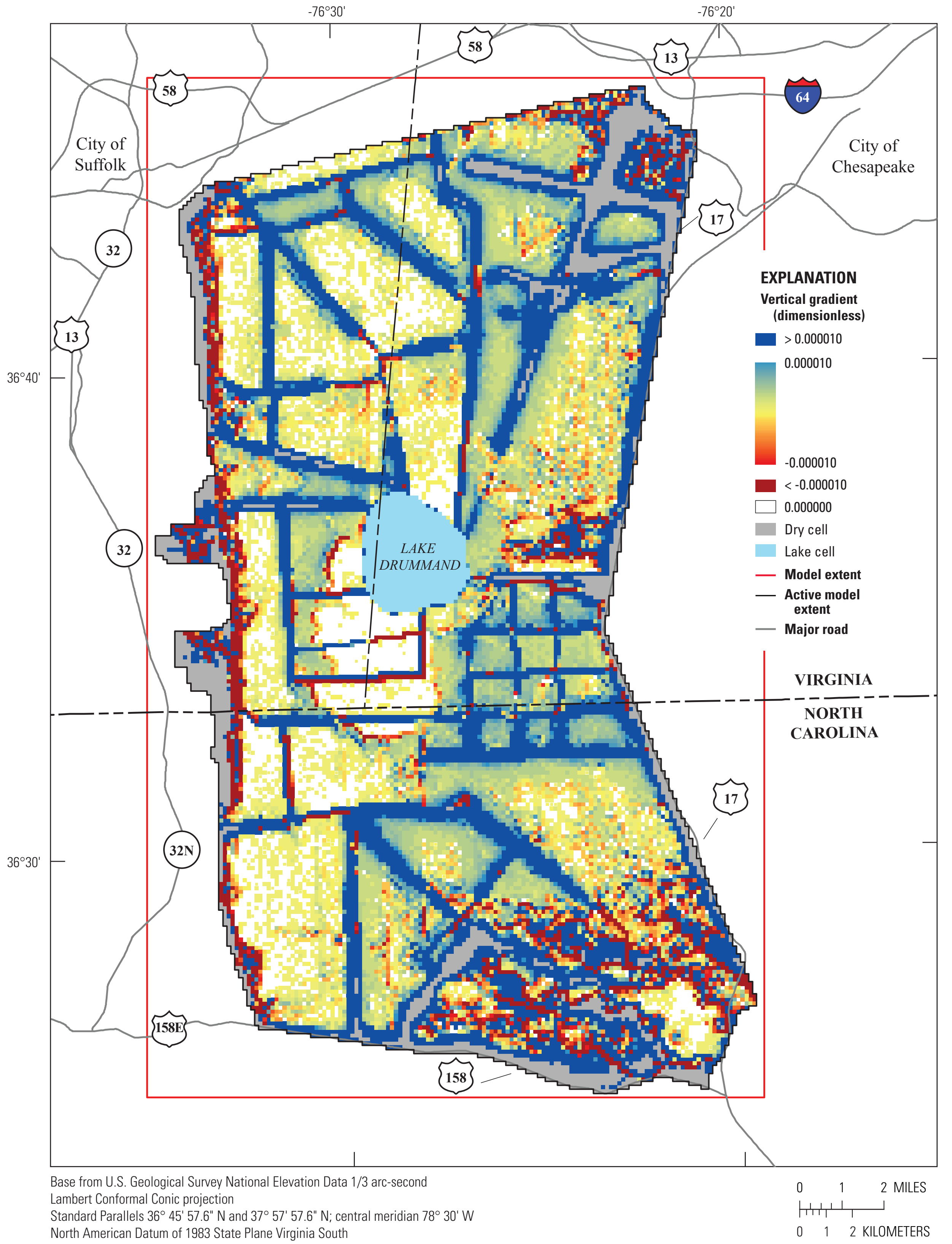


Figure 26. Simulated vertical head gradients between the water table and Layer 4 in the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. Positive values indicate upward groundwater flow; negative values indicate downward flow.

vertical gradients indicate upward groundwater flow, and negative values indicate downward flow. The small magnitude of the vertical head gradients is a result of low topographic gradients (figs. 2 and 4) and an absence of groundwater withdrawals or other aquifer stresses across most of the study area. Vertical gradients are upward at ditches, with the exception of a few locations, again indicating groundwater discharge to most ditches. The few locations where surface water recharges the aquifer are shown as red model cells containing a ditch or SWR1 reach (fig. 26). These locations include South Ditch, the eastern portion of Lateral Ditch, Sherrill Ditch, Cross Canal Ditch just west of Weyerhauser Ditch, and East Ditch near Juniper Ditch.

On the basis of simulated groundwater and surface-water levels and of simulated groundwater flow paths, subbasins draining to points of major discharge are delineated for baseline average spring conditions (Scenario 1; fig. 27). Under different climatic conditions or weir level settings, some of these drainage subbasin boundaries can be expected to change (not shown). Flow leaving Lake Drummond moves east to the intersection of the Feeder Ditch and the Dismal Swamp Canal, and at that point flow divides and moves north to Deep Creek and south to South Mills. Although not simulated in this study because it was outside the study's scope, changing lock weir levels at Deep Creek and South Mills can be expected to affect the part of Lake Drummond outflow going to each end of the Dismal Swamp Canal.

Simulated groundwater flow paths (fig. 28) indicate groundwater generally discharges to the nearest ditch, which is in agreement with the expectation of little underflow beneath ditches. In just a few locations, such as at West Ditch at the foot of the scarp (fig. 29), simulated groundwater passes under a ditch without discharging upward, then continues on to discharge at a more distant ditch, but this is an exception to the general pattern. The pattern of most simulated groundwater discharging to the nearest ditch is likely affected by the assigned thickness of the model layers. Ditches penetrate the entire thickness of model Layers 2 and 3 and a part of model Layer 4. Adding a model layer below Layer 4 or assigning a greater thickness to model Layer 4 would likely result in more simulated groundwater passing under ditches without discharging.

Simulated inundation (fig. 25*A*) indicates areas of the Swamp that are relatively wetter or drier on the land surface. Because Layer 1 holds water stored on the land surface, any Layer 1 cell that is not dry indicates land-surface inundation; that is, the water table is above land surface. Simulated wet areas generally correspond to wet areas reported by Refuge staff, including the Burn Area south of Lake Drummond, the foot of the western scarp, and the northwestern Swamp. In the hummocky terrain of the Swamp, complete inundation of the land surface is rare, except in Burn Area where there has been substantial peat loss. Typically, inundation in the Swamp manifests as standing water in low elevation hollows, whereas slightly higher elevation hummocks remain above water. Because the modeled land-surface elevation represents the low end of the lidar derived elevations in a model cell, inundation estimates likely overpredict the extent of standing water during average spring conditions. If the model is converted to be transient in the future, it could be used to simulate seasonal inundation conditions.

Depth of the water table below land surface is an important factor for plant growth and ground fire risk and is simulated by the model (fig. 30). Under average spring conditions (model Scenario 1), simulated depths to the water table range from more than 10 ft along the western scarp to less than zero in inundated areas. Simulated depths to groundwater help to illustrate where existing groundwater conditions match those described in the literature for undrained peatlands. The early spring (April) is typically when seasonal water levels in the Swamp (Day and others, 1988) and nearby forested peatlands in North Carolina are highest (Heath, 1975; Richardson, 1991). In undrained pocosin peatlands similar to those in the Swamp, spring water-level highs are near 0 ft below land surface, and late summer and fall lows approach 2 ft below land surface (Richardson, 2003; Wang and others, 2015). Areas of the Swamp that are inundated or have depths to groundwater near 0 ft (fig. 30) likely approximate where the effects of drainage on spring water levels are less pronounced. Depth to groundwater approaching 2 ft during spring is indicative of drained conditions and corresponds to portions of the Refuge with a high density of ditches (fig. 30). Measures of vegetation response to water-table depth typically take into account the time-varying nature of water-table depth; for example, see USACE Environmental Laboratory (1987). Future work could include simulation of time varying water levels and percent time inundated if the model were updated to be transient.

Wet and Dry Simulation Results

Hydrologic conditions under hypothetical wet and dry climatic conditions are simulated by making changes to boundary conditions: recharge, ET, lateral inflows, and weir settings (tables 1, 2, and 10). For simulated wet conditions (Scenario 2), weirs were left at the same elevations as the average conditions in baseline Scenario 1, whereas for dry conditions (Scenario 3), weir elevations were raised to reflect the typical Refuge management actions of adding stop logs (boards) to weirs to raise water levels and prevent the Swamp from drying out.

As expected, groundwater levels are higher under wet conditions (Scenario 2, fig. 31*B*) than during average climatic conditions (Scenario 1, fig. 31*A*), with greater groundwater-level increases adjacent to ditches, to the north and west of Lake Drummond, and along the Pasquotank River (fig. 32*A*). Under wet conditions 7,654 model cells, or 43,928 acres, that are unsaturated under average conditions contain water owing to higher simulated water-table elevations. Cells that are least partially saturated under average conditions have an average water-table elevation increase of 0.48 ft under wet conditions. Simulated flows at major WCSs increase by an average factor of 2.0, which can be seen in the comparison of simulated flows

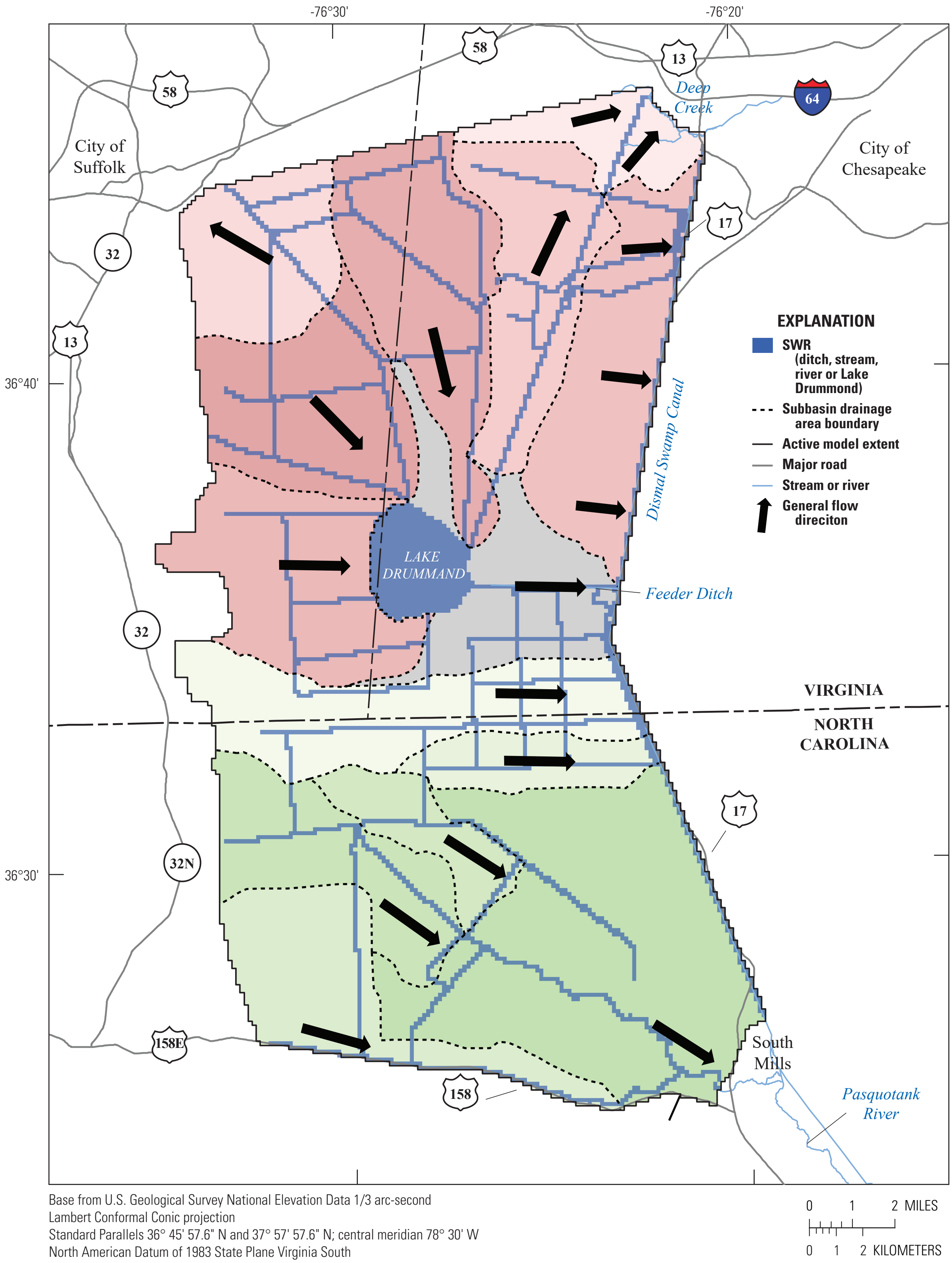


Figure 27. Subbasins and generalized flow directions that are based on simulated baseline hydrologic conditions, model Scenario 1, in the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (SWR, surface-water reach simulated with the MODFLOW- SWR1 Process)

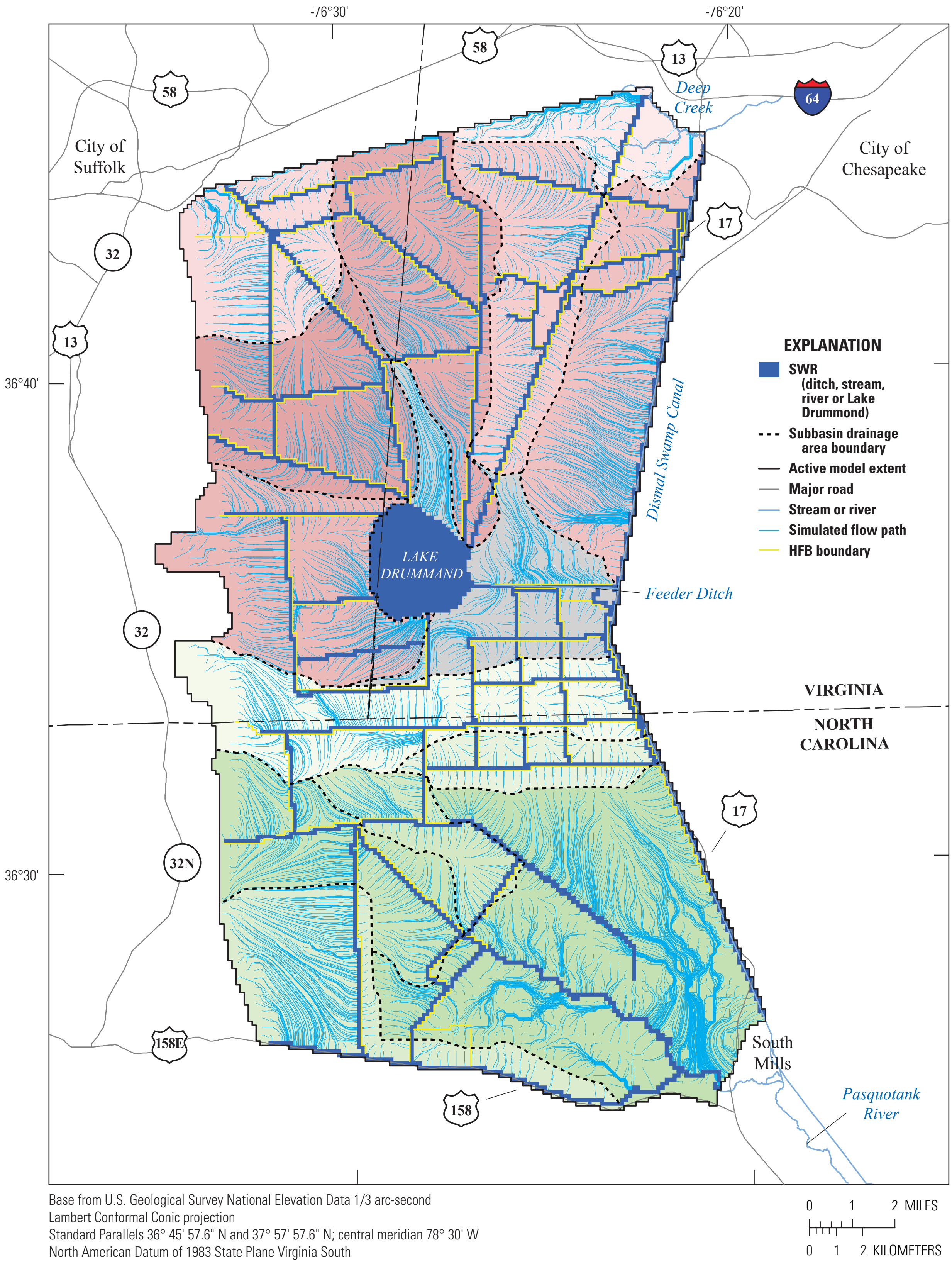


Figure 28. Simulated flow paths under baseline conditions, model Scenario 1, in the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (SWR, surface-water reach simulated with the MODFLOW- SWR1 Process; HFB, Hydraulic Flow Boundary)

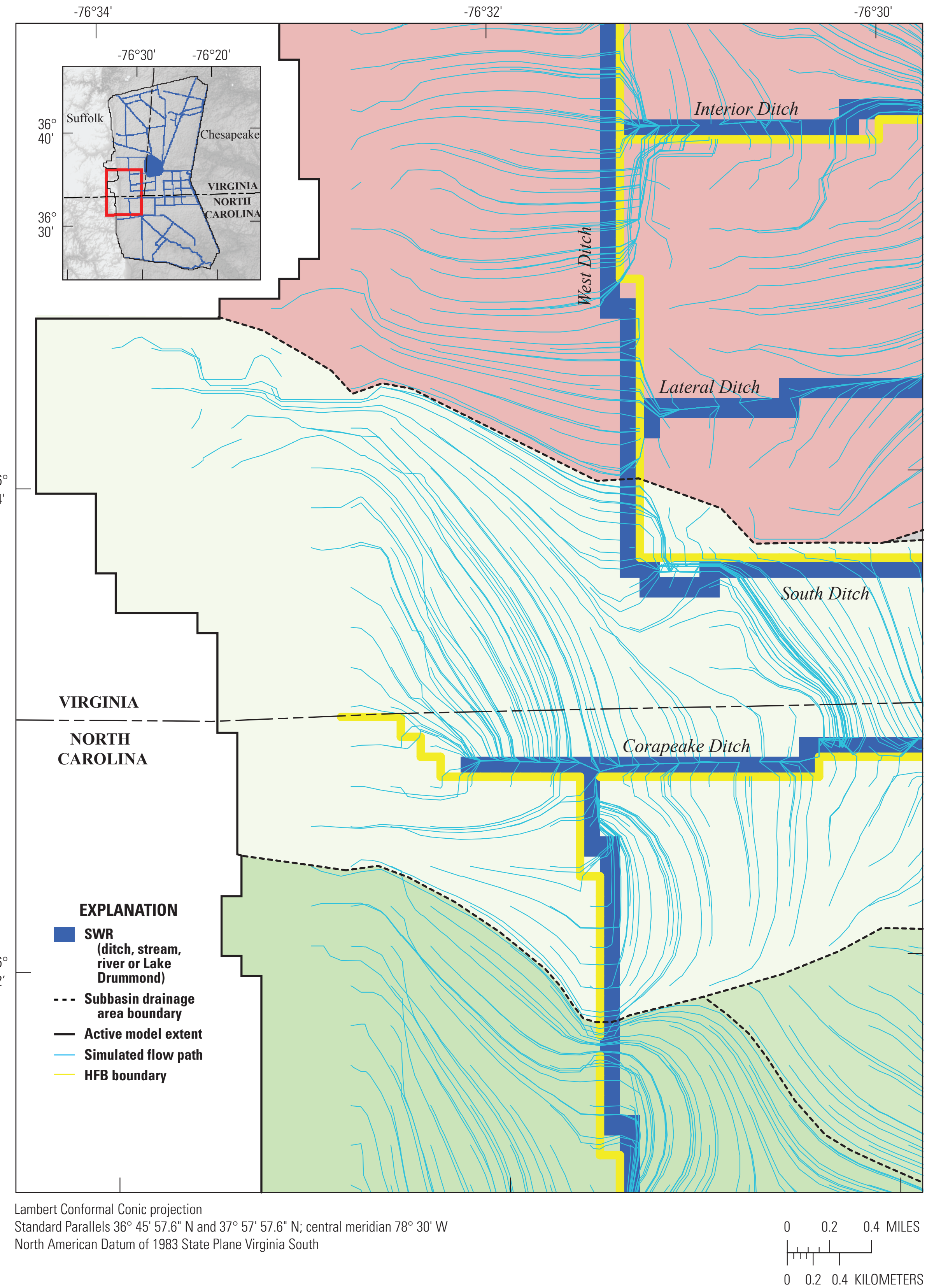


Figure 29. Simulated flow paths at the foot of the scarp near the intersection of West Ditch and South Ditch, Great Dismal Swamp, Virginia and North Carolina, under baseline conditions, model Scenario 1, of the three-dimensional model. (SWR, surface-water reach simulated with the MODFLOW-SWR1 Process; HFB, Hydraulic Flow Boundary)

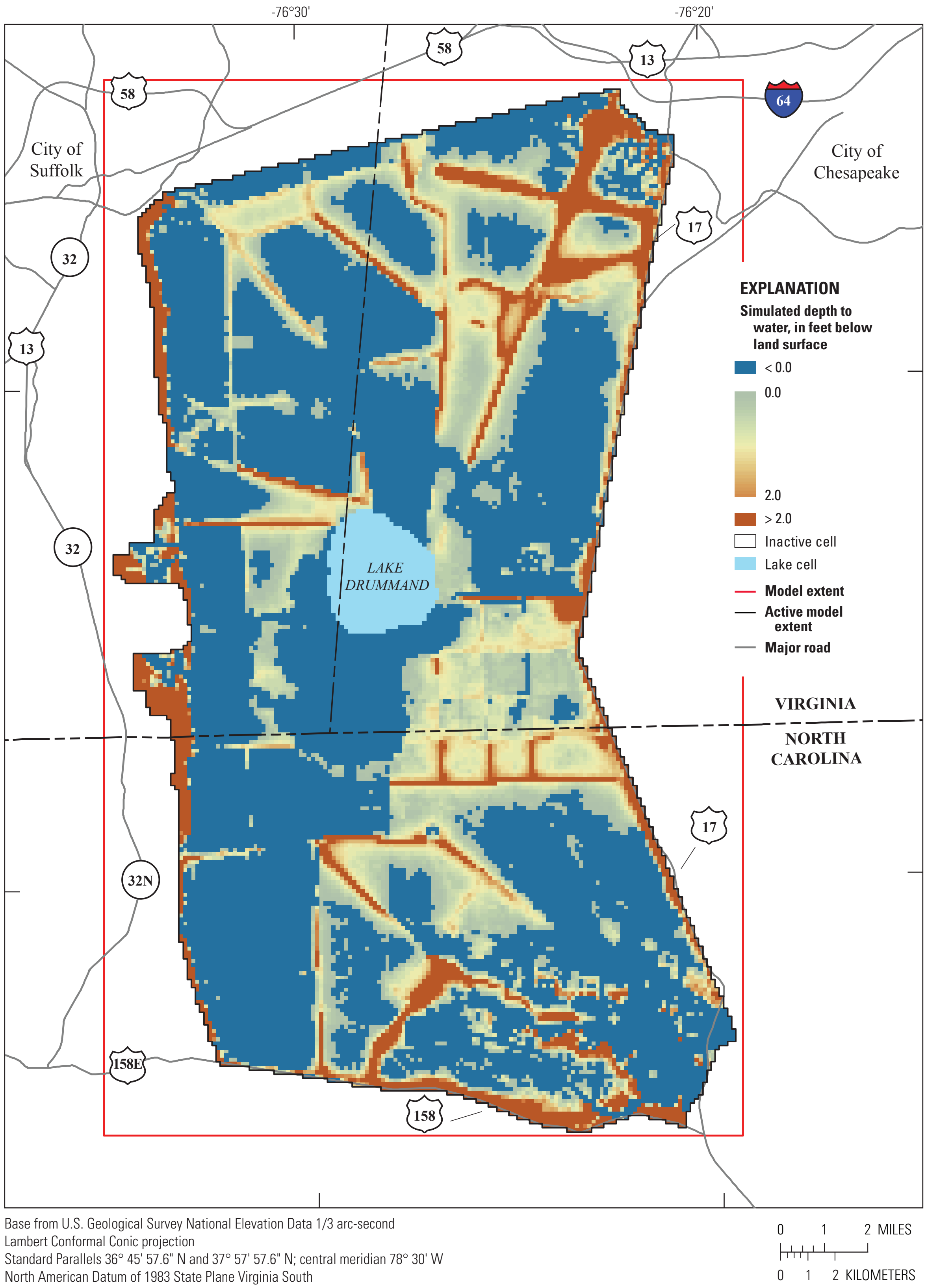


Figure 30. Simulated depth to water table under baseline conditions, model Scenario 1, of the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina.

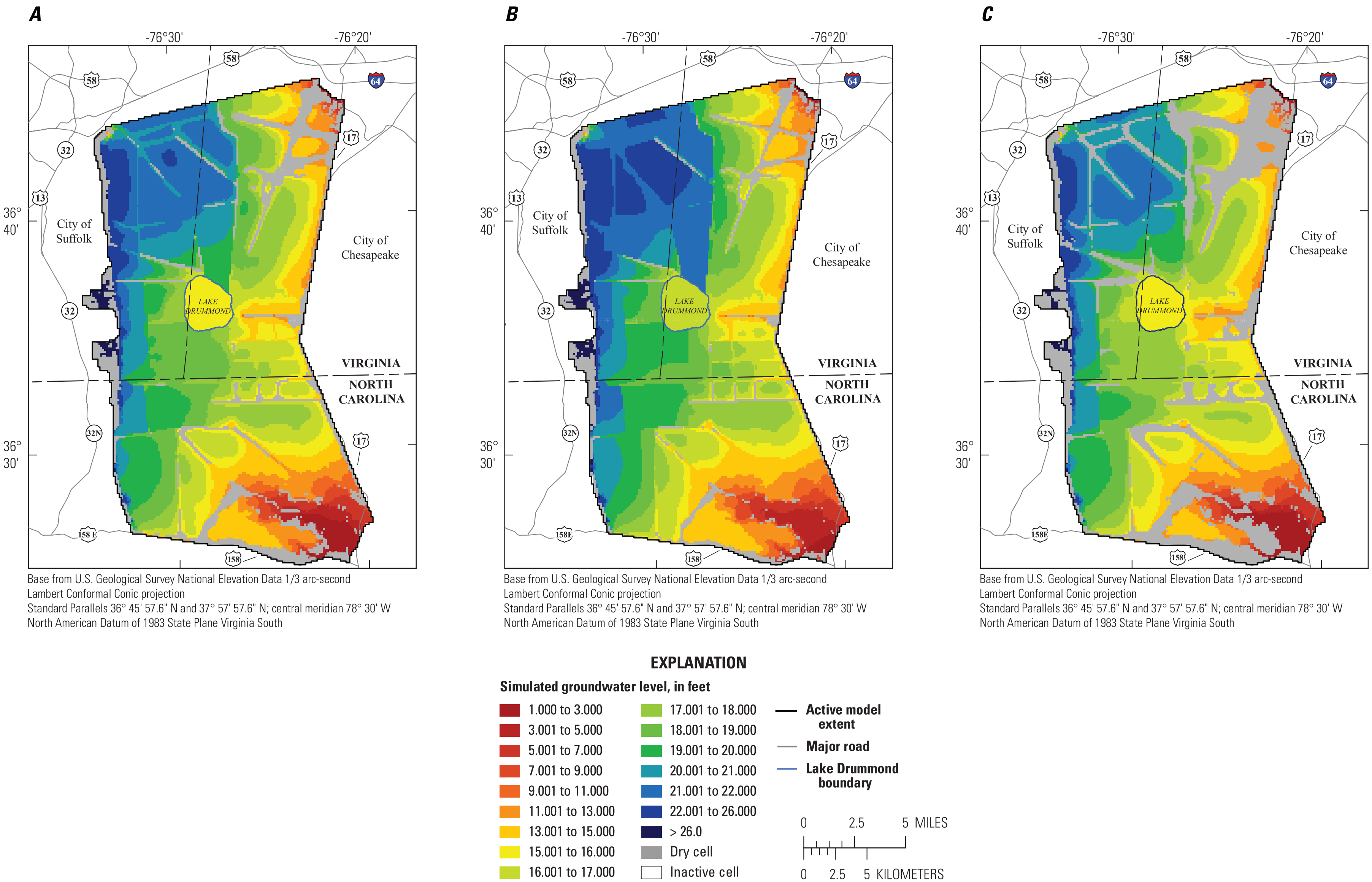


Figure 31. Simulated groundwater levels in model Layer 4 of the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina, under *A*, baseline (model Scenario 1), *B*, wet (model Scenario 2), and *C*, dry (model Scenario 3) climatic conditions.

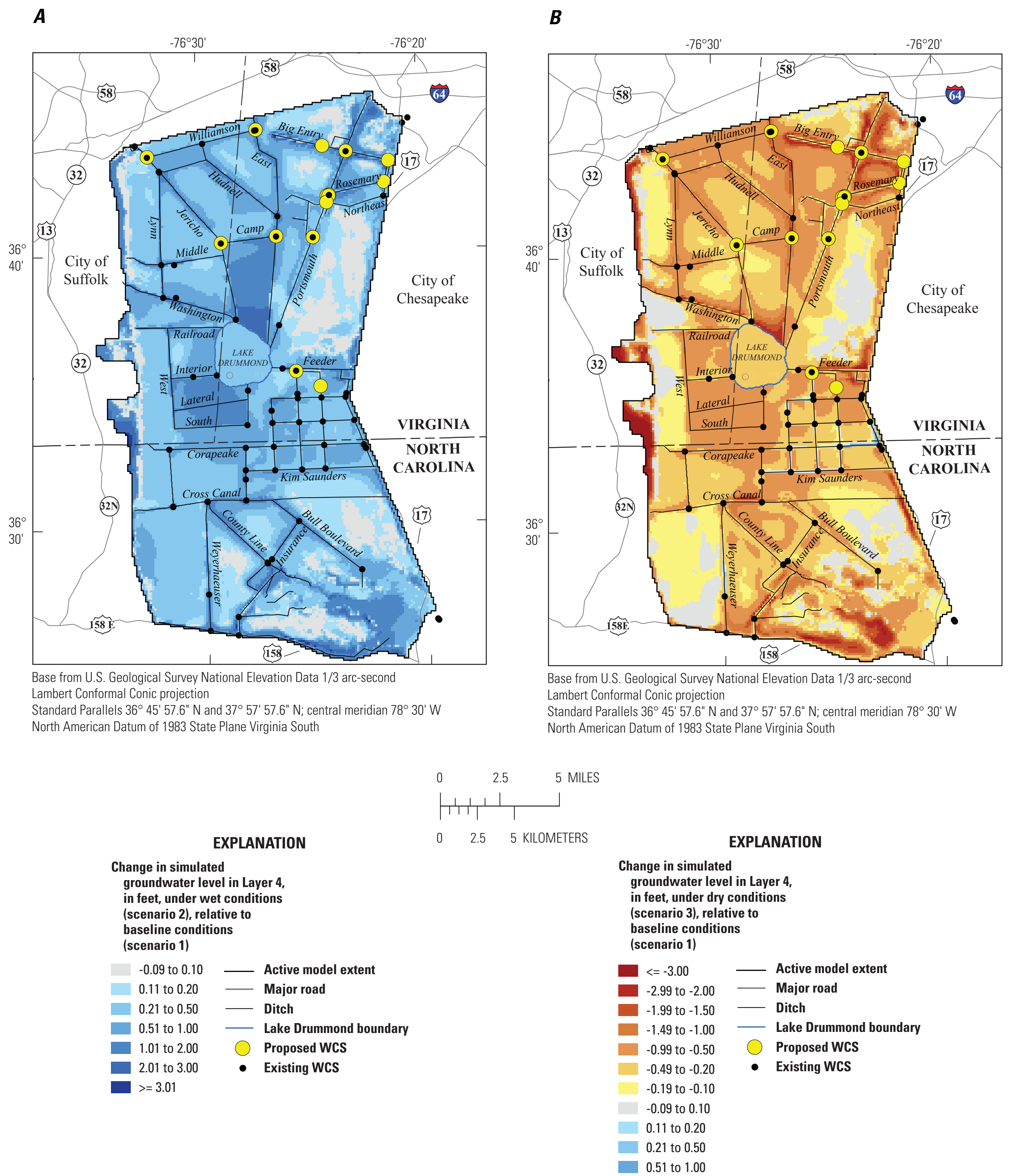


Figure 32. Change in simulated groundwater levels relative to baseline conditions for *A*, wet conditions (model Scenario 2 levels minus Scenario 1 levels) and *B*, dry conditions (model Scenario 3 levels minus Scenario 1 levels) from the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (WCS, water control structure)

for Scenarios 2 and 1 (table 18). The WCS at the intersection of Bull Boulevard Ditch and Insurance Ditch has a simulated flow increase from 0 to 6.9 cubic feet per second.

Simulated groundwater levels are lower under dry climatic conditions (Scenario 3, fig. 31*C*) than under average conditions (Scenario 1, fig. 31*A*), with the greatest groundwater-level decreases seen adjacent to ditches, to the north and west of Lake Drummond, and along the Pasquotank River (fig. 31*B*). Simulated groundwater levels are lower under dry conditions, despite higher weir levels being assigned at many WCSs to simulate the Refuge practice of adding stop logs to raise water levels during dry conditions. Under dry climatic conditions, 9,799 model cells, or 56,238 acres, which are at least partially saturated under average conditions, become unsaturated as a result of falling groundwater levels. Model cells that remain saturated have a simulated mean groundwater level decrease of 0.44 ft. In a comparison of Scenarios 3 and 1, simulated flow decreased by an average of 56 percent at major WCSs (table 18).

Water Management Simulation Results

The Refuge has expanded its ability to manage water levels in recent years (2010–16) by installing additional WCSs with adjustable weirs. An important goal for the hydrologic simulation model is to serve as a tool to improve the Refuge staff's understanding of how different weir level settings in the Refuge affect water levels and flows and to help guide Refuge management decisions about installation of additional WCSs. To understand how changing weir levels and adding WCSs could affect Swamp hydrology, five model scenarios were simulated (Scenarios 4–8) with various WCS weir settings under wet and dry climatic conditions (table 16).

Simulation of Proposed Water Control Structures

New WCSs proposed for construction in the Swamp were added to the model in Scenario 4 (table 1, figs. 12 and 33). Eight new WCSs were added, and eight existing WCS were modified in the model with new weir elevations corresponding to proposed changes. The locations and weir levels for the new and modified WCSs were provided for the study by Refuge staff. Higher weir levels and additional WCSs were added in Scenario 4; otherwise, the model was unchanged from the average baseline conditions (Scenario 1).

The changes to WCSs cause simulated water levels and flows to change relative to the baseline conditions (Scenario 4 – Scenario 1) (fig. 33). Surface-water levels increase in most ditches in the north with the exception of East Ditch, and adjacent groundwater levels also increase (fig. 33). Raising groundwater water levels in the northeastern part of the study area is a management goal for the Refuge, and simulation results indicate the proposed WCSs will achieve that goal. The simulated groundwater budget also changes relative to the baseline with more discharge to ditches (+0.6 percent), more recharge to groundwater from ditches (+7.2 percent), more water lost to ET (+0.2 percent), and less groundwater discharge to tidal stream boundaries (-0.6 percent).

Simulated surface-water flows under the proposed new WCSs (Scenario 4) and assigned higher weir levels both increase and decrease relative to the baseline (Scenario 1). More surface-water flow exits the Swamp from Portsmouth

Table 18. Simulated flow rates at major water control structures in Great Dismal Swamp, Virginia and North Carolina, using a three-dimensional model.

[All flows are measured in cubic feet per second. WCS, water control structure; Blvd, boulevard; --, no data]

Description of Flow	WCS Number[1]	Flow rates at WCS under different scenarios							
		1 Baseline	2 Wet	3 Dry	4 Future WCS added	5 Flood the swamp, wet	6 Flood the swamp, dry	7 Drain the swamp, wet	8 Drain the swamp, dry
Canal discharge at South Mills Lock	70	111.7	216.0	50.4	89.1	190.9	40.8	213.0	53.5
Canal discharge at Deep Creek Lock	1	111.3	209.0	53.3	93.7	214.5	46.2	213.1	56.9
Portsmouth Ditch discharge to Big Entry Ditch	6	24.2	49.5	11.2	34.4	60.4	17.6	25.0	6.2
Jericho Ditch discharge to Shingle Creek	4	20.4	38.6	8.6	24.5	51.0	10.1	48.3	7.6
Big Entry Ditch discharge towards Canal	8	1.0	1.9	0.5	1.2	4.8	0.7	1.9	0.5
Weir 1 discharge to Martha Washington Ditch	47	39.9	61.7	12.4	24.2	--	--	88.0	24.3
Lake Drummond discharge to Feeder Canal	28	110.5	216.3	60.4	86.3	168.1	45.2	201.0	61.4
Bull Blvd Ditch discharge to Insurance Ditch	62	--	6.9	--	--	--	--	2.9	0.0
County Line Ditch discharge towards the Pasquotank River	65	29.3	82.0	7.8	46.8	14.1	--	132.9	23.5
Newland Dike Ditch discharge to 158 Ditch	72	1.4	2.3	1.0	1.4	2.2	1.0	2.3	1.0

[1]WCS number shown in figure 12.

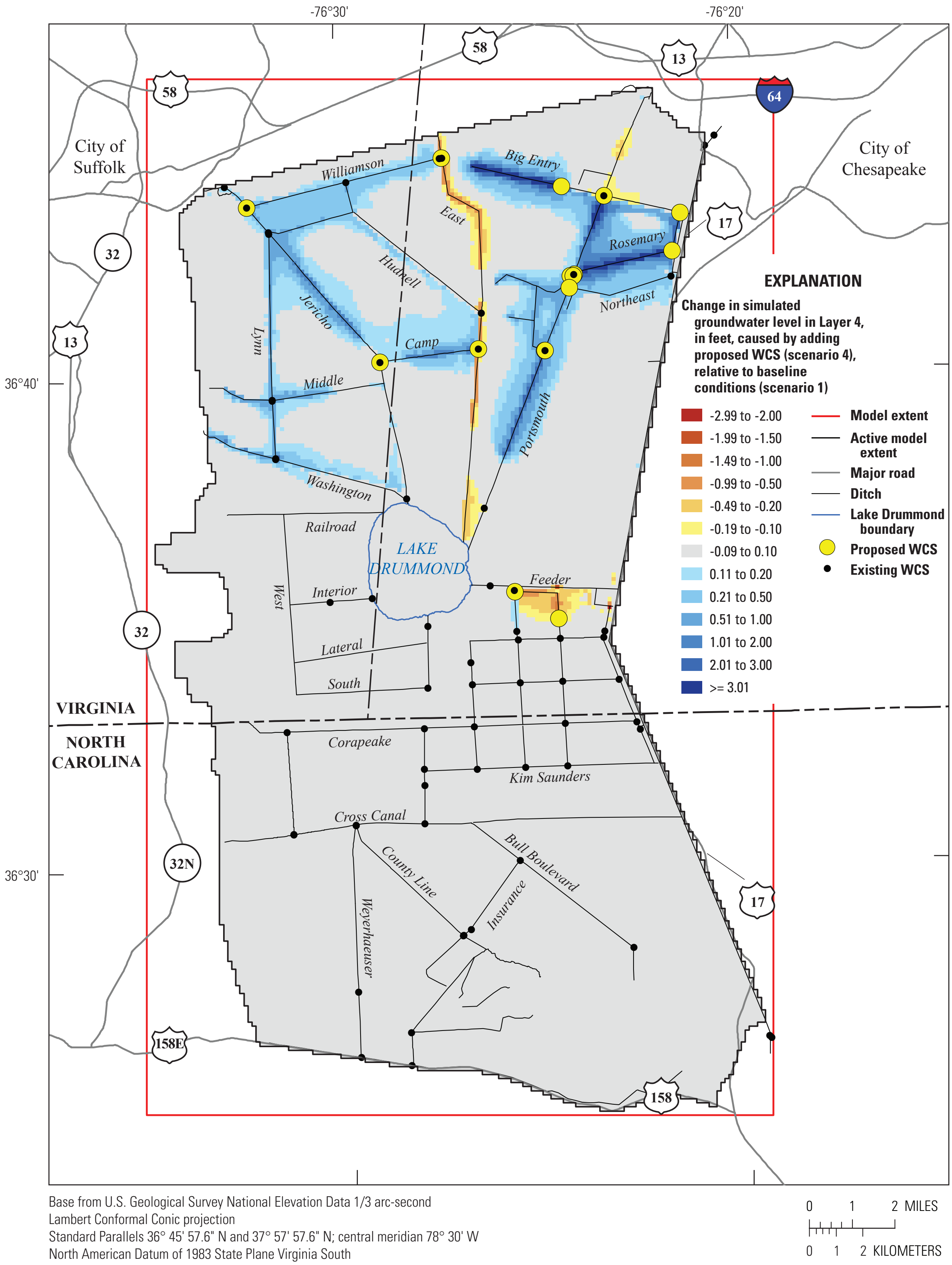


Figure 33. Changes in simulated groundwater levels caused by the addition of proposed water control structures and raising of weir levels at existing water control structures (model Scenario 4 levels minus Scenario 1 levels) from the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (WCS, water control structure)

Ditch (+49.5 percent) and Jericho Ditch (+44.1 percent), whereas less flow exits the Dismal Swamp Canal at South Mills (-12.6 percent) and Deep Creek (-10.4 percent) (table 18).

Flood the Swamp Wet/Dry

In model Scenarios 5 and 6, weir levels are raised to their highest possible elevations at all WCSs, including proposed structures. Such a hypothetical management action would be carried out in practice by adding stop logs and closing screw gates, generally raising ditch water levels as high as possible. These management actions are not expected to occur in practice, and the model scenario was simulated to evaluate the maximum limit of WCS effects on hydrologic conditions in the Swamp. Raising weirs to their highest possible levels is simulated under wet conditions (Scenario 5) and under dry conditions (Scenario 6).

Under wet conditions, extreme maximum weir levels (Scenario 5) increase simulated spring surface-water levels and groundwater levels relative to standard weir levels (Scenario 2). Groundwater levels in active cells rise by an average of 0.28 ft, and the land surface is inundated in an additional 3,103 cells, equivalent to 17,809 acres (fig. 34*A*). Under dry conditions, extreme maximum weir levels (Scenario 6) increase simulated spring surface-water levels and groundwater levels relative to those for standard weir levels (Scenario 3). Groundwater levels in active cells rise by an average of 0.19 ft, and the land surface is inundated in an additional 5,526 cells, equivalent to 31,715 acres (fig. 34*B*). Under wet and dry conditions (Scenarios 5 and 6), flows mostly increase slightly relative to those for standard weir levels (Scenarios 2 and 3) at WCSs north of Lake Drummond and decrease slightly at WCSs from Lake Drummond to the south (table 18). This is likely caused by increased weir levels on Portsmouth, East, and Jericho Ditches (WCS 18, 19, 20, and 21 in fig. 12) that retain more water in the north and reduce flows south toward Lake Drummond.

Drain the Swamp Wet/Dry

Weir levels are lowered to their lowest possible elevations at all WCSs, including proposed structures, in model Scenarios 7 and 8. Such a hypothetical management action would be carried out in practice by removing all stop logs and opening all screw gates, generally lowering ditch water levels as much as possible. These management actions are unlikely to occur in practice, and the model scenario was included primarily to evaluate what might occur if the WCSs are managed to actively drain the Swamp during either wet or dry climatic conditions. Lowering weirs to their lowest possible levels under wet conditions is simulated in Scenario 7 and under dry conditions in Scenario 8.

Under wet conditions, extreme minimum weir levels (Scenario 7) decrease simulated spring surface-water levels and groundwater levels relative to those for standard weir levels (Scenario 2). Groundwater levels in active cells fall by an average of 0.17 ft, and water levels drop below land surface (surface no longer inundated) in 2,177 cells, or 12,494 acres, compared to standard weir levels (fig. 35*A*). Under dry conditions, extreme minimum weir levels (Scenario 8) decrease simulated surface-water levels and groundwater levels relative to those for standard weir levels (Scenario 3). Groundwater levels in active cells fall by an average of 0.22 ft, and water levels drop below land surface (surface no longer inundated) in 1,072 cells, or 6,152 acres (fig. 35*B*).

Imposing extreme low weir levels (Scenarios 7 and 8) increases and decreases flows (table 18) at major WCSs relative to flows for standard weir levels (Scenarios 2 and 3). The largest flow changes under wet conditions are decreases in Portsmouth Ditch discharge to Big Entry Ditch (WCS 6), decreases in Lake Drummond spillway discharge to the Feeder Ditch (WCS 28), and increases in Weir 1 and County Line Ditch discharges to the Pasquotank River (WCSs 47 and 65). These changes are caused by the interplay of various factors, including altered ET fluxes caused by changes in water-table depths, reduced base levels at the downstream ends of ditches, and changes in directions and rates of flow in ditches and in the aquifer. The distance to which groundwater levels change in response to changes in ditch water levels depends on the distance from the ditch, the magnitude of water-level changes in the ditch, and the presence of other nearby ditches.

Model Limitations

Users need to be aware that the hydrologic model has limitations and provides an imperfect representation of Swamp hydrology. Model limitations are caused by spatial and temporal discretization, boundaries, and inaccuracies associated with parameterization and assignment of parameter values. The model does not simulate hydrology outside the horizontal boundaries of the active model area (fig. 2) or to depths below land surface of about 25 ft in most areas. Although groundwater flow rates below the 25-ft depth are expected to be very small relative to flow above the 25-ft depth, as discussed in the “Groundwater Levels and Flow Patterns” section, the chosen depth of the active model does affect simulations of deeper flow, such as groundwater flowing under ditches, and ignores any possible interactions with the deeper regional groundwater-flow system. Because the model cells are 500 ft on a side, the model cannot simulate variability in water levels or flows at resolutions less than 500 ft.

Land-surface elevation assignments in the model affect simulated groundwater and surface-water levels, which can introduce simulation errors. Assignment of a single land-surface elevation to each 500-ft model cell contributes to these errors because the actual land-surface elevation has variability within each model cell. Assigned land-surface elevation values in the model represent lower land-surface elevations, such as depressions between trees, rather than the higher land-surface elevations, such as hummocks surrounding trees. Bias can

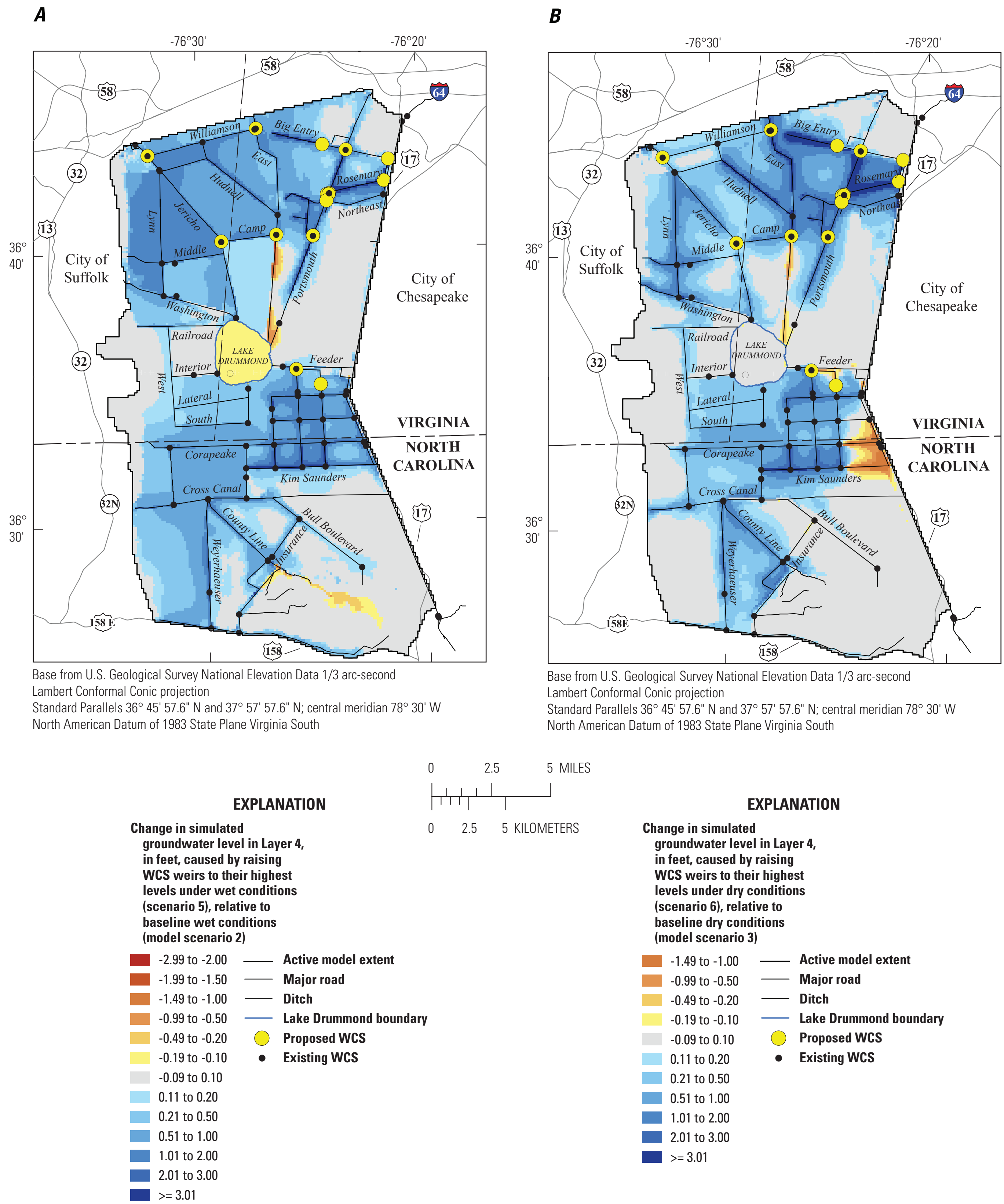


Figure 34. Changes in simulated groundwater levels caused by raising weir levels to their highest possible elevations at existing and proposed water control structures under *A*, wet conditions (model Scenario 5 levels minus Scenario 2 levels) and *B*, dry conditions (model Scenario 6 levels minus Scenario 3 levels) in the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (WCS, water control structure)

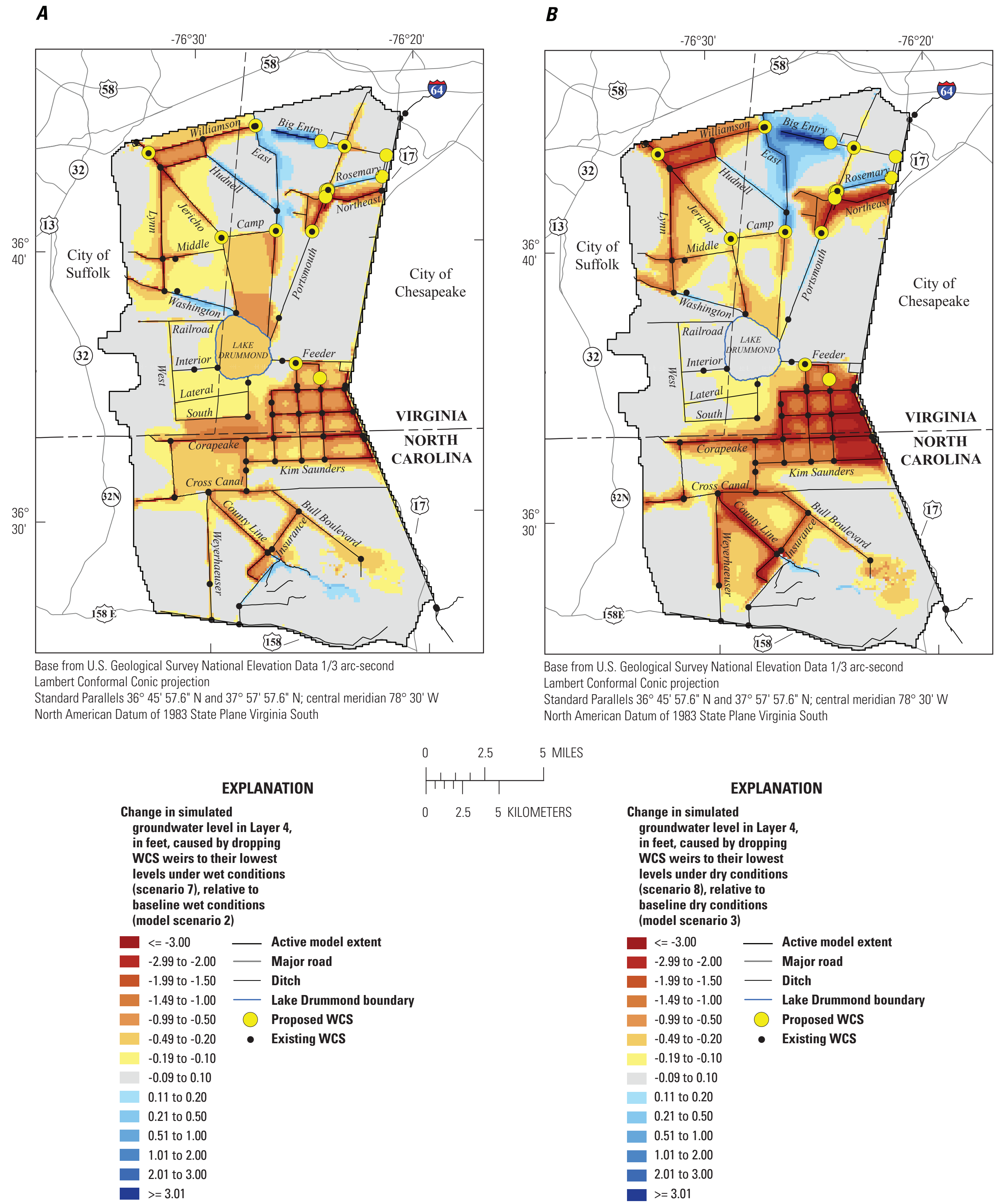


Figure 35. Changes in simulated groundwater levels caused by lowering weir levels to their lowest possible elevations at existing and proposed water control structures under *A*, wet conditions (model Scenario 7 levels minus Scenario 2 levels) and *B*, dry conditions (model Scenario 8 levels minus Scenario 3 levels) of the three-dimensional model of Great Dismal Swamp, Virginia and North Carolina. (WCS, water control structure)

be expected when comparing simulated depth to water with actual depth to water, unless observations are made at low points and not on the top of hummocks. Depth to the water table is important in the model because it affects simulated ET.

Because the model is steady-state rather than transient, it has the limitation of being unable to simulate hydrologic changes over time. For example, seasonal fluctuations in water-table elevations or flows resulting from a storm cannot be simulated with the steady-state model. Actual hydrologic conditions in the Swamp are constantly changing as climatic conditions change, and the system adjusts to these changes. The simulations of hypothetical wet and dry conditions performed in this study do not represent actual conditions in spring 2011 or 2015, respectively, but rather hypothetical dry and wet climatic conditions imposed for an indefinite length of time. The model is designed so that, in the future, it can be readily updated to be capable of simulating transient conditions.

Assigning recharge equal to 100 percent of observed precipitation and then relying on the EVT package to remove water is appropriate for the setting of the study area but can introduce error, namely overassignment of net recharge, if the water table is deeper than 8.86 ft and therefore below the extinction depth and unavailable to the ET boundary condition. Results for all eight of the model scenarios, presented in the "Simulated Hydrology and Water Management" section, indicate that from 0.9 percent to 1.3 percent of active model cells have water-table depths greater than 8.86 ft. Nearly all of those cells are located along the western boundary where land-surface elevations are higher along the scarp than elsewhere. For the scenarios studied here, the potential for over-assignment of net recharge does not outweigh the benefits of the approach used to assign recharge and ET. However, the user needs to be aware of the approach when simulating conditions where the water table is more than 8.86 feet below the land surface over much of the study area and may want to consider using alternate assignment of recharge and ET.

Summary and Conclusions

In a study conducted by the U.S. Geological Survey, in cooperation with the U.S. Fish and Wildlife Service (USFWS), a three-dimensional numerical model based on MODFLOW-NWT and the Surface Water Routing Process was developed to simulate groundwater and surface-water in the Great Dismal Swamp (Swamp) of Virginia and North Carolina. Development of the numerical model has led to improved understanding of hydrology in the Great Dismal Swamp and provides a tool to assist USFWS National Wildlife staff who manage water in the Swamp. The model simulates historical average spring hydrologic conditions for the years 2005 through 2015. Calibration results indicate that the model provides a reasonable representation of average spring hydrologic conditions in the study area. Simulated heads and flows are most sensitive to model parameters controlling evapotranspiration rates and to Manning's roughness coefficients, which control frictional head loss in ditches.

Simulation results show that hydrologic input to the Swamp is dominated (92%) by precipitation. More than one-half of simulated outflow from the Swamp is through evapotranspiration, and the remainder is mostly surface-water discharge. Ditches capture most groundwater flow, although that simulated result likely depends on the assigned layer thicknesses in the model.

Simulations of water-management scenarios can be used by Refuge staff to inform their water-management decisions. Raising weir levels can be used to suppress fires in the Swamp; model results indicate that raising all weirs from their standard levels to their highest levels under dry conditions will inundate an additional 31,709 acres, equivalent to 21 percent of the active model area. Raising weir levels during wet conditions provides only a small amount of water retention capacity in the context of preventing flooding during large rainfall events. Model results indicate that 0.28 feet (ft) of water can be stored by raising all weirs, including proposed water control structures (WCSs), to their highest levels. This is considered a high-end estimate because simulation results are for steady-state conditions, whereas actual conditions require some time (perhaps weeks or months) for groundwater in interior areas of the Swamp to fully respond to changes in weir levels.

The three-dimensional model can be used to simulate additional water management scenarios besides those studied and presented in this report. The model could also be quite useful for analyzing time varying hydrologic conditions if future work was done to make the model transient. For example, the fraction of time that the land surface was inundated could be simulated and used to inform decisions about forest management within the Swamp.

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For additional information, contact:
Director, Virgina Water Science Center
U.S. Geological Survey
1730 East Parham Road,
Richmond, VA 23228

or visit our website at:
http://va.water.usgs.gov/

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