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Water-Resources Investigations Report 96–4277

Hydrology and Tree-Distribution Patterns of Karst Wetlands at Arnold Engineering Development Center, Tennessee

Prepared by the
United States Geological Survey

in cooperation with the
United States Air Force,
Arnold Engineering Development Center

Cover photograph: Flooded interior of Sinking Pond. Photograph by W.J. Wolfe.

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BY WILLIAM J. WOLFE

United States Geological Survey

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Prepared in cooperation with the
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Nashville, Tennessee
1996

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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
millimeters (mm)	0.0397	inch
centimeter (cm)	0.3937	inch
meter (m)	3.28084	foot
kilometer (km)	0.621504	mile
square kilometer (km^2)	0.3861	square mile
cubic meter per second (m^3/s)	0.0283	cubic foot per second
degree Celsius (°C)	([1])	degree Fahrenheit (°F)

[1]Temp °F=1.8 temp °C+32.

Sea level and water level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic reference datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Well-numbering system: The U.S. Geological Survey assigned each well in this report a local well number and a station identification number. The local well number is used as a concise label for a well. The station identification number is used as an identifier for site data stored in the national computer system of the U.S. Geological Survey. These numbering systems are used in addition to the well numbers assigned by Arnold Engineering Development Center.

The local well number in Tennessee consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7.5-minute quadrangle on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. For example, the local well number Cf:G-067 indicates that the well is located in Coffee County on the "G" quadrangle and is identified as well 67 in the numerical sequence. Quadrangles are lettered from left to right, beginning at the southwest corner of the county.

The station identification number is a unique number for each well based on latitude and longitude. The number consists of 15 digits. The first 6 digits denote degrees, minutes, and seconds of latitude; the next 7 digits denote degrees, minutes, and seconds of longitude; and the last 2 digits sequentially identify wells within a 1-second grid.

Hydrology and Tree-Distribution Patterns of Karst Wetlands at Arnold Engineering Development Center, Tennessee

By William J. Wolfe

Abstract

Flooding regimes, ground-water interactions, and tree distribution patterns were determined in seasonally flooded sinkhole wetlands at Arnold Engineering Development Center near Manchester, Tennessee. The wetlands are ecologically significant because they support coastal-plain plants and animals far from their typical ranges.

Surface-water stage, ground-water levels, rainfall, and streamflow were monitored at or near five wetland sites. Sinking Pond, Willow Oak Swamp, and Westall Swamp are compound sinks with depths greater than 2.5 meters, visible internal drains, and complex bottom topography dominated by coalesced sinkholes and connecting channels. Tupelo Swamp and Goose Pond are karst pans with depths less than 1.5 meters, flat bottoms, and without visible internal drains. Stage rose and fell abruptly in the compound sinks. Maximum water depths ranged from 2.6 meters in Westall Swamp to 3.5 meters in Sinking Pond. Water levels in wells adjacent to Sinking Pond and Westall Swamp rose and fell abruptly, corresponding closely to surface-water stage throughout periods of high water. The two karst pans filled and drained more gradually, but remained flooded longer than the compound sinks. The maximum recorded water depths were 1.1 meters in Tupelo Swamp and 0.7 meter in Goose Pond. Water levels in nearby wells remained lower than the stage in the pans throughout the study period. Tree species were identified and the elevations and diameters of individual trees were measured along 10 transects. Two transects crossed Sinking Pond, two crossed Tupelo Swamp, and one crossed Willow Oak Swamp. The remaining five transects crossed intermittent drainageways that carry flow into or out of Sinking Pond. Transects through ponds had fewer trees but more basal area per unit area of land surface than did transects through channels. Water tupelo (*Nyssa aquatica* L.) dominated the interior of Tupelo Swamp and had minimal overlap in terms of elevation and flooding duration with other wetland trees that were confined to the pond's periphery. Overcup oak (*Quercus lyrata* Walt.) dominated the interior of Sinking Pond. Overlap between overcup oak and other wetland trees in terms of elevation and flooding frequency was minimal across the deeper Sinking Pond transect but was substantial across the shallow transect. Willow oak (*Quercus phellos* L.) dominated the interior of Willow Oak Swamp and had a relation to other wetland trees similar to that of overcup oak in the shallow Sinking Pond transect. Transects across broad swales had a relatively large degree of vertical zonation among wetland and upland tree species. Along transects through well defined channels, elevation distributions of wetland and some upland tree species were grouped near each other and near the distribution of land-surface elevations.

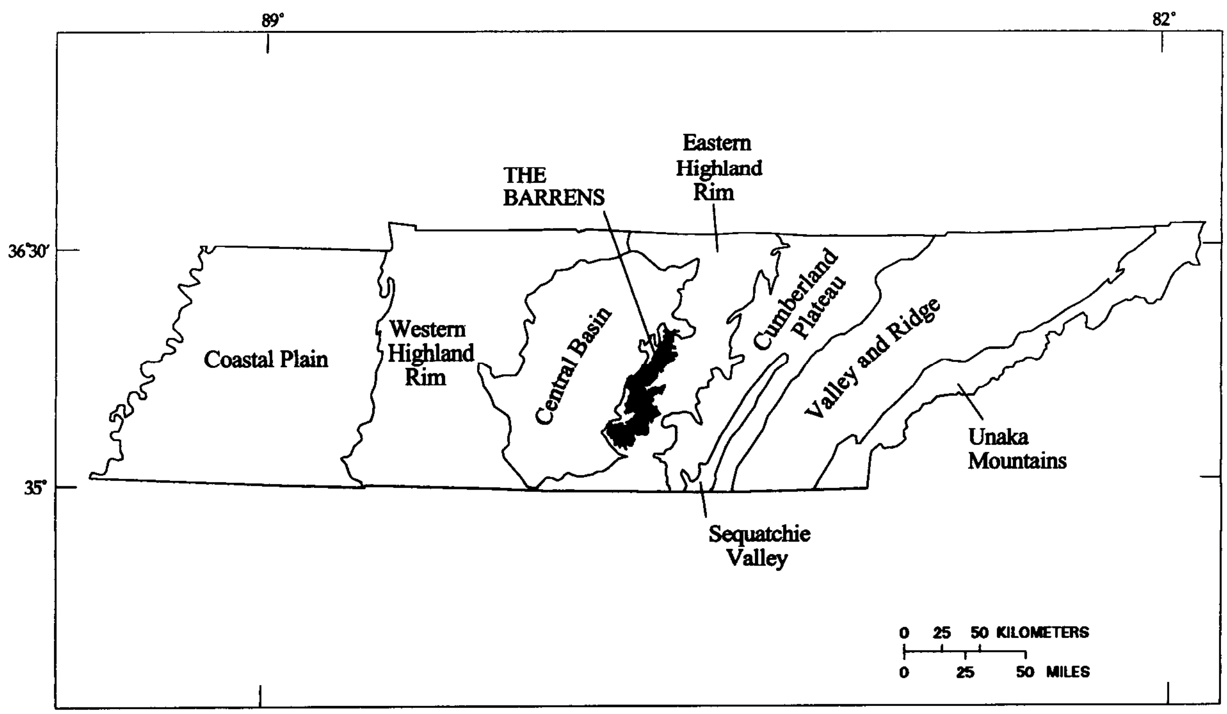
INTRODUCTION

Wetlands within karst landforms are distributed across the unglaciated uplands of the southeastern and south-central United States (Barclay, 1957; Greear, 1967; Ellis and Chester, 1989; Jones, 1989). Southern karst wetlands constitute a small fraction of the regional wetland area compared with the coastal plains and large alluvial valleys (Mitsch and Gosselink,

1993), but they make up a much larger proportion of wetlands within extensive areas underlain by carbonate rocks. Many karst wetlands support northern and coastal-plain plants and animals that are otherwise rare or absent in southern uplands. The ecological significance of karst wetlands is thus disproportionate to their limited area (Killebrew and Safford, 1874; Svenson, 1941; Barclay, 1957; Greear, 1967; Ellis and Chester, 1989; Jones, 1989; Bowen and Pyne, 1995).

One extensive concentration of karst wetlands, known locally as "The Barrens," occurs on the Eastern Highland Rim (fig. 1). Within the context of southern karst wetlands, The Barrens contains an exceptionally rich and diverse assortment of disjunct plants and animals. Disjunct plants have been reported from three distinct ecological regions: the northern Appalachians, the southern Atlantic and Gulf coastal plains, and the northern prairies (Svenson, 1941; Shanks, 1958; Kral, 1973; DeSelm, 1981, 1986, 1989, 1990; Bowen and Pyne, 1995). Recently, several coastal-plain reptiles and amphibians have also been identified (Brian Miller, Middle Tennessee State University, written commun., 1995; Edward Clebsch, University of Tennessee, oral commun., 1995). Disjunct taxa are not distributed evenly across The Barrens, but are highly localized in discrete sites, notably in seasonally flooded karst depressions.

One of the most notable concentrations of well-preserved Barrens wetlands is located in and around Arnold Engineering Development Center (AEDC), an aerospace testing facility operated by the U.S. Air Force near Manchester, Tennessee (fig. 2). The reservation lies within The Barrens and includes about 0.24 square kilometer (km^2) of wetlands. These wetlands include three Registered Natural Landmarks (Sinking Pond, Goose Pond, and the AEDC Powerline Barrens); a fourth (May Prairie) is separated from the reservation boundary by a road (Benham Group, 1989; Bowen and Pyne, 1995). All of these sites and many other wetlands in the area support rare or protected plants and animals including a wide variety of coastal-plain disjuncts (Svenson, 1941; Benham Group, 1989; Patterson, 1989; Bowen and Pyne, 1995). At least 68 rare and endangered plants and animals have been identified at AEDC, most of them in or near karst



Physiographic regions modified from Miller, 1974
The Barrens based on soil data from Soil Conservation Service, 1991

Figure 1. Physiographic regions of Tennessee and location of The Barrens.

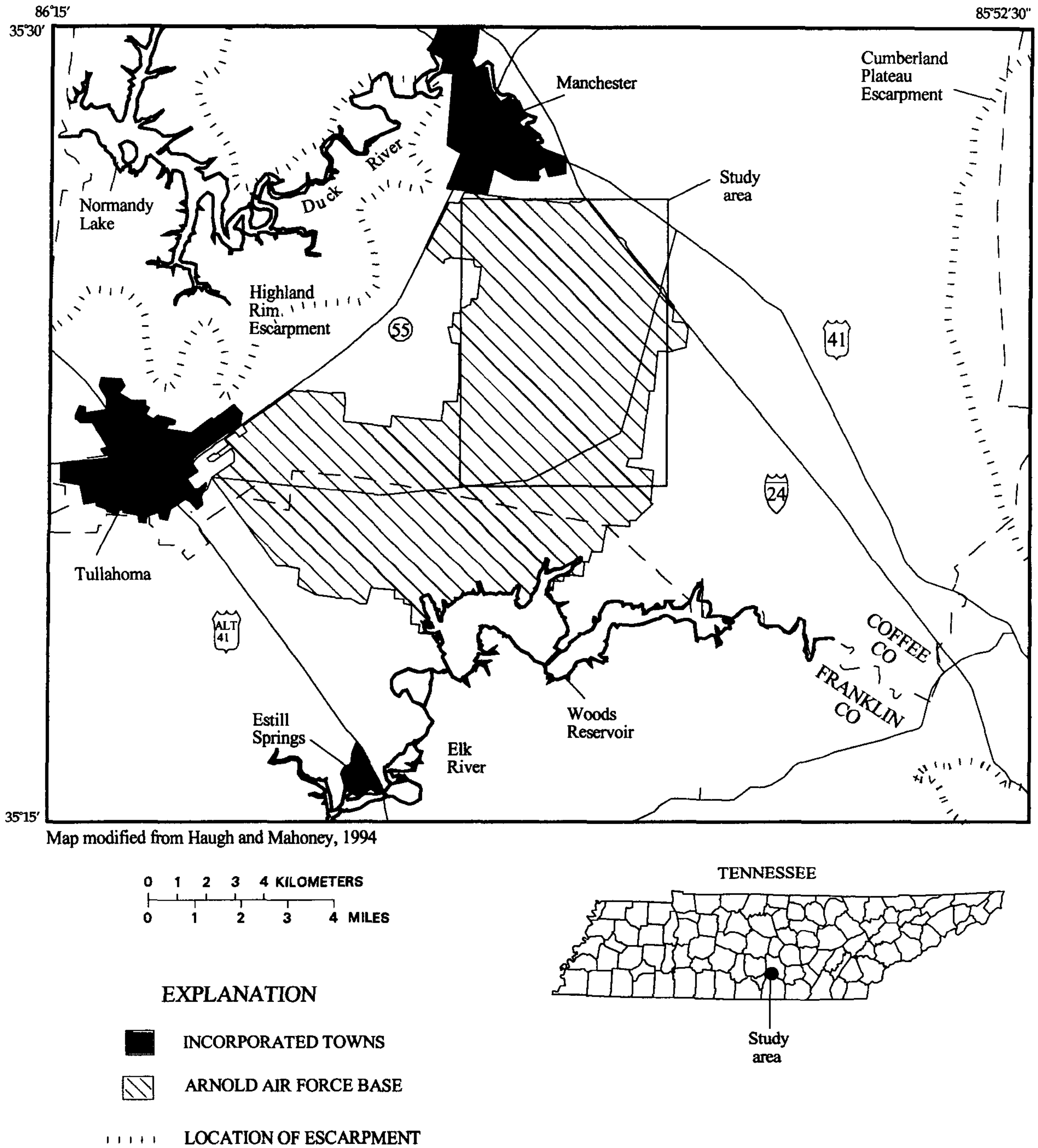


Figure 2. Location of Arnold Engineering Development Center and study area.

wetlands (David Campbell, Tennessee Nature Conservancy, written commun., 1995).

Balancing the goals of protecting natural resources with the mission of an active military facility requires a detailed knowledge of environmental factors that affect ecologically sensitive sites. In the case of karst wetlands, understanding the interactions among geomorphic characteristics, flooding patterns, and plant distribution is critical for effective natural resource management and protection. In order to develop such an understanding, the U.S. Geological Survey, in cooperation with the U.S. Air Force, conducted a study of the geomorphic features, hydrology, and tree-distribution patterns of several karst wetlands at AEDC.

Purpose and Scope

This report describes the results of the hydrologic study at AEDC. The technical scope of the report includes field observations of geomorphic features, hydrologic processes and tree-species distribution and continuous or periodic monitoring of precipitation, surface- and ground-water levels, and streamflow. Specific objectives are:

1. Describe typical geomorphic features associated with karst wetlands at AEDC.
2. Determine the relation between wetland water regimes and ground-water system among karst wetland sites with contrasting vegetation and sinkhole morphology.
3. Characterize the distribution of tree-species within karst wetlands with different geomorphic and hydrologic characteristics and along the transitions between such wetlands and well-drained uplands.

Acknowledgments

The staff at Arnold Engineering Development Center played a central role in this study from its inception through its conclusion. The support and assistance of Clark Brandon, Dennis Flatt, and Mark Moran are gratefully acknowledged. William Patterson of Louisiana State University generously shared his intimate knowledge of the soils and vegetation of the Sinking Pond area, including a strenuous week in the field. David Campbell and Robert Brown of the Tennessee Nature Conservancy and Milo Pyne, Tennessee Department of Environment and Conservation, assisted with plant identification. Professor Laurence Lewis of Clark University, Dr. Virginia Carter of the U.S. Geological Survey Wetlands Research Program, and Dr. L. Katherine Kirkman of the J.W. Jones Ecological Research Center reviewed early drafts of this report and provided numerous helpful comments. Bradley Bryan and Timothy Diehl of the U.S. Geological Survey were active in site reconnaissance and planning the investigation. Along with Donald League and Ronald Kemp, they also provided invaluable assistance in the field.

Study Area

AEDC occupies an area of about 160 km^2, of which about 10 percent is developed for industrial activities. The remainder is managed for multiple uses, including wildlife, forestry, and agriculture (Benham Group, 1989). The study area straddles the divide between the Duck and Elk River drainage basins and typifies the low-relief upland topography of The Barrens (Burchett, 1977; Smalley, 1983). Surface drainage networks are weakly to moderately well developed, with a high proportion of seasonally flowing streams. Many of these streams flow into or out of seasonally flooded sinkholes. Ridges are typically broad and relatively flat or gently undulating. The ridgetops are generally well drained but commonly contain small, shallow depressions with poor drainage. The elevation difference between headwater-valley bottoms and the tops of adjacent ridges rarely exceeds 20 meters (m). Valley side-slope gradients typically range from 5 to 15 percent.

Karst Features

Sinkholes—closed karst depressions with depth less than diameter (White, 1988)—and other karst landforms are common features at AEDC and elsewhere in The Barrens. In comparison with the Pennyroyal Plateau (White and others, 1970) in southern Kentucky or the base of the Cumberland Plateau in Tennessee (White and White, 1983), karst features in The Barrens have low relief and subtle surface expression. A few sinkholes are deeper than 3 m, but most are less than 2 m deep.

At AEDC, wetlands occur in two distinct types of karst depressions—karst pans and compound sinks (Wolfe, 1996). Karst pans are shallow, flat bottomed depressions with diameters ranging from 2 m to greater than 100 m and depths less than 1.5 m (fig. 3).

Figure 3. A karst pan in the Sinking Pond area.

The pans lack visible internal drains, but commonly have well-developed overflow channels. A few pans drain areas as large as 0.2 km^2, but most have much smaller drainage areas or are situated at intermittent stream heads atop flat ridges. Most pans at AEDC support wet forests of willow oak, sweetgum, black tupelo, or red maple, but several support rare or disjunct plants. For example, Goose Pond supports numerous rare herbaceous plants (Benham Group, 1989), and a karst pan north of Sinking Pond contains a locally rare stand of water tupelo (Wolfe, 1996). The wetland vegetation in many small ridge-top pans contrasts sharply with the surrounding upland vegetation.

Compound sinks are relatively large, steep-sided depressions that include several discrete or coalesced sinkholes. The largest compound sink at AEDC is the main body of Sinking Pond. Other examples include a tributary basin northwest of Sinking Pond and the northern part of Westall Swamp. Diameters of these depressions range from about 50 m to greater than 500 m. Overall depths are generally greater than 3 m. Compound sinks are distinguished by complex internal drainage networks and intermittent surface outlets. Typically, the internal drainage networks consist of elongated or coalesced sinkholes connected by well-defined channels (fig. 4). Other karst features at AEDC include small, well-drained sinkholes on slopes and ridges, vertical shafts as deep as 7 m, and slope-break springs (Wolfe, 1996).

Soils, Vegetation, and Climate

Soils belong to the Dickson-Mountview-Guthrie soil association and consist chiefly of Ultisols developed on a thin (<1.5 m), silty mantle overlying cherty limestone residuum (Love and others, 1959; Springer and Elder, 1980; Smalley, 1983; Patterson, 1989). The Dickson silt loam and Mountview silt loam are the most important soils on well-drained slopes and ridges. Both of these soils are strongly to very strongly acid, moderately permeable in their surface horizons, and low in fertility; they differ primarily in that the Dickson soil has a discontinuous fragipan (relatively impermeable layer) at the base of the silty upper mantle (Love and others, 1959).

The Guthrie silt loam is the characteristic soil of headwater wetlands in The Barrens. This soil is developed on parent materials similar to those of the Dickson and Mountview soils and contains a discontinuous fragipan. It is strongly to very strongly acid and low in fertility. The Guthrie silt loam differs from the Dickson silt loam primarily in its poor drainage and landscape position. The most extensive occurrences of Guthrie silt loam occupy the bottoms of intermittent headwater streams and sinkholes. Small patches of

Figure 4. The internal drainage system of a compound sink northwest of Sinking Pond. Dark moss lines at the bases of trees mark normal seasonal high water level.

this soil occur as wet inclusions within the Dickson silt loam and other upland soils on ridgetops. Other soils within the association are the moderately well-drained Sango silt loam and the somewhat poorly-drained Taft (formerly Lawrence) silt loam (Love and others, 1959; Patterson, 1989).

Vegetation is generally correlated with topography, drainage, and soil (Patterson, 1989). Well-drained ridges and slopes support deciduous trees such as scarlet oak, southern red oak, and mockernut hickory, except where cleared or planted in pines. Moister, moderately well-drained slopes are characterized by white oak, hornbeam, sourwood, and yellow poplar. The vegetation of poorly drained sites commonly includes sweetgum, black tupelo, red maple, and willow oak. Some of the wettest sites support stands of coastal-plain trees such as overcup oak, and water tupelo (Benham Group, 1989; Patterson, 1989). Other poorly drained sites are occupied by emergent herbaceous vegetation and shrubs (Benham Group, 1989).

Long-term weather records for Tullahoma, Tennessee, near the southwest boundary of AEDC, are representative of average conditions in the study area. Mean annual precipitation is 1,438 millimeters (mm). Monthly mean precipitation ranges from 83 mm in October to 171 mm in March. Monthly mean temperatures range from 3.50 °C in January to 25.11 °C in July (National Oceanographic and Atmospheric Administration, 1991).

Hydrogeology

The bedrock geology of the Eastern Highland Rim is dominated by gently dipping Mississippian limestones and interbedded cherts and shales. Most of the AEDC area is mapped as Upper Mississippian Warsaw and St. Louis Limestones (Wilson, 1976). Both units are heterogeneous, including lenses and beds of sand, silt, and chert. In the study area, both formations are weathered to clay-rich residuum with inclusions of chert and limestone. The uppermost unit of relatively unweathered bedrock is the Lower Mississippian Fort Payne Formation. The Fort Payne Formation consists primarily of chert, limey chert, and cherty limestone with interbedded units of shale and shaley limestone. The Fort Payne Formation is underlain by the Upper Devonian/Lower Mississippian Chattanooga Shale (Wilson, 1976; Burchett, 1977; Benham Group, 1989).

The primary aquifers in the study area are, from top to bottom, the shallow aquifer, the Manchester aquifer, and the Fort Payne aquifer. The shallow aquifer consists of 1.5 to 23 m of clay-sized chert and includes the soil cover and root zone. The Manchester aquifer, a product of the weathering of the lower

Warsaw Limestone and the Fort Payne Formation (Burchett and Hollyday, 1974), is the most productive aquifer, and the most complex. The upper part of the Manchester aquifer consists of chert gravel, weathered limestone, and rubble. The lower part includes fractures and solution openings in bedrock. These openings are most common near the top of bedrock in the Fort Payne Formation, but some are 25 m or more below the top of bedrock (Haugh and others, 1992). The Fort Payne aquifer consists of that part of the Fort Payne Formation which is relatively dense, with few small fractures or solution openings. The thickness of this aquifer is variable, depending on the depth of the weathering profile.

In general, the northern part of the base is characterized by weathering profiles less than 15 m thick (Haugh and others, 1992) and a high concentration of solution openings in the Fort Payne Formation (Haugh and Mahoney, 1994). The shallow aquifer and the upper part of the Manchester aquifer are better developed in the southern part of AEDC where the regolith is relatively thick and rich in coarse-grained chert. The relatively greater density and coherence of the Fort Payne Formation in the southern part of AEDC limit ground-water flow in the lower part of the Manchester aquifer (C.J. Haugh, U.S. Geological Survey, oral commun., 1995).

HYDROLOGY

Sinkhole wetlands at AEDC fall into two major geomorphic classes: karst pans and compound sinks. Both types are generally connected to fluvial systems with drainage areas of less than 5 km^2 but karst pans are more numerous and occupy a wider variety of landscape positions ranging from ridges to the bottoms of small headwater hollows. Compound sinks invariably occupy headwater valley bottoms. The two wetland types also differ in their internal geometry. Karst pans have relatively flat internal topography and depths of less than 1.5 m. In contrast, compound sinks have relatively complex internal topography comprising several intermittent, funnel-shaped sinkholes, some of which have coalesced to varying degrees, and well-developed internal channels; compound sinks generally have depths greater than 2.5 m.

The geomorphic differences suggest differences in water regime and hydrologic functions. On the basis of field observations, it was hypothesized that:

1. Karst pans have lower maximum flooding depths than compound sinks.
2. Karst pans are relatively isolated from the ground-water system.
3. Compound sinks are closely connected to the ground-water system.

Site Selection and Data Collection

Surface-water stage and ground-water levels were monitored in or near five wetland sites (fig. 5). The monitored wetlands include Sinking Pond, Westall Swamp, Goose Pond, and two depressions that overflow into Sinking Pond. One of the tributary depressions, north of Sinking Pond, supports a locally rare stand of water tupelo and is referred to as "Tupelo Swamp" in this report. The second tributary depression, designated "Willow Oak Swamp" in this report, is northwest of Sinking Pond.

Sinking Pond, Westall Swamp, and Willow Oak Swamp are seasonally flooded compound sinks that support forests of water-tolerant oaks and other trees. Sinking Pond and Willow Oak Swamp contain well-developed internal drainage systems with depths of 3 to 4 m. The internal drainage system at Westall Swamp is disrupted by a constructed berm that separates the pond's main body from its natural internal drain. The drain receives flow through a pipe in the berm. The bottom of the main body of Westall Swamp is about 0.8 m higher than the bottom of the internal drain. Goose Pond and Tupelo Swamp are karst pans with depths less than 1.5 m.

Pond stages were monitored with continuous-stage recorders at Sinking Pond, Tupelo Swamp, Westall Swamp, and Goose Pond and with a crest-stage gage at Willow Oak Swamp. Streamflow was monitored in two channels flowing into and out of Sinking Pond. The channel running from Tupelo Swamp to Sinking Pond, designated Sinking Pond inflow (fig. 5), drains an area of 0.57 km^2, about 17 percent of the 3.34 km^2 catchment of Sinking Pond (table 1). Sinking Pond outflow was located at a culvert south and downstream of Sinking Pond (fig. 5). The Sinking Pond catchment represents 84 percent of the 3.99 km^2 drained by the Sinking Pond outflow gage (table 1).

Daily rainfall was monitored with two tipping-bucket rain gages, one at Westall Swamp and the other at Rowland Creek, about 5 km from Westall Swamp (fig. 5). Data from the Rowland Creek rain gage were used as estimates for rainfall in the Sinking Pond/

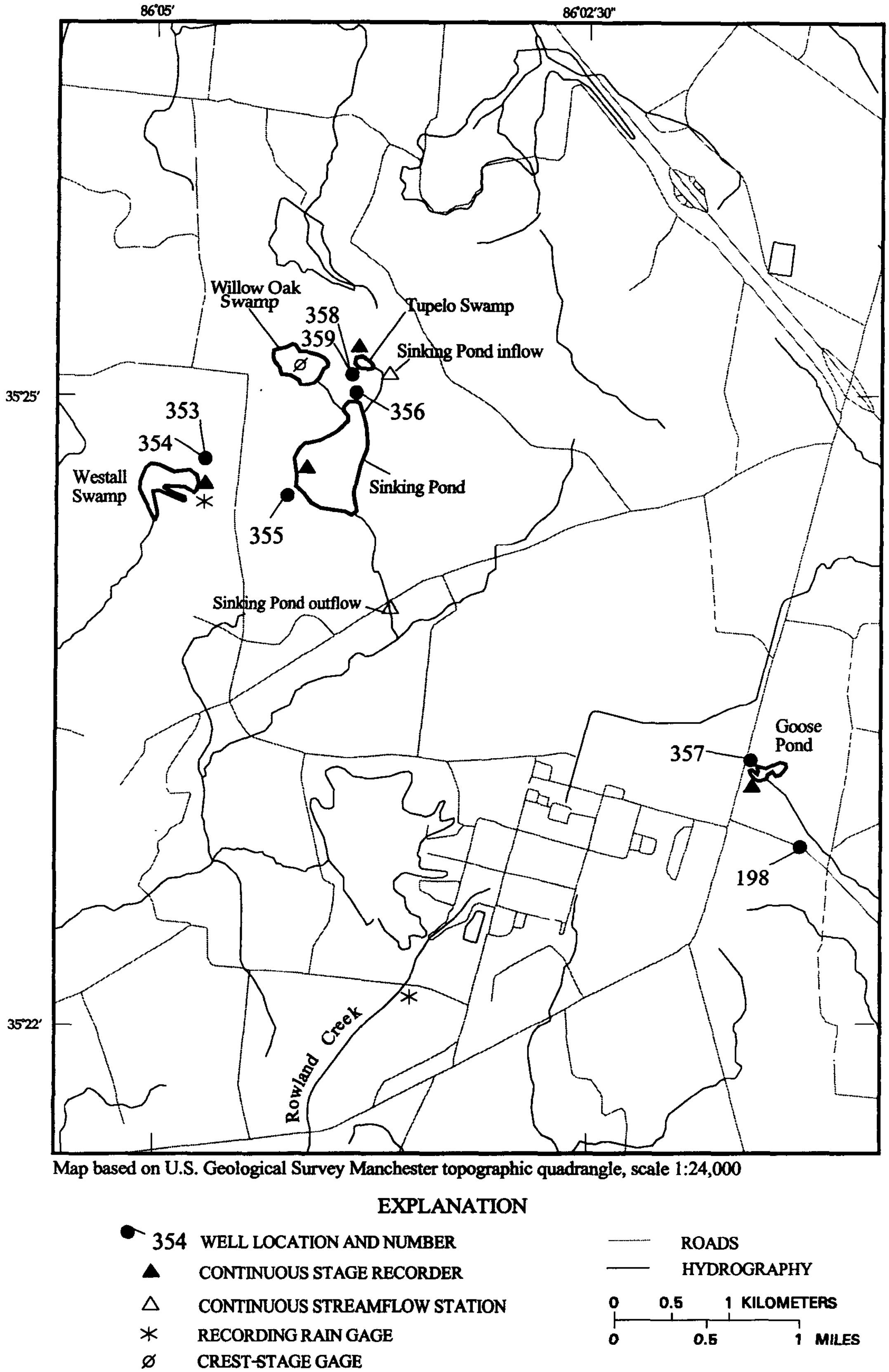


Figure 5. Location of monitored wetland sites and wells, Arnold Engineering Development Center.

Table 1. Gage data for surface-water stations at Arnold Engineering Development Center wetlands

[d-m-s, degrees-minutes-seconds; masl, meters above sea level; km^2, square kilometer]

Station name	USGS site identification number	Latitude and longitude (d-m-s)	Station type	Gage datum (masl)	Drainage area (km^2)
Tupelo Swamp	03596073	35° 25′ 07″ N 86° 03′ 45″ W	Continuous stage	325.215	0.135
Willow Oak Swamp	3525090860410	35° 25′ 09″ N 86° 04′ 10″ W	Crest stage	312.80	.785
Sinking Pond inflow	03596074	35° 25′ 04″ N 86° 03′ 32″ W	Continuous streamflow	313.24	.570
Sinking Pond	03596075	35° 24′ 36″ N 86° 04′ 11″ W	Continuous stage	321.03	3.351
Sinking Pond outflow	035960755	35° 24′ 00″ N 86° 03′ 41″ W	Continuous streamflow	308.575	3.996
Westall Swamp	035960815	35° 24′ 41″ N 86° 04′ 46″ W	Continuous stage	322.125	1.512
Goose Pond	035785012	35° 23′ 11″ N 86° 01′ 33″ W	Continuous stage	322.03	.318

Westall Swamp area during the period October 1, 1992 through November 5, 1992.

Ground-water levels were continuously monitored at eight wells (fig. 5) to assess the relation of wetland water regimes to the local ground-water system. Seven new wells were constructed near the wetland sites, and one pre-existing well in the study area was monitored.

Two wells were constructed at Sinking Pond. One well (355) was located on the southwest side of the pond, adjacent to the stage recorder. The second (356) was located on the north side of the pond. Both were drilled to the top of bedrock and screened in the upper part of the Manchester aquifer (table 2). At Westall Swamp, two wells were drilled in close proximity to the stage recorder. One well (353) was drilled in bedrock and screened in the lower part of the Manchester aquifer. The second well (354) was drilled to the top of bedrock and screened in the upper part of the Manchester aquifer. Similarly, wells 358 and 359 were installed and monitored next to the Tupelo Swamp stage recorder; they were screened in the upper and lower parts of the Manchester aquifer, respectively. Well 357 was drilled next to Goose Pond and screened in the shallow aquifer. A pre-existing well (198), located about 0.8 km southeast of Goose Pond (fig. 5) and screened in the Fort Payne aquifer (table 2), was also monitored. Elevations above sea level were established for all wells and surface-water gages.

Hydrologic measurements were made at Sinking Pond, Sinking Pond outflow, Westall Swamp, and Goose Pond from October 1992 through January 1995. Hydrologic monitoring at Tupelo Swamp, Sinking Pond inflow, and Willow Oak Swamp began in October 1993 and continued through January 1995. Continuous-stage recorders recorded surface-water stage every 15 minutes. Monthly discharge measurements were made to relate discharge to the stage records of streamflow stations. Continuous recorders on wells recorded ground-water level every hour. Data from the continuous stage, streamflow, and ground-water level stations were reduced to daily averages for use in this report. The stage of Willow Oak Swamp was observed every month and crest-stage marks were measured. Probable dates of flood crests were estimated based on daily stage and rainfall records from the Sinking Pond/Westall Swamp area. Tipping-bucket rain gages recorded depth of rainfall every 5 minutes. The rainfall data were reduced to daily totals for use in this report.

Table 2. Well-construction data for continuously monitored wells near wetlands at Arnold Engineering Development Center

[AEDC, Arnold Engineering Development Center; USGS, U.S. Geological Survey; --, no data; masl, meters above sea level; km, kilometer; SH, shallow aquifer; LMN, Manchester aquifer, lower part; UMN, Manchester aquifer, upper part; FP, Fort Payne aquifer]

AEDC well number	Local well number	USGS site identification	Location	Land surface altitude (masl)	Surface casing depth (meters)	Depth to bottom of seal (meters)	Screened interval (meters)	Depth to bottom of borehole (meters)	Hydro-geologic unit	Date of construction
198	Cf:G-032	3522530860119011	0.8 km southeast of Goose Pond	326.78	32.3	35.1	37.2-40.2	40.5	FP	01-18-91
353	Cf:G-062	352441086044501	East side of Westall Swamp	325.53	7.9	25.0	25.9-29.0	49.4	LMN	04-22-93
354	Cf:G-063	352441086044502	East side of Westall Swamp	325.28	--	3.7	4.0-7.0	7.3	UMN	04-26-93
355	Cf:G-064	3524360860412	West side of Sinking Pond	326.33	--	6.1	6.4-9.4	9.8	UMN	04-22-93
356	Cf:G-065	352458086034702	North side of Sinking Pond	326.26	--	6.4	7.0-10.1	10.4	UMN	04-26-93
357	Cf:G-066	352312086013500	West side of Goose Pond	326.11	--	6.1	6.1-9.1	9.4	SH	04-28-93
358	Cf:G-067	352507086034501	South side of Tupelo Swamp	326.93	--	5.5	6.1-9.1	9.1	UMN	11-03-93
359	Cf:G-068	352507086034502	South side of Tupelo Swamp	327.06	9.8	18.9	22.9-25.9	25.9	LMN	11-03-93

The topography of Sinking Pond was surveyed to illustrate the geomorphic complexity of a compound sink and the relation between sinkhole morphology and hydrologic response. A circuit of temporary control points was established using a total station. Vertical control was the Sinking Pond gage, and horizontal control was mapped trail intersections. Horizontal and vertical closure of the temporary control points was less than 3 cm. Topographic points were surveyed with a total station centered above the temporary control points. The internal topographic points were incorporated in a digital elevation model previously established by AEDC and the USGS. New contours were generated using the Lattice-Contour utility of the ArcInfo geographic information system (Environmental Systems Research Institute, 1992). A contour interval of 1 foot (0.3048 m) was selected to facilitate comparison with pre-existing topographic maps of the area and because this interval is appropriate to the size and relief of the surveyed area.

Water Levels and Discharge

Abrupt seasonal rises and falls are a striking feature of the Sinking Pond hydrograph. For example, on November 3, 1992, Sinking Pond stage rose 2 m in less than 24 hours. Subsequent seasonal rises and falls were similar in magnitude and abruptness (fig. 6). Recorded stages in Sinking Pond, in meters above sea level (masl), ranged between a fully drained minimum

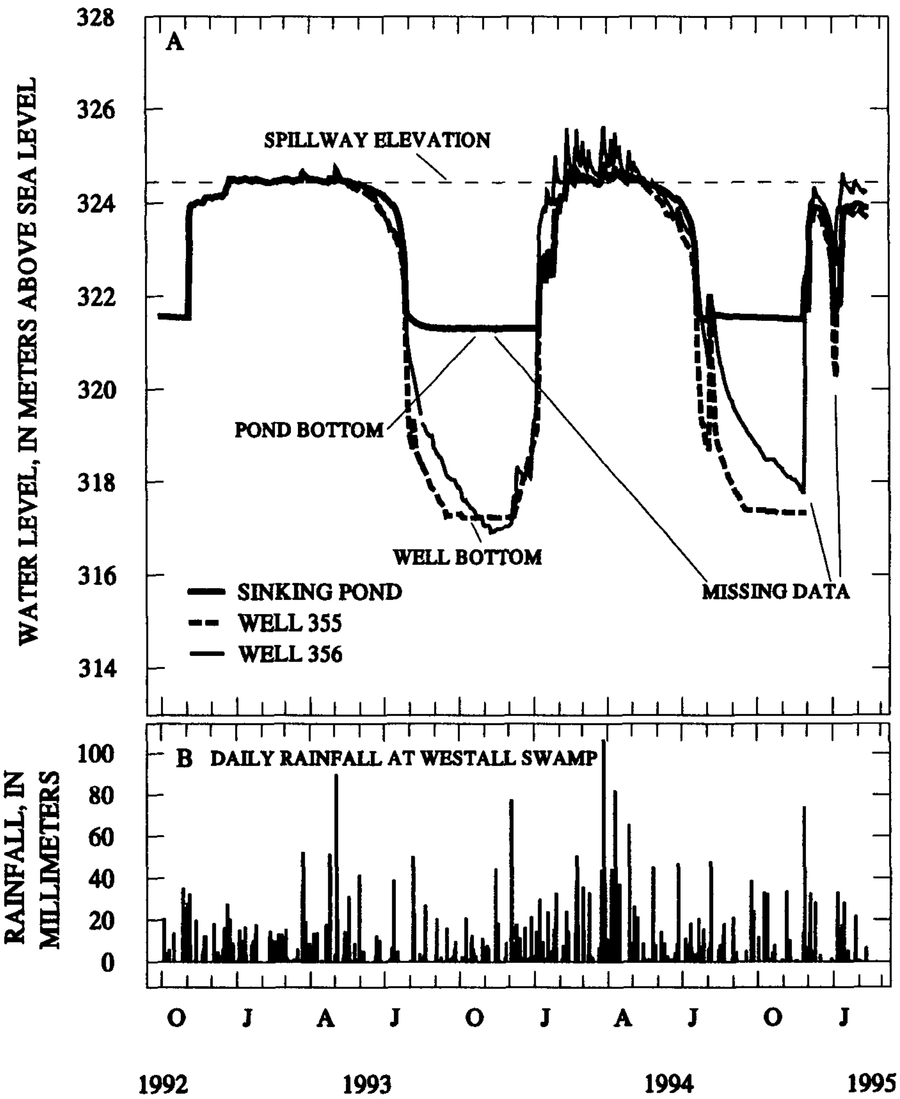


Figure 6. (A) Water levels in Sinking Pond and adjacent wells and (B) daily rainfall at Westall Swamp.

of 321.31 to a maximum of 324.81 (fig. 6) with corresponding maximum water depths of 0 to 3.5 m.

The frequency distribution for Sinking Pond stage is distinctly bimodal. Pond stage was below 321.6 masl for 27 percent and above 324 masl for 65 percent of days in water year 1993 (October 1992 through September 1993). The intervening 2.4 m accounts for 71 percent of the annual range but only 8 percent of the distribution (fig. 7). Flooding came later in water year 1994 (fig. 6) but the shape of the cumulative frequency distribution for daily stage in Sinking Pond is similar to that for water year 1993 (fig. 7). Forty-six percent of days in water year 1994 had stages below 321.7 masl, and 41 percent had stages higher than 324 masl (fig. 7). The intervening 2.3 m, 66 percent of the annual range, represents 13 percent of the distribution.

The differences in the Sinking Pond hydrographs and stage-frequency curves between water years 1993 and 1994 (figs. 6 and 7) suggest that 1994 was the drier of the 2 years. However, rainfall records from the Rowland Creek gage and Tullahoma, Tennessee, indicate that the annual total rainfall for water year 1994 was about 500 mm greater than that for 1993 (fig. 8). The fall and early winter months of water year 1993 were wetter than the corresponding months in 1993, but the difference is relatively modest compared to the annual total (fig. 8). Nonetheless, rainfall during these months and late summer seems to be a critical determinant of the hydrologic behavior of Sinking Pond and similar systems. At Tullahoma, monthly rainfall for water year 1993 was closer to the 30-year average than were monthly totals for water year 1994 (fig. 8). These observations suggest that the

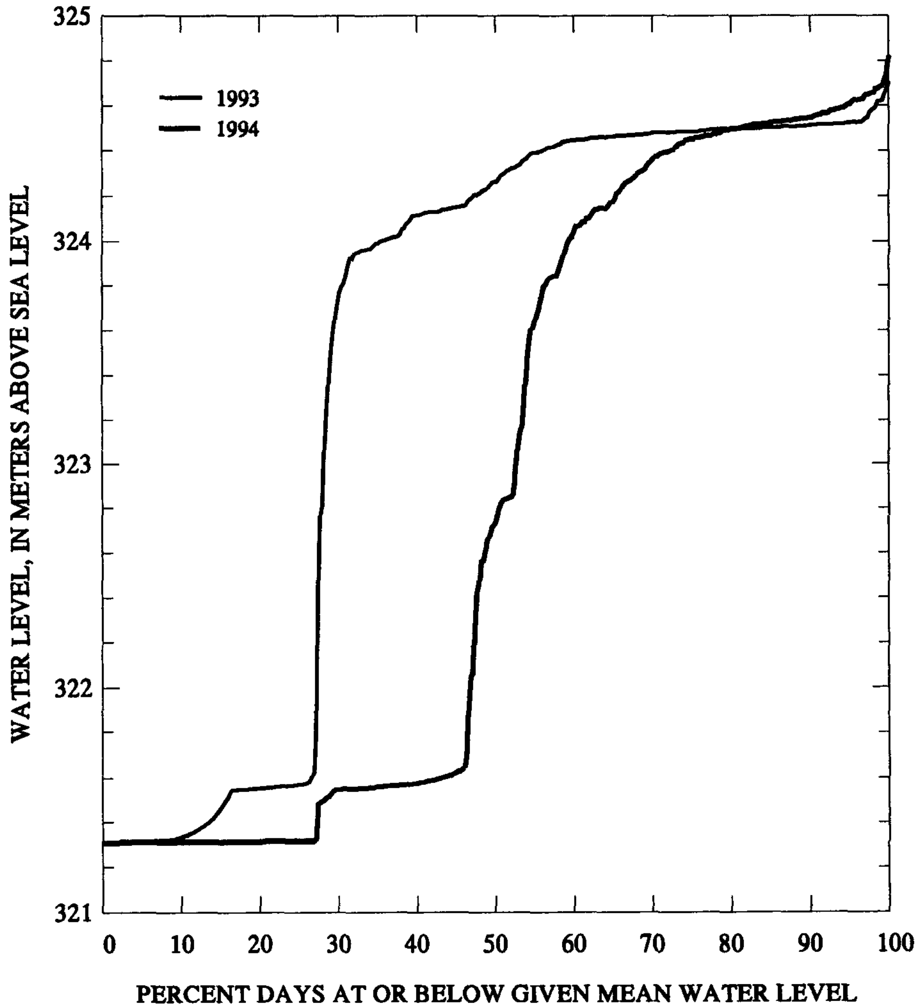


Figure 7. Cumulative frequency distributions of daily mean water level in Sinking Pond for water years 1993 and 1994. Water year begins 3 months earlier than corresponding calendar year.

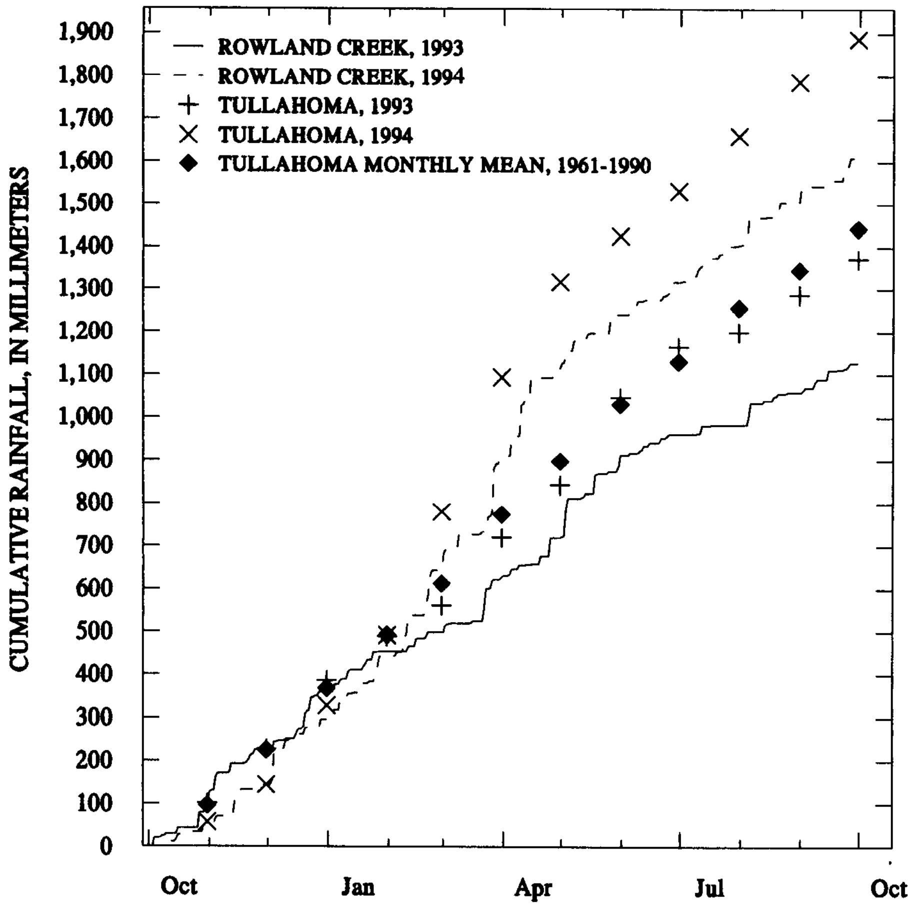


Figure 8. Comparison of daily rainfall at Rowland Creek, Arnold Engineering Development Center, with monthly rainfall at Tullahoma, Tennessee, for water years 1993 and 1994 and with mean monthly rainfall at Tullahoma for 1961-1990. Tullahoma data from National Oceanographic and Atmospheric Administration, 1991-1995.

1993 hydrograph for Sinking Pond is more representative of average conditions than the 1994 hydrograph.

Sinking Pond stage displayed a close relation to ground-water levels in nearby wells. Beginning at the seasonal rise, and continuing through much of the periods of inundation, the water level in the well on the southwest side of Sinking Pond (355) was essentially identical to the pond stage (fig. 6). Water level in the well at the north end of Sinking Pond (356) rose 0.3 to 1.5 m above Sinking Pond stage during storms, then fell toward equilibrium with the pond. The head difference between the two wells coincides with a general north-to-south flow gradient that affects surface- and ground-water flow throughout the Sinking Pond area. During seasonal recessions in 1993 and 1994, water levels in wells 355 and 356 fell 0.3 to 0.6 m below Sinking Pond stage from mid-May through late July. Ground-water levels fell rapidly as the pond drained and continued to decline after the pond was dry, reaching depths about 4 m below the pond bottom in October and November.

The hydrologic response of Sinking Pond to rainfall reflects the interaction of antecedent basin conditions, ground-water levels, and sinkhole morphology. A given depth of rainfall is more likely to produce runoff during winter, when evapotranspiration is lowest, than during other seasons. Mechanisms that produce runoff in the Sinking Pond catchment include:

1. Seepage near slope breaks and the up-gradient ends of sinkholes.
2. Diffuse overland flow.
3. Intermittent channelized flow.

Once runoff is initiated, its routing within the pond is controlled by ground-water conditions. When the local water table is below a threshold of about 320 masl, runoff drains quickly into the sinkholes that dominate the interior of Sinking Pond. When the water table rises above the 320-masl threshold, runoff cannot

infiltrate and instead remains in surface storage in the pond. The threshold water-table elevation for rapid drainage of Sinking Pond appears to be about 321.6 masl—about 1.6 m higher than the threshold for filling.

When the water table is high enough to promote ponding, the surface-water response of Sinking Pond to a given volume of runoff depends on antecedent stage. At stages between 321.31 and 323.6 masl (below the 1,061-foot contour on fig. 9), ponded water is confined to the sinkholes within the pond. These sinkholes represent about 15 percent of the maximum ponded area (fig. 9) but 65 percent of the range of recorded stages. Within this range, a relatively small volume of runoff can abruptly increase surface-water stage by 2 m or more. At stages above 323.6 masl, ponded water overflows the interior sinkholes and floods the rest of the pond.

At stages above 324.45 masl (the spillway elevation), Sinking Pond discharges to the Sinking Pond outflow channel. The maximum recorded stage in Sinking Pond, 324.8 masl, represents a water depth of 0.35 m across the spillway. Overflow of Sinking Pond increases the effective drainage area of the Sinking Pond outflow gage from 0.65 km^2 to 3.99 km^2. The sixfold increase or reduction of effective drainage area results in relatively rapid fluctuations in streamflow. Daily mean discharges at the Sinking Pond outflow gage south of Sinking Pond ranged from 0 to 1.23 cubic meters per second (m^3/s) (fig. 10).

The hydrographs of two headwater sub-basins, Willow Oak Swamp and Tupelo Swamp, illustrate some of the geomorphic controls on runoff in the Sinking Pond catchment. The importance of these tributary depressions in routing surface runoff to Sinking Pond became evident from field observations during 1993. Water levels were monitored beginning October 1993 to determine interaction between these basins and Sinking Pond.

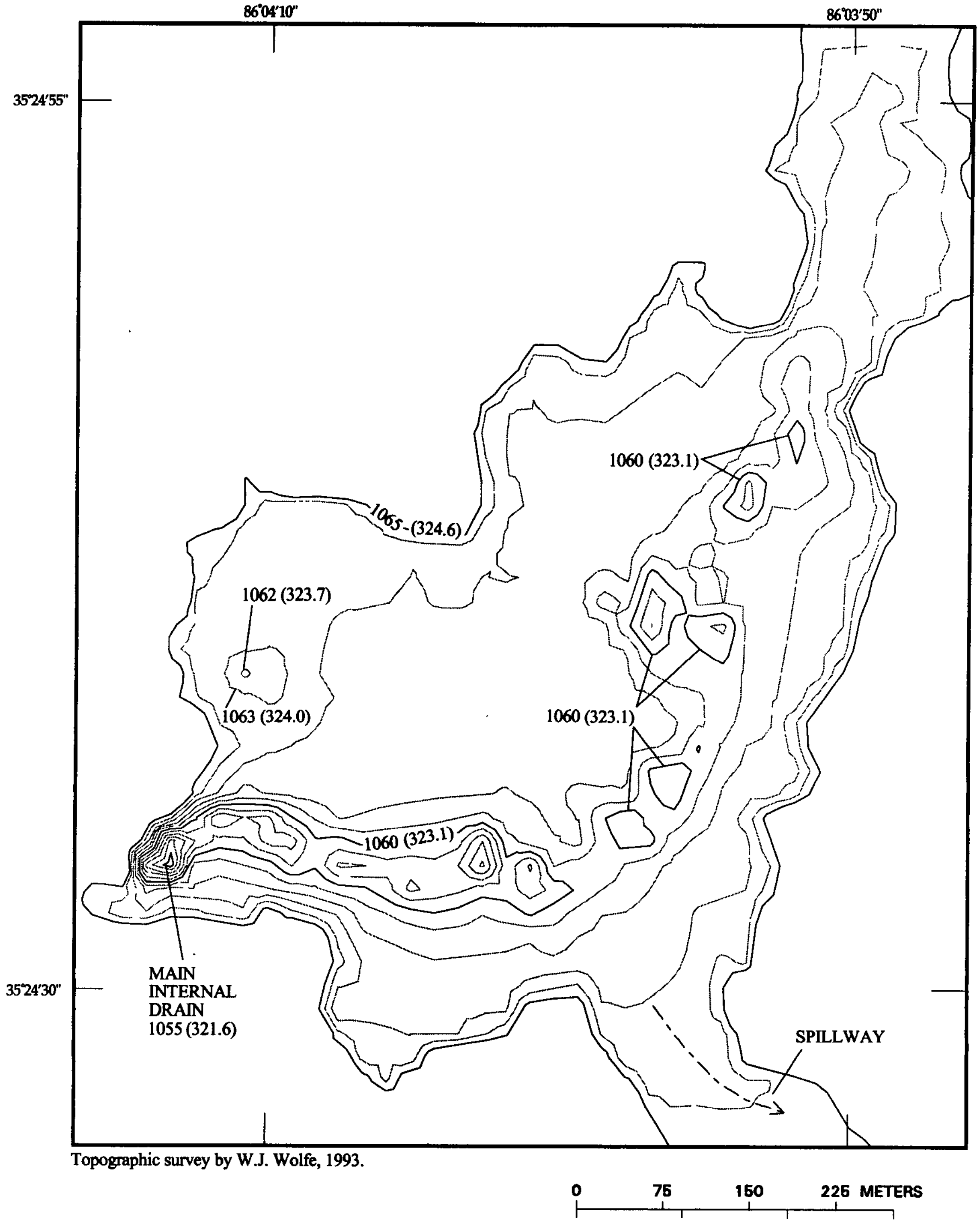
Willow Oak Swamp contains a prominent sinkhole about 3 m deep. Observed stages in Willow Oak Swamp ranged from 322.82 masl under fully drained conditions to 325.88 masl (fig. 11). Filling and draining of this depression follows a pattern similar to that of Sinking Pond. However, this sub-basin begins to fill later than Sinking Pond and drains earlier (fig. 11). The difference in timing of seasonal rises and recession probably reflects the difference in the bottom elevations of the two ponds but also may indicate connection to a different point in the subsurface conduit flow system. Willow Oak Swamp, like Sinking Pond, acts as a closed basin for most of the time, but overflows into Sinking Pond when its surface storage is exceeded.

Tupelo Swamp differs from Sinking Pond and Willow Oak Swamp in its relatively shallow depth (about 1 m), flat internal topography, and the absence of a visible internal drain. Tupelo Swamp rarely behaves as a closed basin, but overflows throughout the winter and early spring. Seasonal flooding generally occurred earlier and persisted longer than in Sinking Pond or Willow Oak Swamp. During water year 1994, stage in Tupelo Swamp ranged from 326.11 (fully drained) to 327.20 masl (fig. 12). The range of stage in Tupelo Swamp was roughly one third as large as the ranges observed at Sinking Pond and Willow Oak Swamp.

Both wells at Tupelo Swamp were subject to rapid rises and falls, essentially simultaneous to the responses of other wells and surface-water stages in the Sinking Pond area (figs. 6 and 12). Ground-water levels at Tupelo Swamp remained lower than pond stage throughout the study (fig. 12). The constant downward gradient between surface water in Tupelo Swamp and the water table contrasts with the close connection between Sinking Pond stage and the local ground-water system. Soil borings revealed a clay-rich layer about 1 m below the bottom of Tupelo Swamp. Periodic probing showed that the soil above this layer remains at or near saturation even when the pond is dry but that the underlying material is unsaturated throughout the year. The low permeability of the pond bottom and the absence of a discrete internal drain contribute to the relatively long hydroperiod of Tupelo Swamp.

Overflow from Tupelo Swamp discharges to the Sinking Pond inflow channel. Discharge at this site remained less than 0.15 m^3/s throughout the period of record. The intermittent channel generally remained dry throughout the summer and fall. The earliest winter flows generally followed ground-water emergence in the interior sinkholes of Sinking Pond but preceded the filling of Sinking Pond. Daily mean flow at this station reached or exceeded 0.1 m^3/s during four storms between January and April 1994 (fig. 13).

The water regime of Westall Swamp closely resembles that of Sinking Pond in the abruptness of



EXPLANATION

- - - - - - - -> INTERMITTENT FLOW PATH

1060 (323.1) TOPOGRAPHIC DEPRESSION CONTOUR–SHOWS ELEVATION OF LAND SURFACE. CONTOUR INTERVAL 1 FOOT (0.3048 METER). DATUM IS SEA LEVEL.

Figure 9. Topography of Sinking Pond.

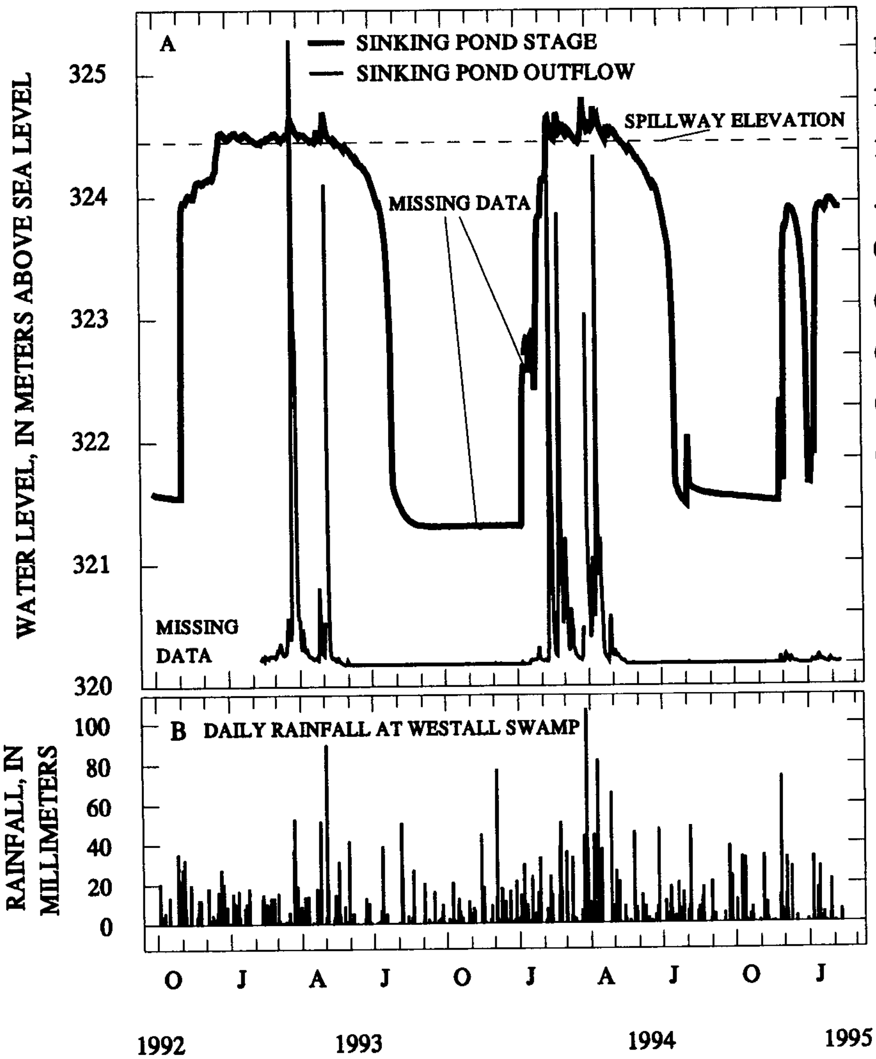


Figure 10. Relation of daily mean discharge at Sinking Pond outflow gage to (A) stage in Sinking Pond and (B) rainfall at Westall Swamp.

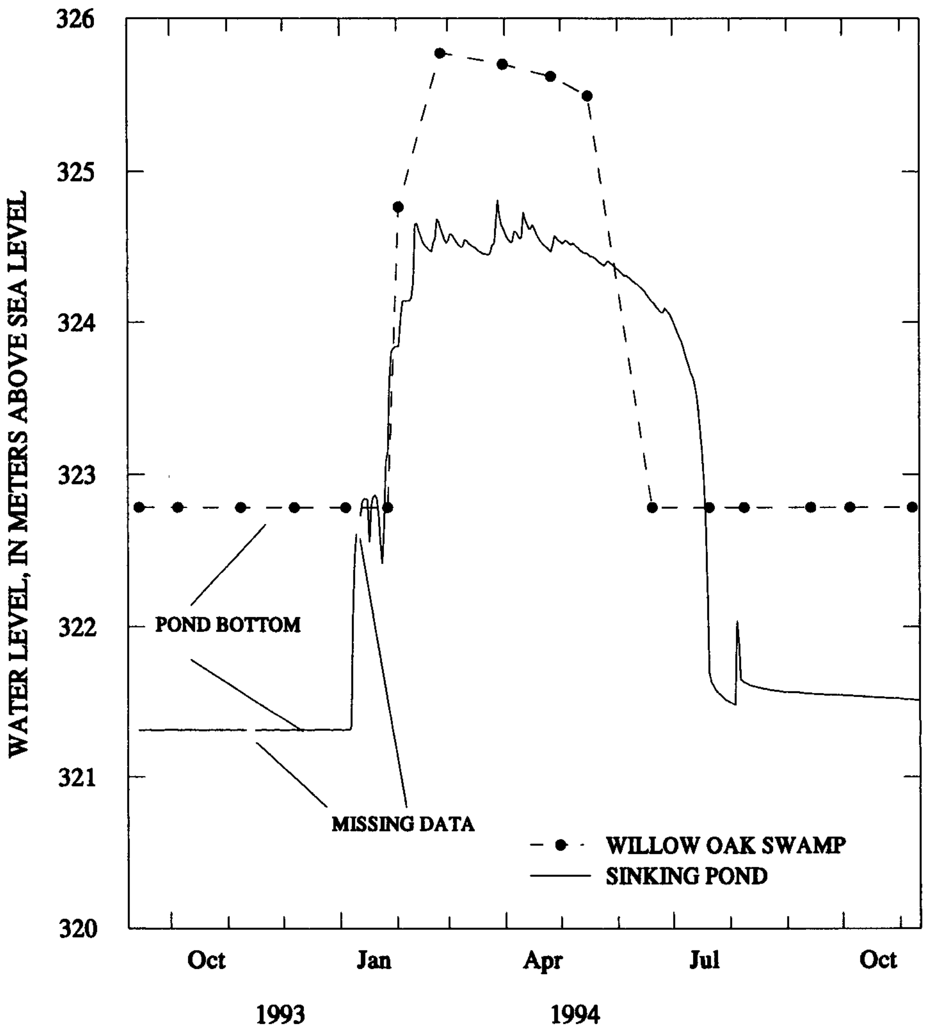


Figure 11. Water levels in Willow Oak Swamp and Sinking Pond.

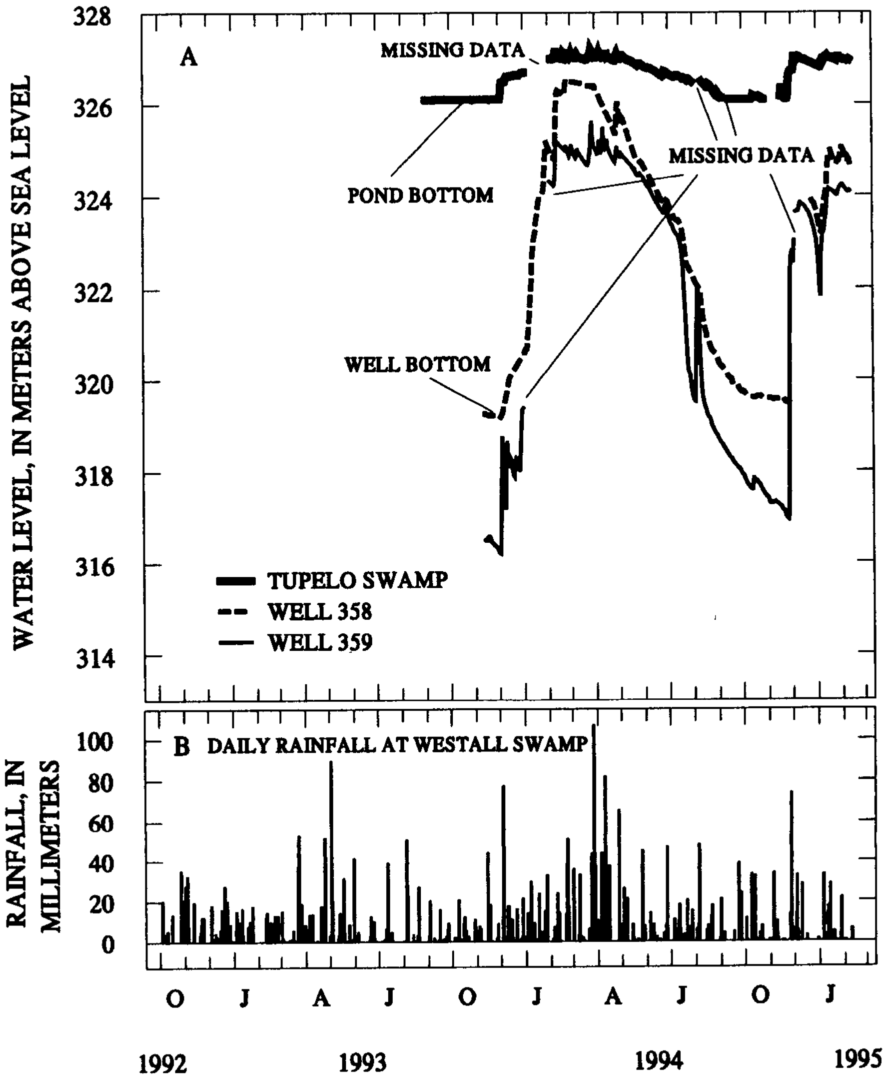


Figure 12. (A) Water levels in Tupelo Swamp and adjacent wells and (B) daily rainfall at Westall Swamp.

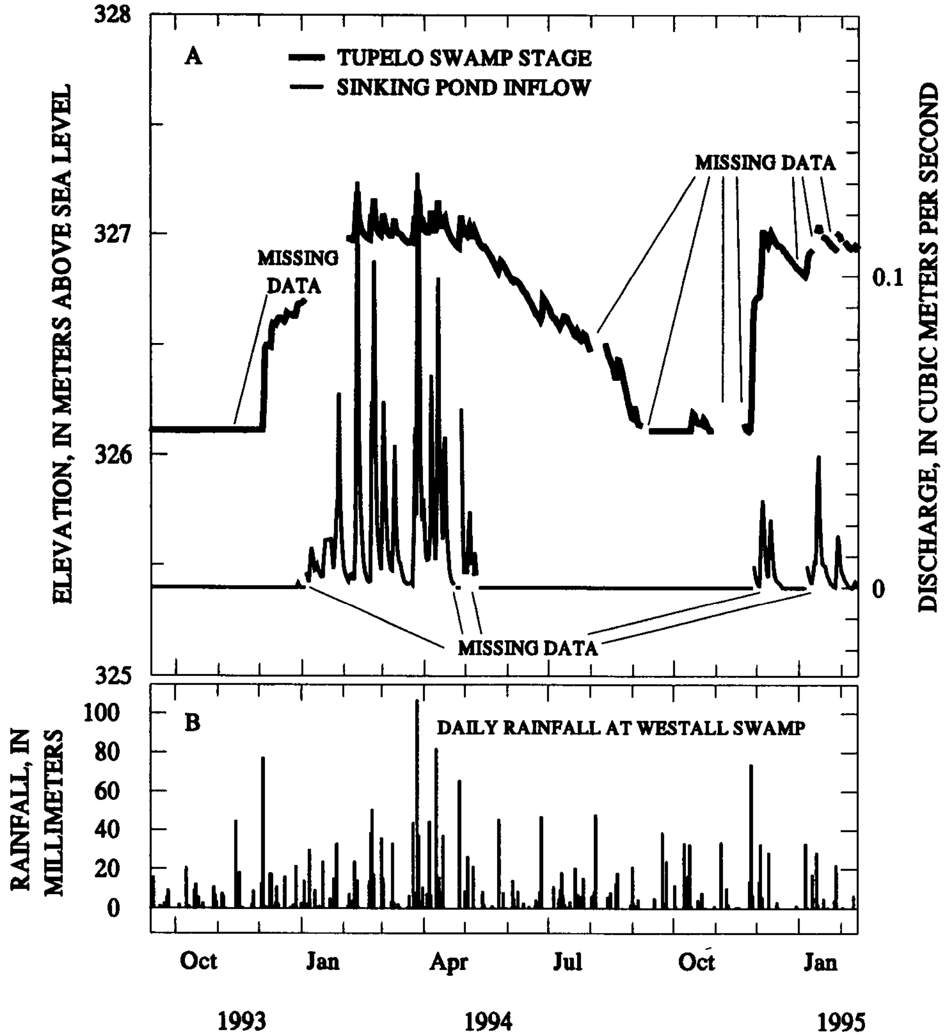


Figure 13. Relation of daily mean discharge at Sinking Pond inflow gage to (A) stage in Tupelo Swamp and (B) rainfall at Westall Swamp.

seasonal rises and recessions, the bimodal frequency distribution of surface-water stage, and the close connection between surface-water stage and ground-water levels. Surface-water stage in the main body of Westall Swamp (west of the constructed berm) ranged from 322.5 masl (fully drained) to 325.2 masl with corresponding water depths of 0 and 2.7 m. Stages between 322.6 and 324.5 masl, about 70 percent of the observed range of stage, accounted for only 7 percent of the stage distribution for water year 1993 and 12 percent of the distribution for water year 1994. Ground-water levels in two adjacent wells stayed within 0.06 m of each other and of Westall Swamp stage during much of the flooding season (fig. 14). Water levels in both wells dropped below the pond bottom during the seasonal recessions. Head differences between the two wells greater than 0.3 m occurred only when the pond was dry, notably in November and December of 1993 (fig. 14).

Westall Swamp fills and drains in response to the same controls that determine the filling and draining of Sinking Pond. Surface runoff flows through Westall Swamp and drains into a prominent sinkhole east of the constructed berm. As with Sinking Pond, surface water ponds after the local water table reaches a certain threshold elevation and persists until the water table recedes to a second threshold. The water-table threshold for filling Westall Swamp is about 320 masl, and the threshold for draining is about 323.5 masl.

The surface-water regime of Goose Pond and its relation to the ground-water system are much more similar to those of Tupelo Swamp than to the other sites examined in this study. Surface-water stage

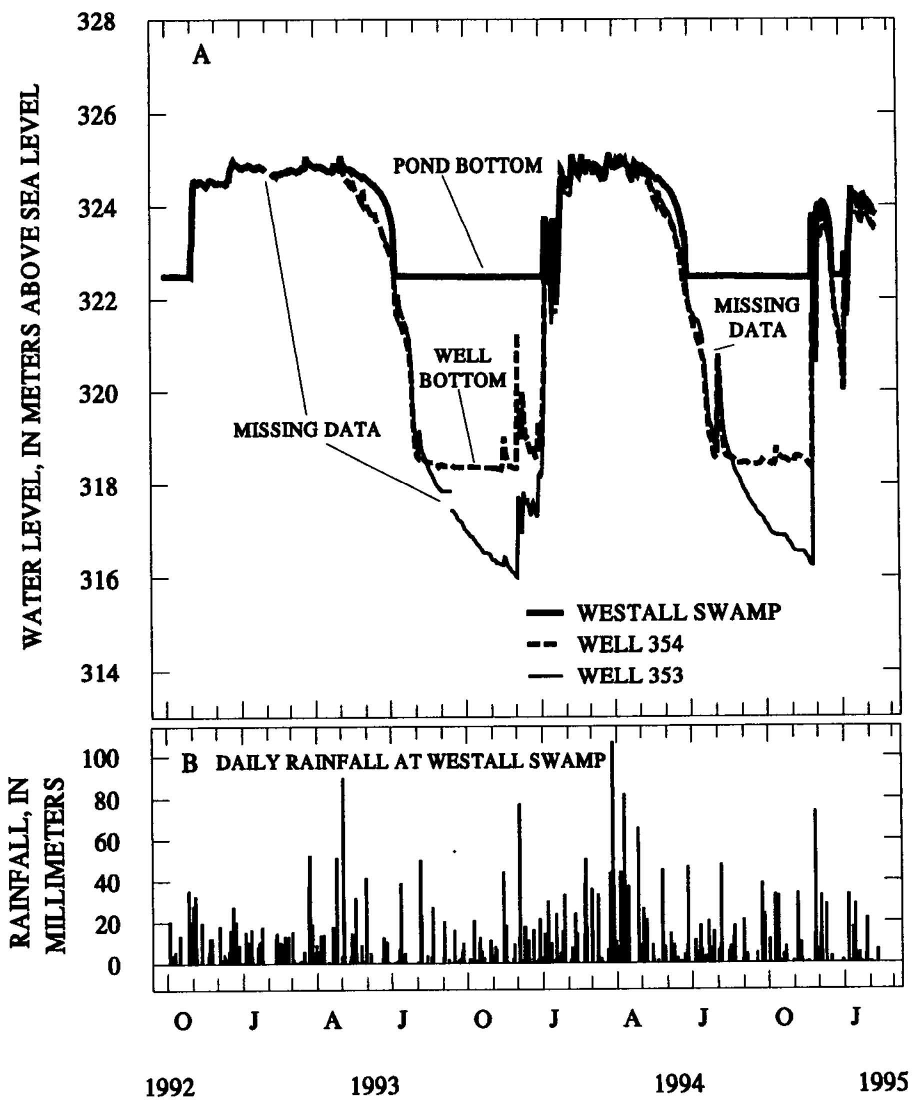


Figure 14. (A) Water levels in Westall Swamp and adjacent wells and (B) daily rainfall at Westall Swamp.

in Goose Pond ranged from 325.2 to 325.9 masl (fig. 15), the narrowest range of the five monitored wetland sites. The frequency of water depth in Goose Pond was relatively evenly distributed within that narrow range. The pond bottom remained saturated within 0.15 m of the surface throughout the study period. Ground-water levels in nearby wells remained consistently below Goose Pond stage throughout the study period. The hydrograph for the shallow-aquifer well (357) next to the Goose Pond gage displays relatively steady rises and falls and a lag in its response to rainfall events compared to that of the pond (fig. 15). Water levels in well 198, about 1.2 km southeast of Goose Pond and screened in the Fort Payne aquifer, were consistently 6 to 10 m below Goose Pond stage and lower than water levels in the shallow aquifer at Goose Pond (fig. 15).

Geomorphic Controls of Wetland Water Regimes

Hydrologic monitoring revealed two contrasting styles of wetland water regime corresponding to the two major geomorphic classes of sinkhole wetlands at AEDC. Three compound sinks, Sinking Pond, Westall Swamp, and Willow Oak Swamp, share the geomorphic characteristics of about 3 m of internal relief and plainly visible sinkhole drains. Surface-water stages in Sinking Pond and Westall Swamp rise and fall abruptly (2 m or more during 1 to 3 days) and reach

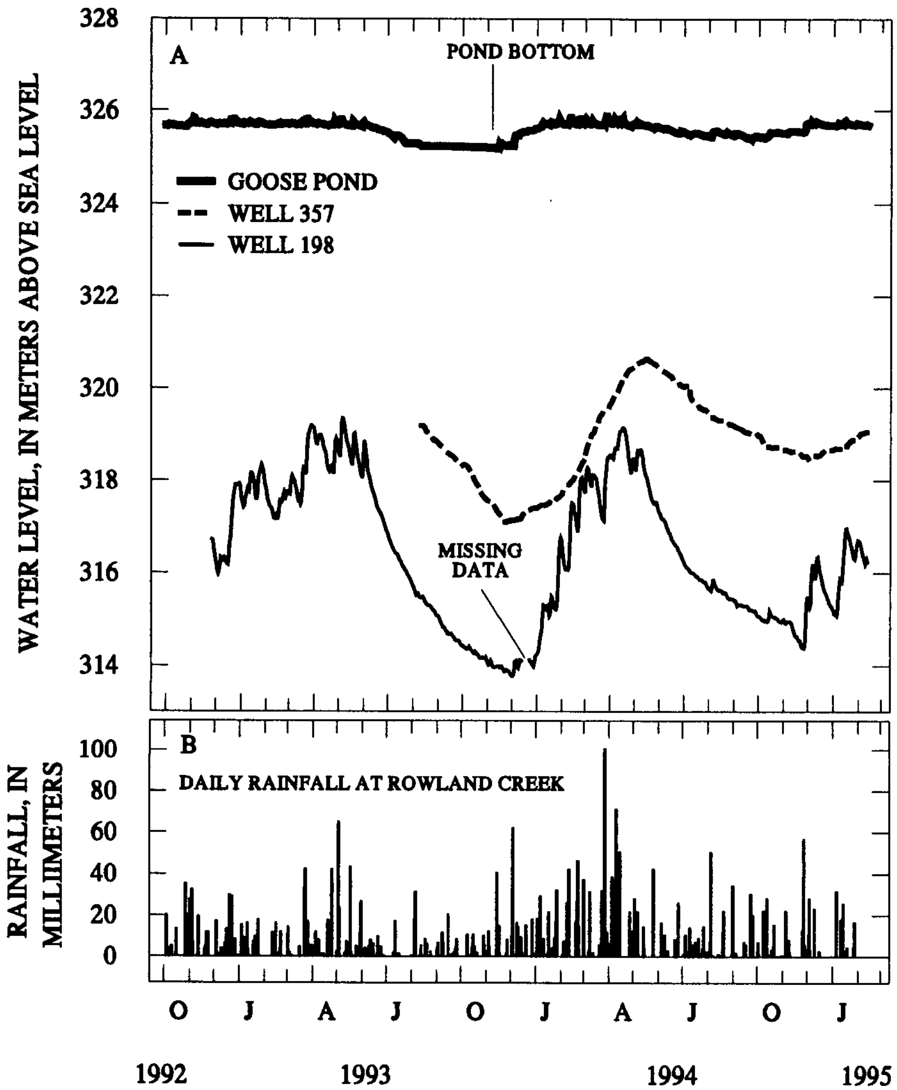


Figure 15. (A) Water levels in Goose Pond and nearby wells and (B) daily rainfall at Rowland Creek.

maximum depths of about 3 m (fig. 16). Surface water in these compound sinks interacts closely with ground water. The interactions include water-table control of sinkhole drainage and rapid fluctuations of the water table in response to recharge.

In contrast to the compound sinks, two karst pans, Tupelo Swamp and Goose Pond, have depths of less than 1.5 m and lack visible internal drains. Surface water in both karst pans is isolated from ground water by relatively impermeable bottom material that acts as a confining layer. The two karst pans fill and drain less abruptly than the compound sinks and have longer hydroperiods. For example, Tupelo Swamp and Goose Pond filled in December 1993 and retained water through September 1994. Sinking Pond and Westall Swamp filled in January 1994 and drained in July 1994 (fig. 16).

The general patterns of the water regimes in compound sinks and karst pans observed at AEDC reflect geomorphic and hydrologic controls that determine the water regimes of sinkhole wetlands in other settings. These controls include:

1. Sinkhole geometry.
2. Connection to the ground-water system.
3. Bottom elevation relative to normal range of water table.
4. Periodicity of water-table fluctuation.
5. Drainage-basin characteristics (basin area, relief, ground cover, and other factors affecting runoff generation).

The relative importance of these factors varies from site to site. Karst pans such as Tupelo Swamp and Goose Pond are poorly connected to the ground-water system and therefore relatively insensitive to either the elevation range or periodicity of water-table fluctuations. Analogous sites have been described in the Coastal Plain of southwestern Georgia (Hendricks and Goodwin, 1952) and the Valley and Ridge of northwestern Georgia (Greear, 1967). In all these cases, pan depth approximated maximum flooding

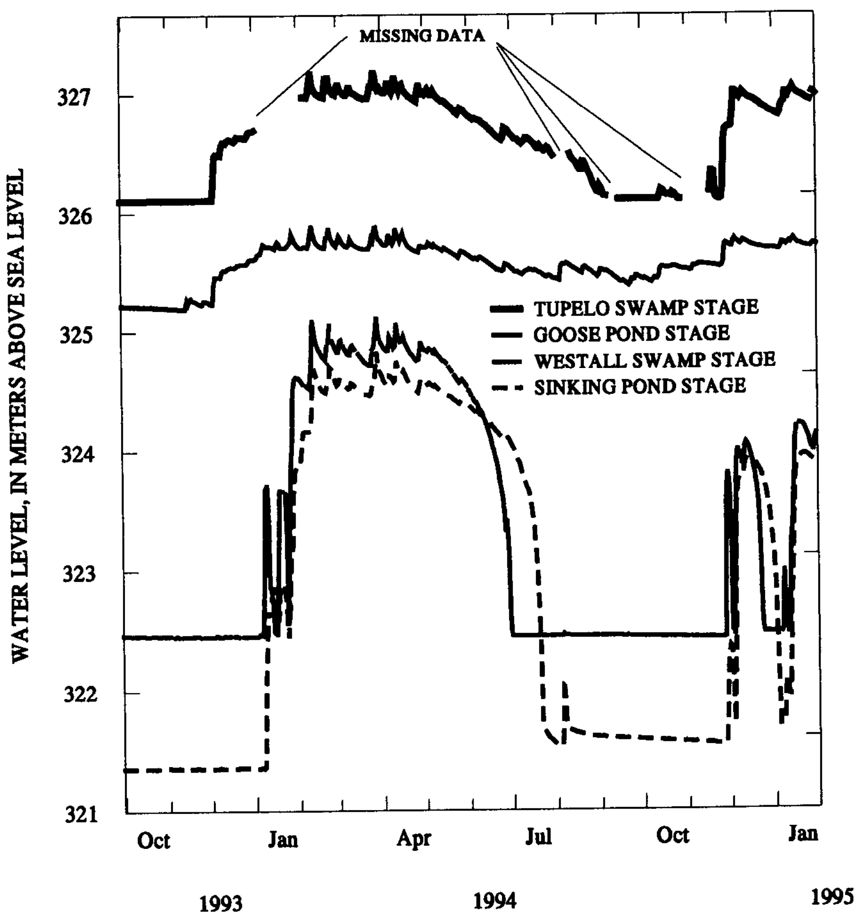


Figure 16. Comparison of water levels in four wetland sites at Arnold Engineering Development Center during the period October 1993 through January 1995.

depth whether the water table remained below the pond bottom or rose above it in wet seasons. At AEDC and in the Georgia studies (Hendricks and Goodwin, 1952; Greear, 1967), basin runoff was sufficient to completely fill karst pans, and shallow pan depths limited maximum stage to an elevation typically 5 to 40 cm above the spillway.

Sinkhole depth limits maximum potential flooding depth in compound sinks and other deep (>2 m) depressions. However, basin characteristics, connection to the ground-water system, and the range and periodicity of water-table fluctuations play a role in determining whether maximum potential flooding depth is realized. At AEDC, deep compound sinks such as Sinking Pond, Westall Swamp, and Willow Oak Swamp generally have efficient internal drains. These depressions overflow when (1) ground-water levels rise sufficiently to block internal drains to the underlying aquifer, and (2) subsequent rainfall generates runoff sufficient to fill the pond. These conditions tend to occur more frequently and persist longer in lower-elevation sinks with larger drainage areas such as Sinking Pond than in higher sinks with smaller drainage areas such as Willow Oak Swamp.

Greear (1967) documented a general correlation between greater sinkhole depth and better internal drainage similar to that described at AEDC. One important difference was that ground-water levels remained below the bottom elevations of both deep and shallow ponds (Greear, 1967). The combination of unimpeded internal drainage and greater sinkhole depth prevented deeper ponds from overflowing during Greear's (1967) study. In contrast, the sinkhole wetlands studied by Hendricks and Goodwin (1952) displayed no relation between depth and internal drainage efficiency. All of these sinkholes received sufficient runoff to cause overflowing (Hendricks and Goodwin, 1952). Deeper sinkholes generally had longer hydroperiods than shallow sinks because greater evapotranspiration was necessary to dry them out in the absence of internal drainage. This relation between hydroperiod and sinkhole depth is opposite that observed at AEDC and in Greear's (1967) study where deeper sinkholes with efficient internal drains dried out faster than shallow sinkholes with poor internal drainage.

At AEDC, sinkhole depth and the presence or absence of visible evidence of internal drainage are good indicators of relative hydroperiods, flooding depths, and ground-water influence. These indicators are potentially useful management tools because assessing them is rapid, simple, and inexpensive compared with hydrologic monitoring. However, evidence from karst wetlands in other settings shows that the relation between geomorphic features and water regimes varies among and within regions, depending on hydrogeologic conditions. Extrapolating the patterns observed at AEDC to other areas without local hydrologic data could produce highly erroneous results. Nonetheless, the same geomorphic and hydrologic processes that control water regimes in the sinkhole wetlands at AEDC—sinkhole development, runoff generation and routing, ground-water perching, and concentrated recharge—exert analogous controls in other karst wetlands.

TREE-DISTRIBUTION PATTERNS

The geomorphically controlled water regimes of the sinkhole wetlands at AEDC have ecological significance. Seasonal patterns of flooding and soil saturation are important controls of wetland plant distribution (Cowardin and others, 1979; Carter, 1986; Gill, 1970). At AEDC and similar settings, karst wetlands support a wide variety of disjunct plants (Benham Group, 1989; Ellis and Chester, 1989; Patterson, 1989). The water regimes of karst wetlands enable disjunct wetland plants to survive in isolated pockets far from their normal ranges (Barclay, 1957; Greear, 1967). This investigation examines the relation of water regime to the distribution of disjunct and local wetland tree species in karst depressions and intermittent drainageways at AEDC.

Wetland trees at AEDC can be grouped according to their normal geographic range (local or disjunct in The Barrens) and their inherent affinity to wetland settings. Table 3 lists the normal geographic ranges and site preferences of six prominent wetland tree species found at AEDC. Two of these species, water tupelo and overcup oak, are coastal-plain disjuncts that occur nearly exclusively in wetland sites under natural conditions. The third species, willow oak, is common in The Barrens where it usually occupies wet depressions and stream bottoms. The three remaining species, sweetgum, black tupelo, and red maple, are among the most widely distributed and adaptable trees in North America. All are common in The Barrens where they occupy a wide range of wetland and upland sites. Other local tree species that are able to exploit some wetland sites, but are not restricted to

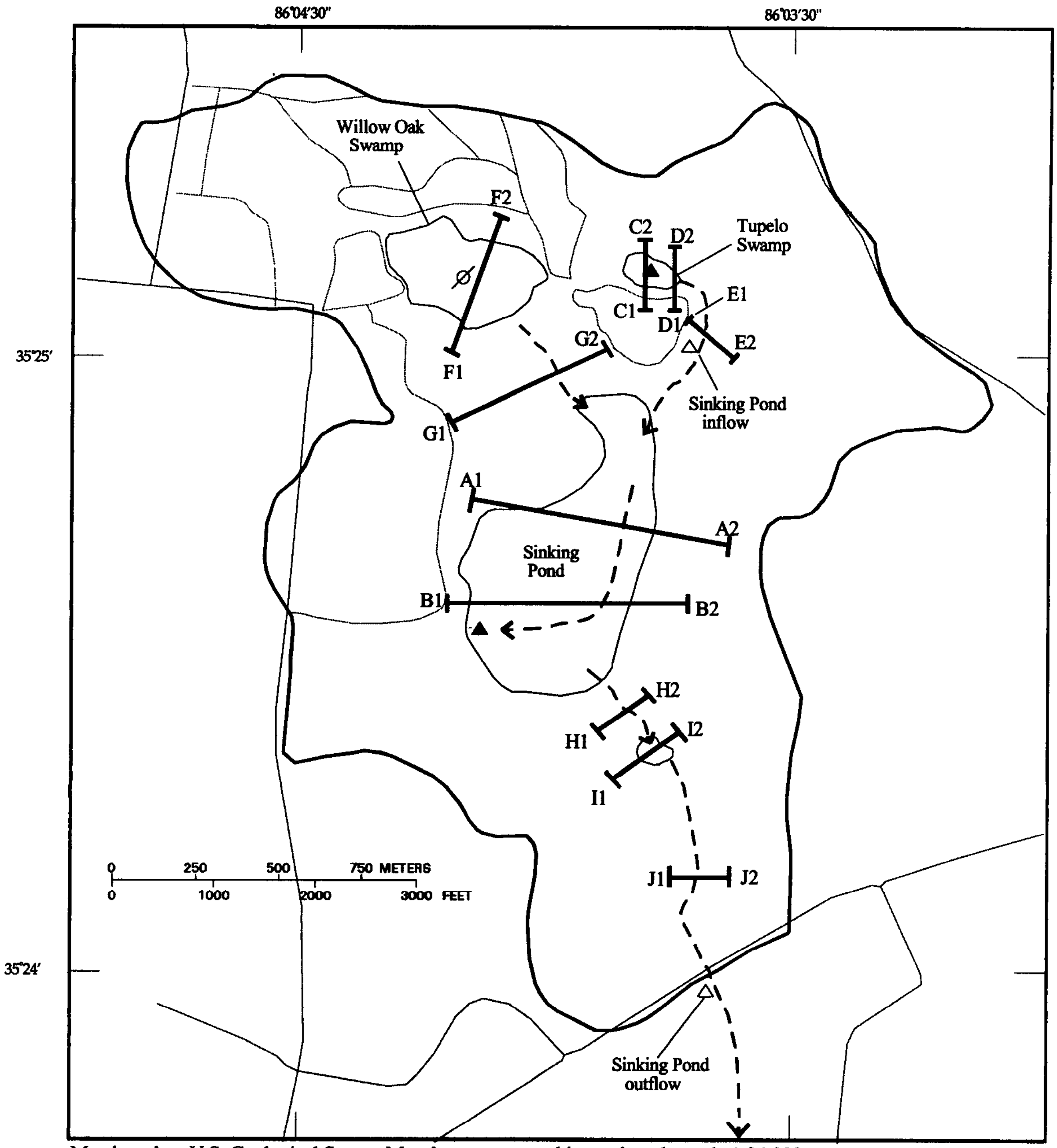
Table 3. Normal geographic ranges and preferred site characteristics for six wetland tree species at Arnold Engineering Development Center

Tree species	Normal geographic range	Preferred site characteristics
Water tupelo	Atlantic and Gulf Coastal Plains north to southeastern Virginia and southern Illinois; rare disjunct in Interior Low Plateaus (Johnson, 1990).	Deep swamps and wet depressions and sloughs; prefers sites with soil at or near saturation throughout growing season; tolerates prolonged flooding to 4 m and occasional flooding to 6 m; seeds develop best in saturated soil with shallow periodic flooding by flowing water (Johnson, 1990).
Overcup oak	Atlantic and Gulf Coastal Plains from northwestern Florida north to Delaware and southern Illinois and Indiana; rare disjunct in Interior Low Plateaus (Solomon, 1990).	Poorly drained, clay-rich alluvial soils of southern river flood plains, shallow swamps and sloughs, first bottoms and terraces of large streams; tolerates continuous flooding through two growing seasons or longer; grows best in well-drained, loamy soil, but natural occurrence in upland sites is rare (Solomon, 1990).
Willow oak	Atlantic Coastal Plain from New Jersey to South Carolina; southern United States from southeastern Texas to southern Illinois to northwestern Florida; endemic to Interior Low Plateaus (Schlaegel, 1990).	Higher sites on first and second bottoms of major streams; minor stream bottoms, wet upland flats and depressions; rare in upland sites; tolerates episodic growing-season flooding; requires ample soil moisture but intolerant of prolonged soil saturation; grows best in deep, loamy, uncompacted soils with water-table depth of 0.6-1.8 m and root-zone pH between 4.5 and 5.5 (Schlaegel, 1990).
Sweetgum	Southeastern United States except southern Florida and high elevations in the Appalachians; Atlantic Coastal Plain north to southwestern Connecticut; endemic to Interior Low Plateaus (Kormanik, 1990).	Adapted to a wide range of soil characteristics and moisture conditions; common along stream bottoms, wet depressions, and on well-drained slopes and ridges; grows best in medium textured soils without hardpan and with moderate to good internal drainage; seedlings moderately tolerant of complete inundation for as long as 10 days (Hosner, 1960; Kormanik, 1990).
Black tupelo	Eastern United States except for lower Mississippi River Alluvial Plain; southern Maine to central Florida, west to eastern Oklahoma, north to southern Ontario; endemic to Interior Low Plateaus (McGee, 1990).	Grows on a wide variety of sites from seasonally flooded river bottoms to well-drained slopes and ridges; grows best on well-drained flood-plain sites; mature trees tolerant of flooding during growing season for 21 days or longer (Broadfoot and Williston, 1973; McGee, 1990).
Red maple	Eastern North America from Newfoundland south to southern Florida, west to southeastern Texas, north to Wisconsin, northwest to southeastern Manitoba; endemic to Interior Low Plateaus (Walters and Yawney, 1990).	Thrives over an extraordinary range of soil characteristics, moisture availability, temperature range; suitable sites range from sand ridges to peat bogs and swamps; grows best in moist, well-drained soil, but commonly found in sites with extreme soil-moisture conditions—either poorly or excessively drained; common in southern swamps, flood plains, and wet depressions; seedlings moderately tolerant of complete inundation for as long as 10 days (Hosner, 1960; Walters and Yawney, 1990).

wetlands, include American hornbeam, eastern hophornbeam, and pawpaw. The spatial distribution of these and other tree species were evaluated across a range of hydrologic conditions to relate tree distribution to elevation and water levels.

Transect Locations and Sampling Methods

Ten transects, 150 to 800 m in length, were established in the Sinking Pond area (fig. 17 and table 4). The transects were located and oriented to cross areas of forested wetlands along soil-moisture and flood-duration gradients. Six transects crossed seasonally flooded ponds. Two transects were established across Sinking Pond (A1-A2 and B1-B2) and two across Tupelo Swamp (C1-C2 and D1-D2). Transect A1-A2 and D1-D2 crossed shallower parts of Sinking Pond and Tupelo Swamp, respectively, near the transitions between the disjunct trees and more typical local wetland trees. Transects B1-B2 and



Map based on U.S. Geological Survey Manchester topographic quadrangle, scale 1:24,000
Pond margins modified from Patterson, 1989

EXPLANATION

DRAINAGE DIVIDE

POND MARGIN

INTERMITTENT FLOW PATH

ROAD

TRAIL

▲ CONTINUOUS STAGE RECORDER

△ CONTINUOUS STREAMFLOW STATION

Ø CREST STAGE GAGE

J1 J2 LOCATION AND DESIGNATION OF VEGETATION TRANSECT

Figure 17. Location of vegetation transects in the Sinking Pond area.

Table 4. *Summary of lengths, areas, and forest density for vegetation transects in the Sinking Pond area*

[m, meters; m^2, square meters; trees/100 m^2, trees per 100 square meters; cm^2/m^2, square centimeters per square meter]

Transect	Geomorphic setting	Length (m)	Area (m^2)	[1]Number of species	[2]Number of trees	Stem density (trees/ 100 m^2)	Basal area (cm^2/m^2)
A1-A2	Compound sink	793	2,898	30	427	15	38.0
B1-B2	Compound sink	730	2,671	24	332	12	41.2
C1-C2	Karst pan	209	766	18	171	22	58.1
D1-D2	Karst pan	189	692	13	115	17	43.5
E1-E2	Channel	168	614	17	265	43	36.1
F1-F2	Compound sink	373	1,363	15	178	13	30.5
G1-G2	Swale	426	1,557	20	543	35	25.9
H1-H2	Swale	181	663	18	169	25	36.1
I1-I2	Compound sink	244	892	16	148	16	35.6
J1-J2	Channel	176	643	21	276	43	30.3

[1]Includes plant varieties identified to genus only; details given in text and Appendix 2.
[2]*Vaccinium* spp. and *Azalea* spp. were not enumerated.

C1-C2 crossed the deeper parts of Sinking Pond and Tupelo Swamp, through the cores of the disjunct stands. Transect F1-F2 bisected Willow Oak Swamp near the crest-stage gage, and transect I1-I2 crossed a small sinkhole pond along the Sinking Pond outflow channel.

Two transects crossed intermittent drainageways that carry flow into the north end of Sinking Pond: transect E1-E2, on the channel from Tupelo Swamp to Sinking Pond, and transect G1-G2, on the broad drainageway between Willow Oak Swamp and Sinking Pond. The two remaining transects crossed the Sinking Pond outflow channel: transect H1-H2, about 100 m downstream of the Sinking Pond spillway, and transect J1-J2 across a relatively well-developed channel about 300 m north of the Sinking Pond outflow gage.

Land-surface elevations in meters above sea level were surveyed to the nearest 0.01 m along the 10 vegetation transects using vertical control from the nearest surveyed gage. Horizontal distance along the transects was measured to the nearest 0.3 m with a fiberglass tape. Breast-height diameter (DBH) of trees and saplings was measured to the nearest 0.5 cm and used to calculate basal area. All trees and saplings within a 4-m wide swath along each transect were identified, measured, and counted. Land-surface elevation at the base of each tree was assumed to equal that along the center line of the transect at the same horizontal distance. Horizontal distance, elevation, species, and DBH were noted for each individual tree and sapling.

Daily records from the continuous-stage recorders were used to relate tree elevations to flooding duration along the transects through Sinking Pond and Tupelo Swamp. A similar relation was developed for the Willow Oak Swamp transect, based on linear interpolation between the periodic stage observations and crest-stage marks. Water year 1994 (October 1993 through September 1994) was selected as the period of comparison because stage was monitored in the three ponds during that time. Elevation was used as a surrogate for moisture availability along the other transects. Lower sites were assumed to be generally wetter than higher sites.

Flooding-Duration and Elevation Distributions of Selected Tree Species

Forty species of trees were identified, and members of six genera were noted but not identified to species (Appendix 1). Water tupelo and overcup oak were restricted to Tupelo Swamp (transects C1-C2 and D1-D2) and the main body of Sinking Pond (transects A1-A2 and B1-B2), respectively. In both cases, the disjunct wetland trees dominated the deeper parts of the ponds in which they occurred, in terms of both relative frequency and relative basal area. Willow oak dominated the interior of Willow Oak Swamp (transect F1-F2) and was prominent in Sinking Pond and along Sinking Pond inflow channel (transect E1-E2). Red maple and sweetgum were among the five most numerous species in all 10 transects. Black

tupelo was present in all transects and among the five most numerous species along seven transects. Other wetland trees such as pawpaw, American hornbeam, and eastern hophornbeam were prominent along one or two transects. Appendix 2 contains the number of individuals, relative frequency, relative basal area, and summaries of the elevation distributions for all tree species noted along the 10 transects.

The 10 transects showed differences between seasonally flooded ponds and intermittent drainageways with respect to stem density (number of trees per unit area) and basal area. In general, the ponds had higher basal areas (normalized by the land-surface area of the transect) but lower stem densities than the drainageways (table 4 and fig. 18). Wilcoxon rank tests (Wannacott and Wannacott, 1985) indicate these differences are statistically discernible at the 0.057 and 0.005 error levels for stem density and basal area, respectively. In addition to the consistent differences between ponds and channels, species composition and distribution also varied considerably among transects.

The transects across Willow Oak Swamp (F1-F2), and the shallow part of Sinking Pond (A1-A2) show similar patterns of wetland tree-species distribution with respect to flooding duration (fig. 19). The flooding-duration distributions for red maple and sweetgum lie close to the flooding-duration distributions for the land surface along these transects. The similarity of the flooding-duration distributions of red maple and sweetgum to that of the land surface

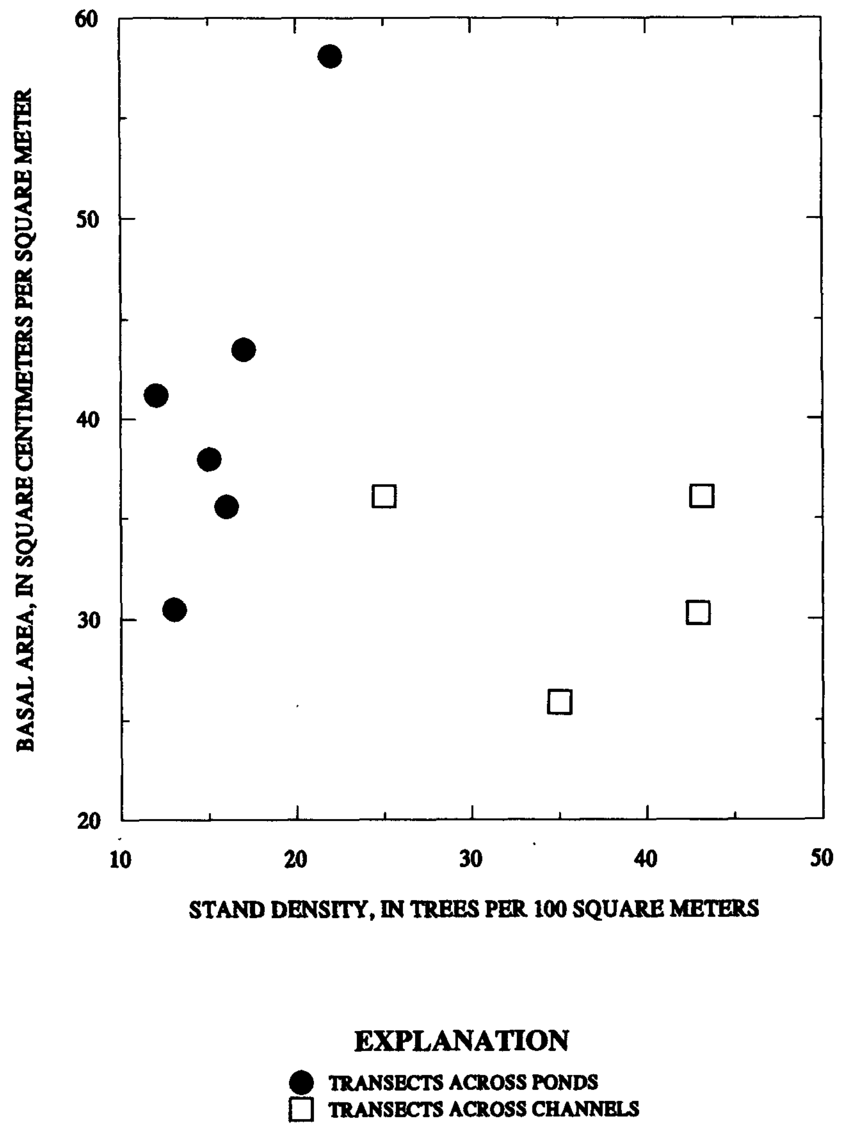


Figure 18. **Relation of basal area to stand density along 10 vegetation transects in the Sinking Pond area.**

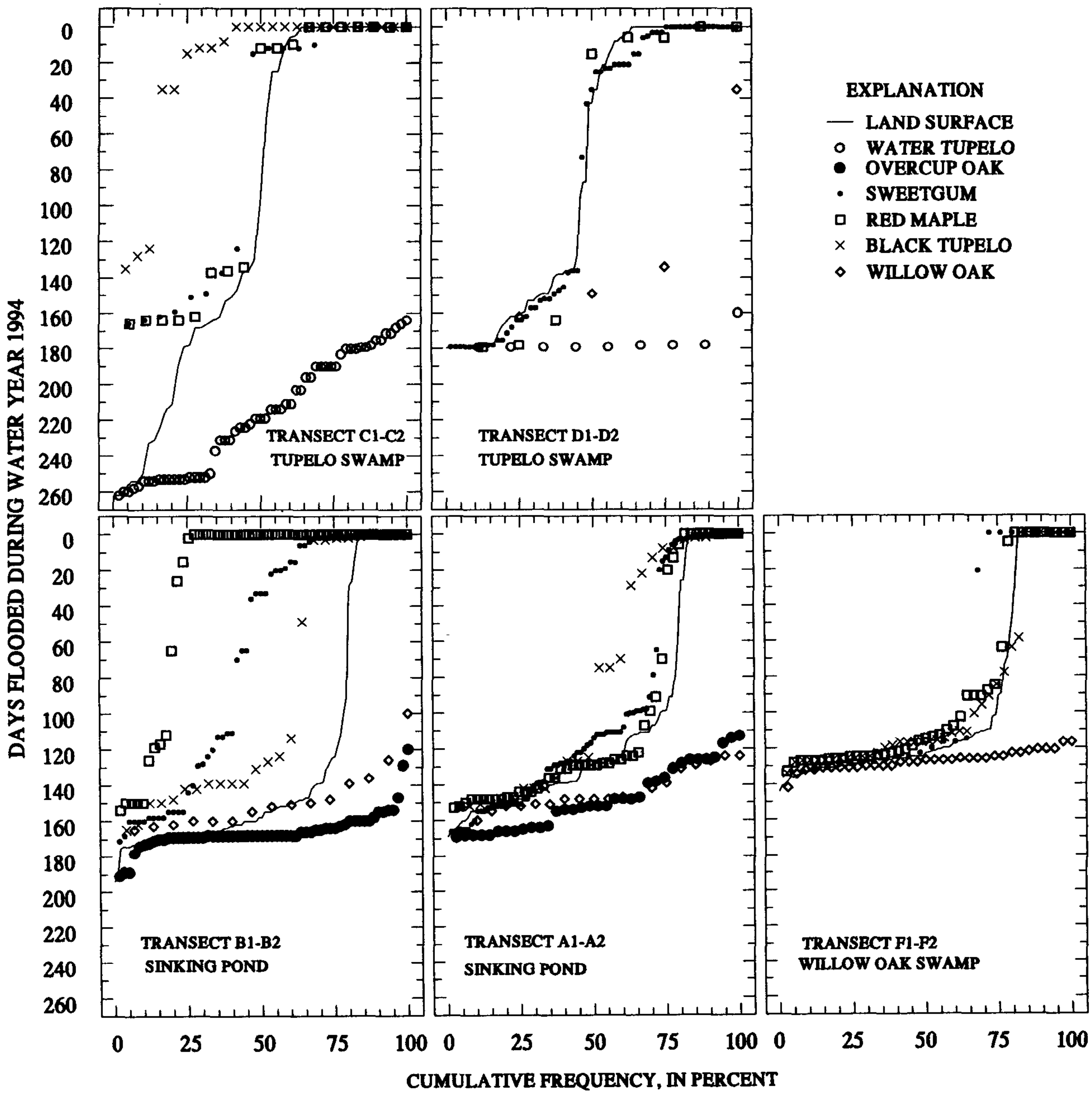


Figure 19. Flooding-duration distributions for selected tree species along five transects through monitored wetland sites in the Sinking Pond area.

indicates that these trees are exploiting the entire range of sites along the two transects with little preference in regard to flooding duration. More specialized wetland trees, overcup oak and willow oak, are concentrated in the wettest sites but share some of these sites with red maple, sweetgum, and black tupelo. Overcup oak and willow oak have similar flood-duration distributions along transect A1-A2; both species were flooded at least 110 days in 1994 (fig. 19). About 60 percent of sweetgum and 70 percent of red maple along transect A1-A2 had 1994 flood durations of 110 days or greater, overlapping the flood-duration ranges of overcup oak and willow oak. Similarly, 45 percent of red maple, 50 percent of black tupelo, and 60 percent of sweetgum along transect F1-F2 had 1994 flooding durations greater than 117 days, overlapping the flood-duration range of willow oak in Willow Oak Swamp (fig. 19).

The deep transect through Sinking Pond (B1-B2) showed pronounced vertical zonation of wetland tree species. Flooding durations for overcup oak along transect B1-B2 ranged from 120 days to 190 days in 1994. Only one willow oak along this transect was flooded fewer than 120 days in 1994, indicating a 90 percent overlap with the flood duration of overcup oak. However, the entire flood-duration distribution of willow oak along transect B1-B2 lies above the corresponding percentiles for overcup oak along this transect (fig. 19). The vertical segregation of overcup oak and willow oak along transect B1-B2 differs from the similar flood-duration distribution of these two species in the shallow part of Sinking Pond (transect A1-A2) (fig. 19). The flood-duration distribution for sweetgum along transect B1-B2 is skewed toward drier sites in comparison to transect A1-A2. The median 1994 flood duration for sweetgum along the deep Sinking Pond transect (B1-B2) is 33 days, compared to 114 days along the shallow transect (A1-A2) (fig. 19). Red maple shows a similar difference between the two Sinking Pond transects. Along the deeper transect (B1-B2), 73 percent of red maple were never flooded in 1994 compared with 19 percent along transect A1-A2 (fig. 19).

Along both Tupelo Swamp transects (C1-C2 and D1-D2), water tupelo occupied sites that were flooded 160 days or longer in 1994. The water tupelo form a single-species stand that occupies the wet interior of the pond. The wettest sites along transect C1-C2 were flooded longer than 260 days in 1994. Sweetgum, red maple, and willow oak were restricted to sites flooded fewer than 180 days in 1994, and fewer than 30 percent of these species had 1994 flooding durations greater than 160 days along either Tupelo Swamp transect (fig. 19).

The two transects across well defined channels showed relatively little vertical zonation of most wetland tree species. The elevation distributions for red maple, sweetgum, and black tupelo are close to each other and to the elevation distribution of the land surface along most of transects E1-E2 and J1-J2 (fig. 20). Willow oak is concentrated in the lower parts of transect E1-E2. Along transect J1-J2, the upper percentile elevations of wetland tree species fall below the corresponding percentile elevations for land surface (fig. 20).

Two transects across broad swales shared a similar pattern of vertical zonation among wetland tree species. Along transect G1-G2, northwest of Sinking Pond, elevation distributions for red maple and sweetgum were skewed downward relative to the elevation distribution for land surface. The lowest part of this transect was dominated by a thick stand of small papaw. Along transect H1-H2, the elevation distribution for red maple lies close to that of the land surface, but the distributions for sweetgum and black tupelo are skewed downward.

The pattern of vertical zonation among wetland trees across a small compound sink south of Sinking Pond (I1-I2) shared some characteristics of the patterns across the larger compound sinks but resembles the patterns across broad swales in other respects. Along this transect, the elevation distribution for one locally common wetland tree, red maple, was skewed upward relative to the distribution of land-surface elevations. Elevation distributions for two other locally common wetland trees, sweetgum and black tupelo were skewed downward relative to land surface (fig. 20).

Geomorphic and Hydrologic Controls on Wetland-Tree Distribution

Tree-species composition and distribution in Tupelo Swamp and Sinking Pond reflect the distinct geomorphic and hydrologic characteristics of the two ponds and the physiological adaptations and competitive strategies of the trees they support. Domination of the wet interior of Tupelo Swamp by water tupelo is nearly exclusive, with minimal overlap in elevation or flooding duration between the water tupelo and other

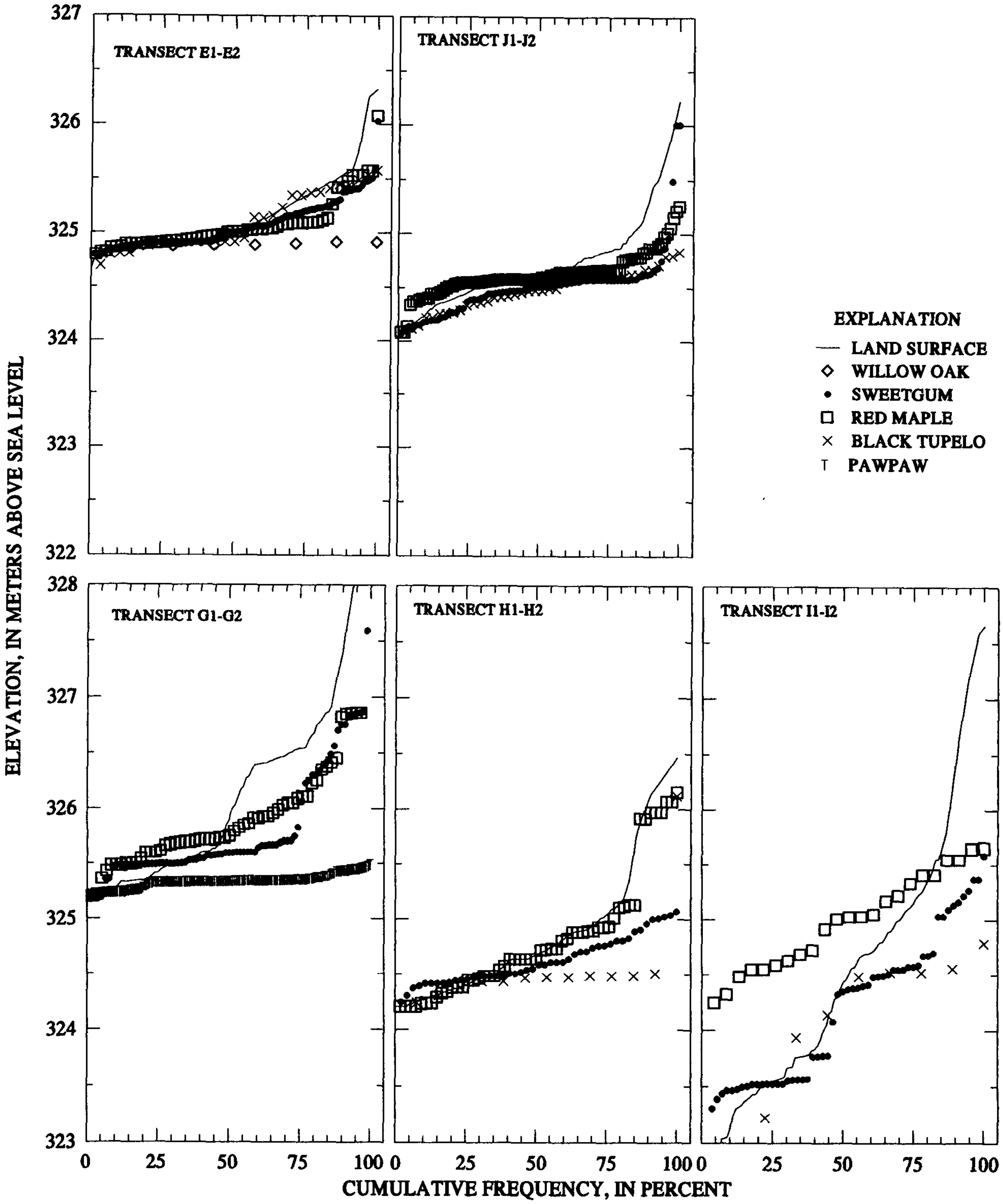


Figure 20. Frequency distributions of elevation for land surface and selected tree species along five transects through uninstrumented wetland sites in the Sinking Pond area.

wetland trees. Water tupelo grows best in saturated soil and thrives in sites that are too wet for most trees (Johnson, 1990). This strong affinity for very wet sites reflects physiological and anatomical adaptations that include controlled anaerobic respiration and root systems that create oxidized zones in the rhizosphere (Johnson, 1990). The single-species stand of water tupelo in Tupelo Swamp, and the rather abrupt transition between the water tupelo and other wetland trees near the pond's periphery, appear to reflect physical site conditions and physiological limitations on the abilities of different tree species to exploit or even tolerate those conditions.

Tree-distribution patterns in Sinking Pond vary from one part of the pond to another. In the shallow part of the pond, overcup oak and willow oak have similar flooding-duration distributions, and both species overlap substantially with red maple and sweetgum in terms of elevation and flooding duration. Near the deeper part of the pond, vertical zonation of wetland trees is much more pronounced. In part this stronger zonation reflects the concentration of overcup oak in the deeper and wetter sites available in the interior of Sinking Pond. However, the mere presence of deeper sites does not explain why red maple and sweetgum are concentrated in drier sites along the deep Sinking Pond transect (B1-B2) than these species occupy along the shallow transect (A1-A2).

One possible explanation is that competition from overcup oak and willow oak actively excludes red maple and sweetgum from otherwise suitable sites in the interior of Sinking Pond. In contrast to water tupelo, overcup oak grows best in well-drained loamy soil (Solomon, 1990). The natural occurrence of overcup oak in wet sites reflects the ability of mature plants to tolerate flooding and developmental adaptations that give its acorns and seedlings a significant competitive advantage in seasonally flooded sites. Unlike most white oaks, overcup oak acorns remain dormant during the winter months until the recession of surface water triggers germination (Solomon, 1990). Some of the wettest sites in Sinking Pond may be too wet for red maple, sweetgum, and other local wetland plants. Such sites, once colonized by overcup oak, would provide a seed source for expansion into adjacent, somewhat drier sites. Sites that would normally be marginal to red maple and sweetgum might become submarginal in the presence of a better adapted tree, while normally suitable sites might become marginal.

Transects across seasonally flowing drainageways revealed two distinct patterns of vertical zonation. Transects across broad, poorly defined channels (swales) had a large degree of vertical zonation, with elevation distributions for locally common wetland trees skewed downwards relative to the land surface—the opposite of vertically zoned transects through pond interiors. In contrast, transects across narrow, well-defined channels were characterized by the near absence of vertical zonation among wetland trees. The difference in vegetation patterns across the two types of channel suggests that even limited incision (or excavation) may have a pronounced drying effect in these small headwater valleys. Conversely, filling small ditches may be a highly effective wetland restoration technique in The Barrens.

SUMMARY AND CONCLUSIONS

Surface-water stage and flow, rainfall, and ground-water levels were measured at or near five sinkhole-wetland sites at Arnold Engineering Development Center, near Manchester, Tennessee. Tree-distribution patterns were determined at three of the sinkhole-wetland sites and across nearby intermittent drainageways. The data were collected to assess the relations between sinkhole morphology, flooding regime, ground-water interaction, and tree-species distribution.

The wetland sites occupied two geomorphically distinct types of karst depression: compound sinks and karst pans. Three sites, Sinking Pond, Westall Swamp, and Willow Oak Swamp, occupy compound sinks—relatively deep, steep sided depressions with depths greater than 2.5 m and readily discernible internal drains. The interior topography of the compound sinks is typically dominated by an internal drainage system that includes coalesced sinkholes and connecting channels. Two sites, Tupelo swamp and Goose Pond, occupy karst pans—flat-bottomed, shallow (<1.5 m) depressions that lack visible internal drains.

The water regimes of compound sinks were characterized by rapid rises and recessions—about 2 m in 24 hours in Sinking Pond and 1.7 m in 24 hours at Westall Swamp. Ground-water and surface-water levels closely tracked each other at Sinking Pond and Westall Swamp during periods of high surface-water stage. During seasonal recessions, ground-water levels fell 3 to 4 m below the bottom elevations of these wetlands. Periodic observations at Willow Oak Swamp

indicate a water regime analogous to Sinking Pond and Westall Swamp. Willow Oak Swamp began filling later and drained earlier than the two other compound sinks. Maximum water depths were 3.5 m in Sinking Pond, 2.6 m in Westall Swamp, and 3.1 m in Willow Oak Swamp.

The two karst pans, Tupelo Swamp and Goose Pond, had narrower ranges of water levels and longer hydroperiods than the compound sinks. Water depths ranged from 0 to 1.1 m in Tupelo Swamp and 0 to 0.7 m in Goose Pond. Periodic sampling indicated the bottoms of both pans remained at or near saturation throughout the year, including periods when standing water was absent. Ground-water levels at Tupelo Swamp and Goose Pond remained below surface-water levels throughout the monitoring period.

Surface-water flow into and out of Sinking Pond occurred primarily during winter and early spring. Flow from Tupelo Swamp to Sinking Pond never exceeded 0.15 m^3/s. Flow at a gage downstream of Sinking Pond was generally less than 0.2 m^3/s but exceeded 0.5 m^3/s during winter storms. Maximum recorded discharge at this gage was 1.23 m^3/s.

The water regimes of sinkhole wetlands reflect geomorphic and hydrologic controls including:

1. Sinkhole geometry.
2. Connection to the ground-water system.
3. Bottom elevation relative to normal range of water table.
4. Periodicity of water-table fluctuation.
5. Drainage-basin characteristics (basin area, relief, ground cover, and other factors affecting runoff generation).

At AEDC these controls produce a consistent relation between sinkhole morphology, ground-water interaction, and flooding regime. Analogous relations have been documented in other karst settings, but the details of such relations vary with hydrologic conditions.

Tree species were identified and the elevations and diameters of individual trees were measured along 10 transects. Two transects crossed Sinking Pond, two crossed Tupelo Swamp, and one crossed Willow Oak Swamp. Two transects crossed intermittent drainageways that carry flow into Sinking Pond. One of the tributary drainageways is a well-developed channel that carries flow from Tupelo Swamp, and the second is a broad swale that carries overflow from Willow Oak Swamp. Three transects crossed different sections of the Sinking Pond outflow channel including (1) a broad swale near the Sinking Pond spillway, (2) a small compound sinkhole downstream of the spillway, and (3) a well-defined channel upstream of the Sinking Pond outflow gage.

Transects through ponds had fewer trees but more basal area per unit area of land surface than did transects through channels. Water tupelo, a coastal-plain tree that is rare in the study area, dominated the interior of Tupelo Swamp but was absent from the other sampled sites. The elevation and flood-duration distributions for water tupelo had minimal overlap with the distributions for local wetland trees such as red maple and sweetgum. The local wetland trees were largely confined to the pond's periphery.

Another coastal-plain tree, overcup oak, was found only in the flooded interior of Sinking Pond where it was the dominant tree species. Overlap between the elevation and flood-duration distributions for overcup oak was minimal across the deeper Sinking Pond transect but was substantial across the shallow transect. Along the deeper Sinking Pond transect, red maple and sweetgum were excluded from elevations at which these trees are common along the shallow transect. Willow oak dominated the interior of Willow Oak Swamp and had a relation to other wetland trees similar to that of overcup oak in the shallow Sinking Pond transect.

Transects across broad swales had relatively large degrees of vertical zonation among wetland and upland tree species. Wetland trees such as red maple, sweetgum, black tupelo, and pawpaw tend to be concentrated in the moist lower parts of the swale transects. Vertical zonation of tree species was much less pronounced along transects through well-defined channels. Red maple, sweetgum, and black tupelo were distributed fairly evenly along the channel transects, showing little preference between sites in or near the channel and sites on adjacent slopes.

The hydrologic and tree-distribution results of this investigation have implications for environmental management in The Barrens. The consistent relation between sinkhole morphology, ground-water interactions, and flooding regime indicate that geomorphic characteristics provide a rapid, inexpensive means for estimating a given wetland's connection to the local ground-water system. Depending on the relation between a wetland's flooding regime and the ground-water system, natural processes such as sedimentation and sinkhole collapse, localized human activities such as ground-water extraction, or global climate change

could have pronounced drying or wetting effects with subsequent ecological consequences.

Compound sinks, with visible internal drains, are closely connected to the ground-water system. Flooding of compound sinks depends upon seasonal rises of the water table to levels that prevent water from entering the sinks' internal drains. Any human activity or natural occurrence that results in a general lowering of the local water table would have a drying effect on compound sinks in the immediate vicinity. Under such circumstances, specialized wetland plants that are successful under the present flooding regime, such as the overcup oak stand in Sinking Pond, would be at risk. Conversely, accelerated sedimentation from logging or other land-use changes has the potential to fill the internal drains of compound sinks. If their internal drains stopped functioning, sites such as Sinking Pond and Willow Oak Swamp would become wetter, possibly exceeding the flooding tolerance of their present vegetation.

Karst pans are relatively isolated from the ground-water system and therefore less sensitive to water-table fluctuations than compound sinks are. The wettest pans, such as Tupelo Swamp and Goose Pond, are too wet for many plants but provide scarce habitat for plants with specialized physiological adaptations. Sinkhole collapse has the potential to turn these sites into compound sinks with drastically altered flooding regimes. Specialized wetland plants such as water tupelo might not survive such a transition. Because the pans are shallow, they are potentially vulnerable to sedimentary filling. Excessive sedimentation would raise the land surface, creating a drying effect with potential ecological consequences similar to sinkhole collapse.

This investigation raises several questions for future study. Karst development is an active process in The Barrens, but its nature, distribution, and rate are not yet understood. In particular, the geomorphic stability of karst pans—and the ecosystems they support—is difficult to assess without a better understanding of the processes by which they formed. Another question is the degree to which soil-moisture, soil-chemistry, and understory-plant gradients interact with flooding patterns and tree-species distribution. This study has documented relatively strong associations between tree distribution and flooding patterns. However, many of the rare or threatened species at AEDC are understory plants which may respond strongly to environmental factors other than surfaces flooding. Finally, the direction and environmental controls on ecological succession associated with disjunct trees is unclear. The peripheral (shallow) transects through Sinking Pond and Tupelo Swamp indicate that the disjunct trees are interspersed with local species near the edges of relatively pure stands. This intermingling may represent a stable transition zone, an expansion of the disjuncts into drier sites from a stable, wetter core, or invasion of the disjunct stands by local species. Periodic resurvey of the vegetation transects established for this study would provide a framework for monitoring the stability of the disjunct stands at AEDC.

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APPENDIXES

APPENDIX 1. COMMON AND SCIENTIFIC NAMES OF PLANTS IDENTIFIED ALONG VEGETATION TRANSECTS

[Nomenclature follows Duncan and Duncan, 1988, unless otherwise noted]

ash	*Fraxinus* spp.
azalea, wild	[1]*Azalea* spp.
birch, river	*Betula nigra* L.
buckthorn, Carolina	*Rhamnus caroliniana* Walt.
buttonbush	*Cephalanthus occidentalis* L.
cherry, black	*Prunus serotina* Ehrh.
dogwood, flowering	*Cornus florida* L.
silky	[1]*Cornus amomum* Mill.
swamp	*Cornus stricta* Lam.
elm	*Ulmus* spp.
hackberry, sugarberry	*Celtis* spp.
hercules club	*Aralia spinosa* L.
hickory, mockernut	*Carya tomentosa* (Poir.) Nutt.
holly, American	*Ilex opaca* Ait.
hophornbeam, eastern	*Ostrya virginiana* (Mill.) K. Koch
hornbeam, American	*Carpinus caroliniana* Walt.
maple, red	*Acer rubrum* L.
sugar	*Acer saccharum* Marsh.
oak, black	*Quercus velutina* Lam.
northern red	*Quercus rubra* L.
overcup	*Quercus lyrata* Walt.
pin	*Quercus palustris* Muenchh.
post	*Quercus stellata* Wang.
scarlet	*Quercus coccinea* Muenchh.
southern red	*Quercus falcata* Michx.
water	*Quercus nigra* L.
white	*Quercus alba* L.
willow	*Quercus phellos* L.
oleaster	*Eleagnus* spp.
pawpaw	*Asimina triloba* (L.) Dunal
persimmon, common	*Diospyros virginiana* L.
pine, loblolly	*Pinus taeda* L.
privet	*Lingustrum vulgare* L.
sassafras	*Sassafras albidum* (Nutt.) Nees
serviceberry	*Amelanchier arborea* (Michx. f.) Fern.
sourwood	*Oxydendrum arboreum* (L.) DC.
storax (American snowbell)	*Styrax americanus* Lam.
sumac, winged	*Rhus copallina* L.
sweetgum	*Liquidambar styraciflua* L.
sweetshrub	[1]*Calycanthus floridus* L.
sycamore, American	*Platanus occidentalis* L.
tuliptree (yellow poplar)	*Liriodendron tulipifera* L.
tupelo, black (blackgum)	*Nyssa sylvatica* Marsh.
water	*Nyssa aquatica* L.
Vaccinium	*Vaccinium spp.*
Virgina willow	[1]*Itea virginica* L.

[1]According to Britton and Brown, 1970

APPENDIX 2. RELATIVE IMPORTANCE AND ELEVATION QUARTILES FOR TREE SPECIES ALONG VEGETATION TRANSECTS IN THE SINKING POND AREA, ARNOLD ENGINEERING DEVELOPMENT CENTER

[N, number of stems; Min, minimum; P25, 25th percentile; Med, median; P75, 75th percentile; Max, maximum; <.1, less than 0.1 percent]

Transect A1-A2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level)				
				Min	P25	Med	P75	Max
sweetgum	88	20.6	17.7	323.62	324.02	324.34	324.64	329.86
red maple	49	11.5	13.4	323.92	324.08	324.19	324.60	329.83
silky dogwood	46	10.8	<.1	323.99	324.12	324.21	324.29	324.48
American hornbeam	38	8.9	.8	324.35	324.39	324.42	324.47	324.93
overcup oak	35	8.2	23.1	323.49	323.67	323.94	324.15	324.34
flowering dogwood	32	7.5	.4	324.77	324.93	326.06	326.98	329.81
black tupelo	27	6.3	1.8	323.94	324.10	324.49	324.67	325.67
sourwood	22	5.2	4.9	324.51	325.86	327.60	329.37	329.87
willow oak	20	4.7	8.6	323.60	323.98	324.04	324.13	324.25
pawpaw	10	2.3	<.1	324.37	324.42	324.48	324.68	329.68
pin oak	10	2.3	6.8	323.95	324.09	324.12	324.19	324.39
hackberry, sugarberry	9	2.1	2.4	324.35	324.38	324.41	324.42	325.80
white oak	8	1.9	12.2	324.43	324.62	324.97	326.01	328.13
ash	7	1.6	1.7	324.41	324.71	324.93	325.00	325.12
water oak	5	1.2	.8	324.13	324.24	324.36	324.37	324.38
sassafras	3	.7	<.1	325.04	325.30	325.56	327.60	329.64
elm	3	.7	.1	324.54	324.61	324.68	324.68	324.68
storax	3	.7	<.1	323.99	323.99	323.99	324.03	324.08
southern red oak	2	.5	3.6	325.56	326.63	327.70	328.77	329.84
river birch	2	.5	.7	323.60	323.67	323.73	323.79	323.86
swamp dogwood	1	.2	<.1	323.89	323.89	323.89	323.89	323.89
Carolina buckthorn	1	.2	<.1	324.68	324.68	324.68	324.68	324.68
black cherry	1	.2	<.1	324.79	324.79	324.79	324.79	324.79
tuliptree	1	.2	.5	326.53	326.53	326.53	326.53	326.53
American sycamore	1	.2	.3	324.17	324.7	324.17	324.17	324.17
northern red oak	1	.2	.1	324.39	324.39	324.39	324.39	324.39
mockernut hickory	1	.2	<.1	329.83	329.83	329.83	329.83	329.83
eastern hophornbeam	1	.2	.2	324.41	324.41	324.41	324.41	324.41

Transect B1-B2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
sweetgum	60	18.1	11.1	323.21	324.10	324.57	324.79	328.47
overcup oak	60	18.1	43.1	322.51	323.50	323.58	323.71	324.27
sourwood	53	16.0	6.9	324.5	324.77	325.18	327.94	328.3
red maple	51	15.4	7.6	323.89	324.83	324.91	325.05	328.23
black tupelo	25	7.5	4.2	323.65	324.10	324.21	324.75	325.21
flowering dogwood	20	6.0	.2	325.38	327.31	328.19	328.27	328.47
willow oak	15	4.5	9.2	323.65	323.81	323.95	324.08	324.41
tuliptree	9	2.7	<.1	324.90	324.92	324.94	324.98	328.14
white oak	8	2.4	5.4	324.54	324.67	324.74	325.58	327.91
scarlet oak	6	1.8	3.1	325.36	325.89	326.09	326.44	327.82
water oak	5	1.5	1.3	324.14	324.20	324.23	324.58	324.58
sassafras	5	1.5	.1	325.89	326.78	328.05	328.47	328.47
serviceberry	2	.6	<.1	325.64	325.80	325.96	326.13	326.29
post oak	2	.6	.8	325.39	326.12	326.86	327.59	328.32
mockernut hickory	2	.6	4.5	326.91	327.25	327.58	327.92	328.26
black cherry	2	.6	<.1	327.93	327.98	328.04	328.10	328.16
Virginia willow	2	.6	<.1	324.07	324.11	324.15	324.19	324.23
southern red oak	1	.3	1.6	328.11	328.11	328.11	328.11	328.11
river birch	1	.3	.7	324.07	324.07	324.07	324.07	324.07
pawpaw	1	.3	<.1	325.36	325.36	325.36	325.36	325.36
storax	1	.3	<.1	323.99	323.99	323.99	323.99	323.99
elm	1	.3	.1	324.28	324.28	324.28	324.28	324.28

Transect C1-C2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
water tupelo	58	33.9	47.9	326.37	326.47	326.59	326.64	326.73
black tupelo	24	14.0	.7	326.92	327.08	327.36	327.45	328.02
sweetgum	19	11.1	10.3	326.72	326.83	327.08	327.44	328.13
red maple	18	10.5	2.2	326.72	326.78	327.09	327.43	329.42
flowering dogwood	12	7.0	.5	327.45	328.07	330.10	330.52	331.00
sourwood	10	5.8	.7	327.07	327.42	327.60	327.76	328.65
pawpaw	10	5.8	<.1	327.09	327.15	327.17	327.25	327.34
white oak	5	2.9	13.5	327.37	327.65	327.93	328.05	331.10
mockernut hickory	5	2.9	.2	328.48	329.35	330.07	330.22	330.47
tuliptree	3	1.8	11.3	327.58	327.78	327.99	328.86	329.74
willow oak	1	.6	8.0	326.92	326.92	326.92	326.92	326.92
water oak	1	.6	<.1	327.10	327.10	327.10	327.10	327.10
sassafras	1	.6	<1	328.07	328.07	328.07	328.07	328.07
scarlet oak	1	.6	1.3	328.02	328.02	328.02	328.02	328.02
northern red oak	1	.6	3.4	327.86	327.86	327.86	327.86	327.86
loblolly pine	1	.6	<.1	327.00	327.00	327.00	327.00	327.00
eastern hophornbeam	1	.6	<.1	330.22	330.22	330.22	330.22	330.22

Transect D1-D2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
sweetgum	63	54.8	27.3	326.66	326.74	327.04	327.22	331.66
sourwood	12	10.4	4.8	327.21	327.31	327.38	327.56	327.96
water tupelo	9	7.8	6.1	326.66	326.67	326.67	326.67	326.77
red maple	8	7.0	1.8	326.67	326.71	327.09	327.15	327.46
flowering dogwood	4	3.5	.5	327.65	327.65	329.44	331.50	332.29
willow oak	4	3.5	17.4	326.74	326.81	326.88	326.96	327.04
loblolly pine	3	2.6	7.3	331.10	331.31	331.52	331.66	331.80
mockernut hickory	3	2.6	3.8	327.89	328.38	328.87	329.92	330.96
black tupelo	2	1.7	3.9	327.03	327.21	327.40	327.58	327.76
white oak	2	1.7	11.4	327.12	327.15	327.19	327.22	327.26
southern red oak	2	1.7	.5	327.74	327.8	327.85	327.91	327.96
tuliptree	2	1.7	13.5	328.01	328.15	328.30	328.44	328.58
river birch	1	.9	1.8	326.66	326.66	326.66	326.66	326.66

Transect E1-E2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
sweetgum	108	40.8	9.4	324.79	324.90	325.00	325.20	326.03
red maple	57	21.5	17.8	324.79	324.91	325.01	325.09	326.08
black tupelo	30	11.3	3.4	324.69	324.90	324.93	325.36	325.57
water oak	22	8.3	.8	324.83	324.91	324.91	325.19	326.13
white oak	18	6.8	39.8	324.91	324.91	324.91	325.16	325.44
sourwood	7	2.6	.6	324.84	324.84	324.84	324.88	325.19
willow oak	7	2.6	27.7	324.85	324.87	324.88	324.90	324.91
flowering dogwood	4	1.5	.5	324.78	325.08	325.53	325.88	325.88
pawpaw	4	1.5	<.1	324.83	324.84	324.84	324.85	324.85
southern red oak	3	1.1	<.1	324.91	324.91	324.91	325.12	325.33
button bush	1	.4	<.1	324.91	324.91	324.91	324.91	324.91
black oak	1	.4	<.1	324.91	324.91	324.91	324.91	324.91
eastern hophornbeam	1	.4	<.1	325.34	325.34	325.34	325.34	325.34
sassafras	1	.4	<.1	324.79	324.79	324.79	324.79	324.79
tuliptree	1	.4	<.1	324.79	324.79	324.79	324.79	324.79

Transect F1-F2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level)				
				Min	P25	Med	P75	Max
red maple	42	23.6	11.6	324.26	324.91	325.29	325.69	327.09
black tupelo	39	21.9	2.3	324.14	324.9	325.18	325.64	327.15
willow oak	34	19.1	48.6	323.16	324.53	324.81	324.91	325.2
sweetgum	27	15.2	14.2	324.28	324.8	325.21	326.04	327.12
water oak	9	5.1	5.6	325.04	325.16	325.32	325.42	325.87
white oak	7	3.9	6.2	325.46	325.59	325.85	326.04	326.34
privet	4	2.2	<.1	324.95	324.98	325	325.05	325.14
mockernut hickory	4	2.2	.2	325.83	326.04	326.44	326.87	327.15
flowering dogwood	4	2.2	.4	325.79	325.83	325.87	325.94	326.07
sourwood	2	1.1	.6	326.4	326.43	326.47	326.5	326.54
northern red oak	2	1.1	1.4	325.94	326.11	326.27	326.44	326.6
southern red oak	2	1.1	5.9	325.95	325.99	326.02	325.06	326.1
American sycamore	1	.6	2.7	323.76	323.76	323.76	323.76	323.76
elm	1	.6	<.1	325.36	325.36	325.36	325.36	325.36

Transect G1-G2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level)				
				Min	P25	Med	P75	Max
pawpaw	158	29.1	2.7	325.2	325.33	325.34	325.35	325.49
sweetgum	78	14.4	13.1	325.17	325.50	325.60	326.01	328.77
eastern hophornbeam	68	12.5	2.7	325.25	325.57	326.01	326.47	326.54
red maple	58	10.7	14.9	325.2	325.62	325.77	326.10	328.73
American hornbeam	49	9.0	1.8	325.19	325.23	325.39	325.83	326.50
flowering dogwood	38	7.0	1.7	325.20	326.38	326.67	326.95	328.97
sourwood	23	4.2	5.4	326.01	326.47	326.64	327.24	328.89
black tupelo	23	4.2	1.7	325.22	325.58	325.67	326.28	326.75
white oak	18	3.3	47.3	325.34	325.52	325.91	326.49	326.97
mockernut hickory	9	1.7	5.4	325.23	325.42	326.29	326.44	328.79
elm	4	.7	.5	325.23	325.51	325.63	326.38	328.56
ash	4	.7	.1	325.50	325.53	325.61	325.77	326.03
tuliptree	3	.6	<.1	325.70	325.73	325.75	325.92	326.09
sugar maple	3	.6	.3	326.47	326.47	326.47	326.47	326.47
serviceberry	2	.4	.1	326.51	326.52	326.53	326.54	326.54
black oak	2	.4	.3	325.50	325.75	326.01	326.27	326.53
sweetshrub	1	.2	<.1	328.35	328.35	328.35	328.35	328.35
southern red oak	1	.2	2	326.76	326.76	326.76	326.76	326.76
black cherry	1	.2	<.1	325.79	325.79	325.79	325.79	325.79

Transect H1-H2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
red maple	54	32.0	13.9	324.21	324.45	324.68	324.93	326.15
sweetgum	47	27.8	8.3	324.25	324.46	324.58	324.77	325.07
flowering dogwood	17	10.1	2.0	324.64	324.86	325.17	325.30	326.37
black tupelo	13	7.7	4.5	324.24	324.43	324.47	324.48	326.12
mockernut hickory	12	7.1	4.2	324.70	324.98	325.06	325.61	326.24
sassafras	9	5.3	.6	324.56	324.68	325.90	326.14	326.21
white oak	5	3.0	44.6	324.47	324.64	324.68	324.88	325.11
northern red oak	4	2.4	<.1	324.72	325.82	326.18	326.20	326.27
silky dogwood	1	.6	<.1	324.36	324.36	324.36	324.36	324.36
oleaster	1	.6	<.1	325.45	325.45	325.45	325.45	325.45
pawpaw	1	.6	<.1	324.58	324.58	324.58	324.58	324.58
scarlet oak	1	.6	10.1	326.36	326.36	326.36	326.36	326.36
southern red oak	1	.6	11.2	326.45	326.45	326.45	326.45	326.45
sourwood	1	.6	<.1	324.54	324.54	324.54	324.54	324.54
serviceberry	1	.6	<.1	324.90	324.90	324.90	324.90	324.90
water oak	1	.6	.6	324.32	324.32	324.32	324.32	324.32

Transect I1-I2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
sweetgum	56	37.8	12.4	322.88	323.52	324.36	324.58	325.58
red maple	23	15.5	10.2	324.25	324.61	325.03	325.37	325.65
sassafras	20	13.5	.8	324.65	324.97	325.92	327.10	327.62
flowering dogwood	19	12.8	3.7	324.81	325.13	325.61	326.48	327.64
black tupelo	9	6.1	9.6	322.67	323.94	324.48	324.52	324.79
post oak	3	2.0	7.9	325.26	325.32	325.37	325.48	325.58
scarlet oak	3	2.0	14.1	324.72	325.96	327.21	327.40	327.60
sourwood	3	2.0	<.1	324.82	324.82	324.82	324.82	324.83
willow oak	3	2.0	20	323.34	323.36	323.39	323.48	323.58
black cherry	2	1.4	.1	325.15	325.26	325.37	325.49	325.60
mockernut hickory	2	1.4	.3	324.60	324.74	324.89	325.03	325.17
southern red oak	2	1.4	8.7	325.19	325.23	325.26	325.30	325.33
white oak	2	1.4	12.1	324.60	325.32	326.04	326.76	327.48
winged sumac	1	.7	<.1	325.29	325.29	325.29	325.29	325.29

Transect J1-J2

Species	N	Relative frequency (percent)	Relative basal area (percent)	Percentile elevations (meters above sea level) Min	P25	Med	P75	Max
red maple	94	34.1	9.0	324.09	324.54	324.59	324.66	325.26
sweetgum	78	28.3	24.9	324.07	324.39	324.51	324.58	326.01
black tupelo	41	14.9	4.6	324.09	324.35	324.47	324.60	324.83
flowering dogwood	23	8.3	2.8	324.78	324.87	325.10	325.48	326.14
white oak	10	3.6	27.4	324.38	324.49	324.72	324.80	325.48
sassafras	7	2.5	2.5	324.54	324.59	324.66	325.01	325.33
loblolly pine	4	1.4	<.1	324.67	324.79	324.92	325.02	325.05
water oak	3	1.1	<.1	324.51	324.60	324.70	324.71	324.72
oleaster	2	.7	<.1	325.47	325.50	325.54	325.58	325.61
post oak	2	.7	12.4	324.54	324.96	325.38	325.80	326.22
scarlet oak	2	.7	2.8	324.65	324.66	324.66	324.67	324.67
southern red oak	2	.7	11.7	324.81	324.83	324.85	324.87	324.89
sourwood	2	.7	1.7	324.54	324.54	324.54	324.54	324.54
black cherry	1	.4	.1	325.48	325.48	325.48	325.48	325.48
hercules club	1	.4	<.1	325.09	325.09	325.09	325.09	325.09
American holly	1	.4	<.1	324.91	324.91	324.91	324.91	324.91
northern red oak	1	.4	<.1	324.65	324.65	324.65	324.65	324.65
common persimmon	1	.4	<.1	326.01	326.01	326.01	326.01	326.01
serviceberry	1	.4	<.1	324.61	324.61	324.61	324.61	324.61

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AT ARNOLD ENGINEERING DEVELOPMENT CENTER, TENNESSEE