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EFFECT OF LAND DEVELOPMENT AND FOREST MANAGEMENT ON HYDROLOGIC RESPONSE IN SOUTHEASTERN COASTAL WETLANDS: A REVIEW

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Abstract: Land development activities such as agriculture, clear cutting, peat mining, and the planting of forest plantations on wetlands can affect the hydrologic behavior of these ecosystems by affecting their water storage and release patterns on the landscape. The effects of these development activities on hydrologic fluxes in peatlands (Typic Medisaprists) were compared to the effects of forest management practices in North Carolina using a field-tested hydrologic simulation model (DRAINMOD). Simulations revealed that natural peat-based (Histosol) pocosin systems lose 66% (80 cm) of the 123 cm of average annual rainfall by evapotranspiration (ET) and 34% (42 cm/yr) via annual runoff. Annual runoff values were 63 cm/yr for peat mining areas, 48 cm/yr for cleared peatlands, 46 cm/yr for peatlands converted to agriculture and 34 cm/yr for pine plantations, once the forest canopy is closed. Thus, these wetland alterations, except for forestry, significantly increased runoff and decreased ET compared to the natural ecosystem. Forest pine plantation management decreased runoff and increased ET. A case study of the effects of forest management practices was reviewed for a 15-year-old drained loblolly pine plantation growing on fine sandy loam soils (Thermic Typic umbraquults) in the coastal plains of North Carolina. Forestry activities such as thinning (i.e., reduced leaf area index by 50%) decreased ET and canopy interception and nearly doubled drainage loss (38 cm/yr to 60 cm/yr). Commonly applied forest practices, such as drainage, increased the average number of flow events with flows > 5 mm/day to 86 days per year from 26 days per year under natural conditions.

Key Words: pocosin, pine plantations, forest management, evapotranspiration, DRAINMOD modeling, peat mining, agriculture

INTRODUCTION

The way in which wetlands and forests are managed or altered has a major impact on the hydrologic fluxes and the route of water loss from ecosystems. Many wetlands, including the marshes, bogs, pocosins, and peatlands of the southeastern United States, function as "water pumps" on the landscape, losing over two-thirds of their annual water inputs by evapotranspiration (ET) and leaving only 30% or less of annual input for runoff or ground-water recharge (Richardson and Gibbons 1993). An earlier watershed analysis of water budgets and flow-duration curves by Daniel III (1981) showed that construction of only drainage channels in wetlands without further alterations in land or vegetation cover resulted in increased peak flows and low flows at the expense of mid-range flows but not total annual flows. Skaggs et al. (1991) reported that peak runoff rates from developed fields (130 ha) in eastern North Carolina were two to four times those of natural wetlands (25 liter/sec versus 100 liter/sec). The exact ratio of runoff depends on the size of the experimental unit, land use, and antecedent soil water conditions. Skaggs et al. ,(1991) also found that the higher peak outflows occurred sooner on developed sites. In addition, with drainable porosity of coastal wetland soils being 1% to 7% (Skaggs 1978), water tables could rise 200 mm with only a 10 mm infiltration into soil from rainfall (Skagg et al. 1991). Moreover, drainage modifications, coupled with a radical change in vegetation from forest to agriculture, resulted in an increase in total runoff due to a decrease in canopy interception and a shorter residence time for water in the watershed. Precipitation falling on wetlands can be intercepted by the plant canopy, with the rate of interception varying with the canopy density, intensity and duration of rainfall, the season of the year, and other climate conditions (Kozlowski 1983, McCarthy and Skaggs 1992). Rutter et al. (1971) estimated a 20% to 40% interception of precipitation in conifer plantations while McCarthy (1990) reported values of 10 to 30% for a drained forested pine plantation watershed on the coast of North Carolina. Interception of rainfall by agricultural plants is seasonally dependent (i.e., fallow versus covered fields) as well as crop specific (corn versus soybeans or wheat).

Forest management practices in southern plantation pine forests typically consist of site preparation, planting, thinning, fertilization, and harvesting (Campbell and Hughes 1981). Agricultural practices include extensive drainage and site preparation, as well as annual harvesting and fertilizer and pesticide additions (Barnes 1981). In both land uses on flat, poorly drained soils, some form of water management (e.g., free drainage or controlled drainage) is often practiced. An extensive set of experimental field trials since the late 1970s has been used to test and refine the water-management model DRAINMOD, which has been used to predict hydrologic responses for various land-use and forestry practices on the coast of North Carolina (Skaggs 1978, Skaggs et al. 1980, Gregory et al. 1984, McCarthy 1990, Amatya 1993). For an intensive review of the DRAINMOD model algorithms, sensitivity analyses, and management alternatives tested, see the above noted papers. In this paper, we only review and present key aspects of the forestry trials as well as compare our simulation outputs for various land uses to these earlier reported values. Specifically, we (1) use a field-tested model (DRAINMOD) to estimate the effects of wetland drainage and soil and vegetation removal on hydrologic response, (2) compare forest plantation water losses with losses resulting from land clearing, agriculture, and peat mining activities on deep peat wetlands, and (3) review the effect of forest management practices on drainage loss on a coastal mineral soil. In addition, the effects of stand development on forest hydrology are examined over the life of the stand.

The hydrologic estimates we present for forest management on hydric soils of the Deloss fine sandy loam series in Carteret County, North Carolina (Figure 1) are relevant to pine plantation management on poorly drained soils that are typical of pine flatwoods, tall pocosins, and some alluvial bottomlands of the southeast. The evaluations for the organic soils (Pungo series Typic Medisaprists) in Hyde County, North Carolina are representative of deep peat organic soils of the southeastern coastal plain (short pocosins) and typify the effects of land clearing, agricultural land-use practices, peat mining, and forest plantations on hydrologic response of peat-based wetlands.

METHODS

The computer model DRAINMOD was developed as a tool to facilitate the design of agricultural water-management systems (Skaggs 1978, 1980). The model is based on physical processes and requires inputs describing site surface conditions, soil properties, vegetation, and meteorology. It was designed for application to shallow water table mineral soils but has been modified and tested for peat soils (Gregory et al. 1984) and forestry applications (McCarthy 1990, 1992, Amatya 1993). The model has been specifically field-tested and calibrated against watershed runoff for pocosin peatlands subjected to agriculture and peat mining in Dare and Hyde Counties in North Carolina (Skaggs 1980, CEIP 1984, Gregory et al. 1984), and forest managment activities on drained mineral soils (McCarthy 1990, Amatya 1993). The model has been described in detail in Skaggs (1978, 1980) and Gregory et al. (1984), and thus, we will only present the salient features as they pertain to the simulation of wetland development conditions we compared.

DRAINMOD: Background

This field scale model has the capability of simulating on a day-to-day, hour-by-hour basis, the surface runoff, subsurface drainage, evapotranspiration, soil-water content, and water-table position using climatological and soil property input data under both natural and assigned water-management plans (Gregory et al. 1984). The model is based on a soil-water balance for a column of soil that extends from the impermeable layer to the surface where the water balance for a given time frame is as follows:

$$Va = D + ET + DS - F$$

where Va is the change in the air volume, D is the drainage from the column, ET is the actual evapotranspiration, DS is the deep seepage, and F is the infiltration entering the section in time t. All values have units of cm^3/cm^2 or cm (Skaggs 1978, Skaggs 1980). The surface runoff and surface storage are computed with the following water balance equation:

$$RO = P - F - S$$

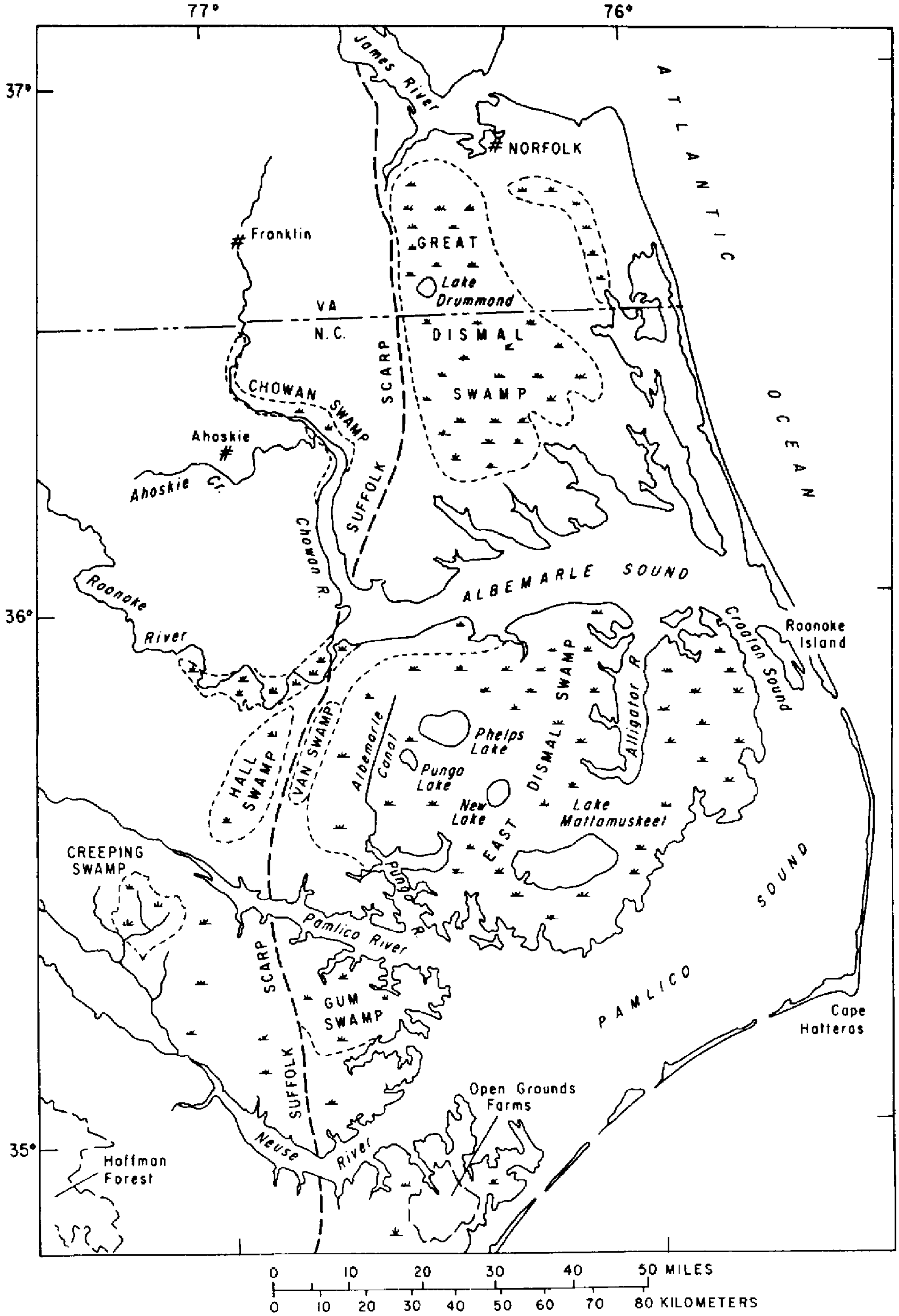

Figure 1. A general map showing the coastal North Carolina locations for experimental field sites used in the DRAINMOD simulations. The mineral soil sites were near Open Grounds Farm and the peat sites between Lake Phelps and Lake Mattamuskeet.

where RO is the surface runoff, P is the precipitation, F is the infiltration, and S is the change in surface storage during time t. All values are in cm, and the time increment used in calculation is one hour. For a more complete description of the model and details of field tests and validation, see Skaggs (1980) and Gregory et al. (1984). The soil properties and conditions modeled in our simulations are shown in Table 1, in McCarthy (1990), and McCarthy et al. (1991).

DRAINMOD: Conditions Modeled

We used DRAINMOD to simulate hydrologic conditions of runoff and evapotranspiration. Runoff in this paper is defined as total runoff and combines both surface runoff and subsurface runoff. We simulated conditions for hourly, daily, and monthly hydrologic flux using a twenty-year period of hourly rainfall input from local weather stations. Annual, seasonal, and monthly conditions, large storm events, and sequential storm events were simulated during different stages of land-use development or vegetation removal. We used natural conditions with mature natural vegetation as our baseline in terms of runoff levels. Simulations have been completed for natural conditions, during mining, agriculture conditions of a corn/soybean crop following peat mining, and a managed loblolly pine (*Pinus taeda* L.) plantation following removal of approximately the top 1 meter of peat.

Natural conditions. The pre-mining natural conditions are based on mature natural vegetation that is found on deep peats (> 1 m) in the pocosin areas of North Carolina. The dominant plant species include pond pine (*Pinus serotina* Michaux), fetterbush (*Lyonia lucida* (Lam.) K. Koch), titi (*Cyrilla racemiflora* L.), sweet bay (*Magnolia virginiana* L.), red maple (*Acer rubrum* L.), red bay (*Persea borbonia* (L.) Sprengel), loblolly bay (*Gordonia lasianthus* (L.) Ellis), etc. We used a peat depth of 1.8 m and present canal distances of 1.2 km, as inputs to the model. (See Table 1 for other conditions modeled.)

During mining. The parameters used during mining simulations were drains placed 46 m apart. Modeling iterations were done for a 30-cm removal of peat. The peat was not removed when ash content rose above 20%. Subsurface drainage was natural since tiles were not employed.

Agriculture. Parameters used in this simulation were peat depths of 30 cm. The number of active drainage ditches were reduced by 50% to a spacing between ditches of 92 m. Seasonal evapotranspiration and higher calculated transpiration values were inputs following data from Gregory et al. (1984). Values used were close to those reported by Skaggs et al. (1991).

Forestry. Parameters used in this simulation were 30 cm of peat depth and drainage ditches at 92 m. We calculated ET rates during pine growth based on monthly correction factors for the Thornthwaite PET model (Thornthwaite 1957) developed from five years of calculated Penman-Monteith ET (Skaggs 1980, CEIP 1984). Amatya (1993) has demonstrated that the Thornthwaite method as calculated is not significantly different from the Penman-Monteith ET method for forests. To account for increased growth and transpiration (in DRAINMOD simulations) on the older pine sites, we corrected ET from March to November by matching reported percent changes in ET values of pine transpiration (Polster 1950, in Kramer and Kozlowski 1960, Table 10.9). The 10 cm of increased ET from the older pine was due to the increased size of the trees. This reduced runoff (increased ET and interception) from forestry as compared to a natural pocosin. Our calculated ET values match those found in the CEIP simulations (CEIP 1984, p. 174). ET values in the forest management simulations (e.g., thinning, drainage) were calculated following the Penman-Monteith equation using hourly weather data (McCarthy et al. 1991).

DRAINMOD: Inputs and Key Parameter Estimates

Precipitation. Hourly rainfall data are the driving function for DRAINMOD simulations. The meteorological data used for a 20-year simulation of peat mining and land development effects in Hyde County were taken from the weather stations at Elizabeth City, North Carolina and Cherry Point, North Carolina for the Carteret County forest managment simulations. These weather data were chosen because of completeness of hourly records and proximity to study sites. The station values were validated against local measurements and were shown to be quite similar on a hourly and daily basis to local climatic events (Skaggs 1980, Gregory et al. 1984, McCarthy 1990). These data were obtained from the computer storage system HIS-ARS (Wiser 1975). Data were checked for missing data and errors. Records made between 1955 and 1989 were used in the simulations. Excluded from the calculations were years with incomplete data sets of partial hourly records (1968, 1970, 1971, 1973) from the Elizabeth City site.

Infiltration. Infiltration rates were determined for each soil profile from the Green and Ampt (1911) equation,

$$f = A/F + B$$

where f is the infiltration rate, F is the accumulated

Table 1. Description of the site conditions used in DRAINMOD simulations.

Item	Location and Land Use Type				
Site	Mineral soil (forest plantation)	Peat soil (natural)	Peat soil (forestry)	Peat soil (mining)	Peat soil (agriculture)
General description	Drained pine plantation	Pocosin vegetation	Pine plantation	Peat removal	Corn–soybeans
Area	75 ha	404 ha	404 ha	404 ha	404 ha
Location	Carteret County, NC	Hyde County, NC	Hyde County, NC	Hyde County, NC	Hyde County, NC
Latitude	34°50′	35°20′	35°20′	35°20′	35°20′
Longitude	76°39′	76°20′	76°20′	76°20′	76°20′
Topography	coastal plain, 0.1% grade	coastal plain, 0.1% grade	coastal plain, 0.1% grade	coastal plain, 0.1% grade	coastal plain, 0.1% grade
Vegetation	Plantation	Natural	Plantation	None	Crops
Species	Loblolly Pine (*Pinus taeda*)	Pond Pine (*Pinus serotina*)	Loblolly Pine (*Pinus taeda*)	NA[1]	Corn–soybean
Stocking level	Planted 1974	NA	seedlings to >10 years	NA	seasonal
Unthinned	1000 trees/ha, 33 m^2/ha basal area	538 trees/ha 8.7 m^2/ha basal area	1000 trees/ha	NA	NA
Thinned	395 trees/ha, 16.3 m^2/ha basal area	NA	NA	NA	NA
Rooting depth	0.40–0.60 m	0.25 m	0.25 m	NA	time dependent 0.003 to 0.25 m
Soil	Mineral	Histosol			
Texture	0–0.5 m: fine sandy loam, >0.5 m clay loam	0–1.6 m muck	0–1.6 m muck	0–1.6 m muck	0–1.6 m muck
SCS Soil classification	Thermic typic umbraqualts	Dysic thermic typic medisaprist	Dysic thermic typic medisaprist	Dysic thermic typic medisaprist	Dysic thermic typic medisaprist
SCS Soil series	Deloss fine sandy loam	Pungo muck	Pungo muck	Pungo muck	Pungo muck
Hydraulic conductivity	3.9 m/day (by auger-hole method)	0–10 cm: 99 cm/hr >10 cm: 5 cm/hr	0–15 cm: 91 cm/hr >15 cm: 0.35 cm/hr	0–4 cm: 70 cm/hr >4 cm: 0.4 cm/hr	0–20 cm: 12 cm/hr >20 cm: 0.6 cm/hr
Depth restricting layer	2.8 m	1.8 m	0.3 m	1.5 m	0.3 m
Drainage design					
Ditch spacing	100 m	1.2 km	92	46 m	92 m
Outlet weir	adjustable height	140 cm	140 cm	100 cm	30 cm
Depth	120° v-notch weir				

[1] NA = not applicable.

infiltration volume, and A and B are parameters that are dependent on the soil properties, such as bulk density, ash content, air space, etc. Infiltration values for each soil type were determined by soil characteristics in 129 soil profiles in Hyde County (Ingram and Otte 1982) and cross-checked against soil characteristics for the sites used in our simulations (Richardson et al. 1987, Table 1). Carteret County soil characteristics were analyzed and presented by McCarthy (1990, Table 1).

Hydraulic Conductivity. This soil parameter varies with direction, depth, and surface conditions. Highest vertical rates are at the top few cm in undisturbed profiles; rates decrease as soil bulk density increases and large pore space decreases with depth. Values for vertical hydraulic conductivity by soil type and vegetation cover have been developed for the pocosin peats in Hyde County, North Carolina by Badr (1978) and Purisinsit (1982). McCarthy developed values for the forestry simulations (McCarthy 1990, Table 1). Analysis of the soil bulk density profile characteristics on the peatlands permitted us to correlate conductivity values with physical characteristics for each site condition or disturbance following Boelter and Verry (1977). Values (Table 1) were cross-checked with those reported by Gregory et al. 1984 for deep peats and were within 10%.

Evapotranspiration. Evapotranspiration (ET) is the combined loss of water vapor from the land to the atmosphere by evaporation and plant transpiration. The determination of actual evapotranspiration (ET) by the model is done by a two-step process where potential evapotranspiration (PET) is calculated from climatological data over 12 daytime hours. Next, the ability of the soil water to supply PET is determined and, if it is not limiting, PET is set equal to ET. If it is limiting, then ET is set equal to the assigned upward flux value. PET in DRAINMOD is calculated by the Thornthwaite (1948) method, which was proven to be surprisingly accurate over the growing season at the coast (Mohammad 1978). Amatya (1993) has shown no statistical difference between the Thornthwaite PET method and the Penman-Monteith ET method in a Carteret County, North Carolina forest. The Thornthwaite method is known to underestimate winter ET, with the result that runoff is estimated at a higher level than actual flow unless monthly correction factors are added to the final solution. Conservative correction values were determined from Thornthwaite and Mather (1957), the NOAA Evaporation Atlas (1982), and Gregory (1984). Specific ET methods following Penman-Monteith calibration procedures and analysis for the forest management study in Carteret County are given in McCarthy et al. (1991).

DRAINMOD: Model Sensitivity

DRAINMOD has been tested for pocosin peatlands and mineral soils, and the parameters have been estimated and refined for all the conditions being simulated (Skaggs 1978, 1980, Gregory et al. 1984, McCarthy 1990, Amatya 1993). An extensive sensitivity analysis done for DRAINMOD by Purisinsit (1982) showed that runoff was more sensitive to PET than any other input parameter. For example, a 50% decrerase in PET increased simulated runoff by a maximum of 56%, while a similar change in rooting depth only altered runoff volumes by 10%. We determined and selected conservative PET estimates for forestry as noted earlier, which may overestimate runoff slightly. For example, during the first few years of forestry operation, we have calculated a low ET with a maximum 20% higher runoff estimate. It is known that pine plantations do, in fact, transpire at a rate considerably higher than native vegetation due to high planting density and year-round physiological activity (Kramer 1983). This strongly suggests that the pine plantation reclamation alternative will significantly decrease runoff conditions. A detailed analysis and verification of these possible rates were later confirmed in the calibrated forestry watershed studies of McCarthy (1990) and Amatya (1993). Skaggs et al. (1991) reported that as ditch spacing in natural pocosin peatlands is reduced from 400 m to 100 m, the predicted annual average ET decreases by about 3% and the average annual total outflow increases by 7%. Drainage ditches at spacing greater than 400 m had no effect on annual runoff predictions.

RESULTS AND DISCUSSION

Natural Conditions On Peat Soils

Precipitation (P) and Evapotranspiration (ET). Over the last twenty years, the average annual rainfall for the Hyde County region of coastal North Carolina has been 123 cm (Wiser 1975). The average monthly distribution of rainfall for that period is shown in Figure 2. On average, the wettest months are July and August. Simulated ET exceeds rainfall only during June but is close to rainfall in both July and August. Average monthly rainfall compared to ET, when integrated over the whole year, indicates that 80 cm of the average annual input of 123 cm is discharged from vegetated pocosin sites as ET. Thus, nearly 66% of annual rainfall leaves a natural pocosin ecosystem as ET and 34% leaves as runoff or ground-water recharge or is stored in the peat.

Ground-Water Discharge (GWD). The organic histosols of the North Carolina coastal plain in Hyde

County are underlain by poorly permeable subsurface layers of clay and sand (Foutz 1983). The predicted flow rate of deep seepage to the Castle Hayne aquifer was determined to be only 0.043 cm/yr (Foutz 1983). Badr (1978) also studied this region and reported that surface-water flow from the organic soils to ground water was only 0.02 cm/yr. Ground-water discharge rates representative of the coastal region are very low and have been estimated to be approximately 1 cm per year (Heath 1975, Daniel 1981). Ground-water discharges are thus estimated to be <1% of the annual water budget of regional wetlands and play an insignificant role in the annual water flux.

Runoff (RO) and water storage. A simulation of runoff for a natural (mature) pocosin ecosystem on deep peat indicates that runoff is highest (> 7 cm) during the winter months and lowest during the summer months (< 2.5 cm) (Figure 2). Given the previous average hydrologic rainfall and ET values, average annual runoff from natural pocosin areas can be estimated as:

$$\mathrm{RO} = \mathrm{P} - \mathrm{ET} - \mathrm{GWD}$$
$$\mathrm{RO} = 123\ \mathrm{cm} - 80\ \mathrm{cm} - 1\ \mathrm{cm}$$
$$\mathrm{RO} = 42\ \mathrm{cm/year}$$

By comparison, Skaggs et al. (1991) calculated an average annual outflow for a natural pocosin area on Portsmouth sandy loam near Wilmington, North Carolina to be 36.5 cm/yr. Physical soil characteristics could account for most of the difference in runoff among the two soil types, but some degree of variation may be due to the amount of depressional storage used in each model simulation. In our simulations, we used 10 mm of storage while Skaggs et al. (1991) used 25 mm or more. Their studies demonstrated that an increase in depressional storage from 10 mm to 75 mm could result in nearly a 10% decrease in annual runoff. Moreover, the annual variation in rainfall and ET over several decades shows that runoff from peatlands can vary considerably from average conditions during periods of extreme rainfall or drought (Figure 3). Following several years of high rainfall and reduced soil storage capacity, runoff nearly reached 75 cm/yr in the mid 1950s, while runoff dropped to near 10 cm/yr following the lower rainfall periods and higher ET of the 1970s. Skaggs reported runoff ranging from 8.4 cm/yr to 65.9 cm/yr for the Portsmouth sites over the 32-year simulation. Thus, high year-to-year variations in runoff can be expected on both peat and mineral soils depending on climatic variability.

A predicted water-table depth profile for peat soils in Hyde County in 1977 is considered representative of an average year and shows that the water table remains above or near the surface until day 85 (Figure 4). Over the next 100 days, the water table remains 10 to 15 cm below the surface. From July until October, the water table dropped to nearly 100 cm below the surface, with the exception of one major rainfall event that drove the water table up to within 20 cm of the surface. This rapid water-level response is due to the limited pore space available in the hydric soils (Skaggs 1978, 1980). By the end of the year, the water table was within a few centimeters of the surface. Similiar seasonal patterns were found in the mineral soils of the Portsmouth soils (Skaggs et al. 1991).

Runoff and ET from Natural and Altered Peat Soils

Using DRAINMOD, we simulated the annual runoff and ET for a 404-ha block of land in Hyde County, North Carolina under natural, disturbed conditions where all the vegetation had been removed from the peatlands, during mining activities where 30 cm of peat surface was removed, agriculture, and managed forestry (both early plantation years 1-3 and closed canopy conditions) (Figure 5a, b). The conditions used in these simulations are shown in Table 1 and are described in the methods sections. This 404-ha area was used as a test-size watershed for the normalization of field measurements and model analysis. The total runoff for any size area with comparable drainage, soils, and plant cover can then be estimated and compared. The highest annual average simulated runoff was 63 cm/yr (2.5×10^6 m^3/yr), which was the water discharge projected during the period of active mining on 404 ha of wetlands. Average annual outflow exceeded natural conditions by 50% (Figure 5a, b). Runoff was simulated for a 20-year period for 30-cm intervals of peat removal (i.e., removal of 30, 60, 90, and 120 cm of peat) during each mining phase. The model indicated that continued peat removal would not result in any increased runoff above initial measured increases at the first 30 cm of removal. This is due to the similarity in hydraulic conductivity conditions below the 30 cm level and a similar but low ET value of 59 cm/yr for disturbed peatlands (Gregory et al. 1984). The next highest level of simulated runoff was 47.5 cm/yr (1.9×10^6 m^3/yr) from land that is classified as disturbed (i.e., ditched and vegetation partly or totally removed) (Figure 5a). Runoff for disturbed landscapes exceeds natural conditions by 13% annually.

Runoff was simulated for a 20-year period on reclaimed peat areas with a land cover characterized by row-crop agriculture with a corn/soybean rotation. The average annual runoff was 45.7 cm/yr (1.8×10^6 m^3/yr) (Figure 5a, 5b). This output exceeded natural levels of runoff by 9%. Simulated runoff from pine plantations for initial conditions during the first three-to-five

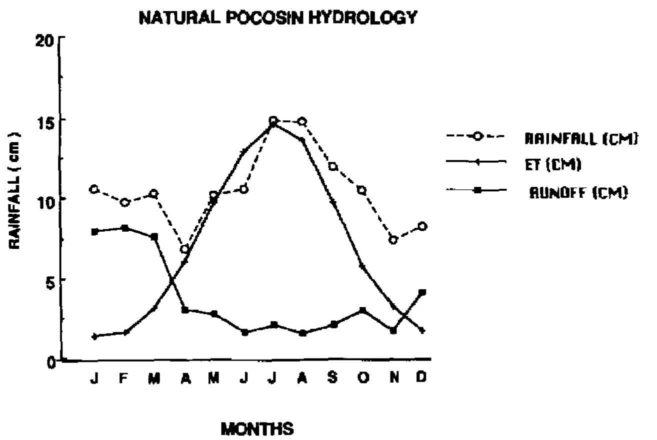

Figure 2. Monthly rainfall, evapotranspiration (ET), and runoff from a mature natural pocosin site on deep peat in Hyde County, NC. Values represent monthly averages from a 20-year simulation with DRAINMOD.

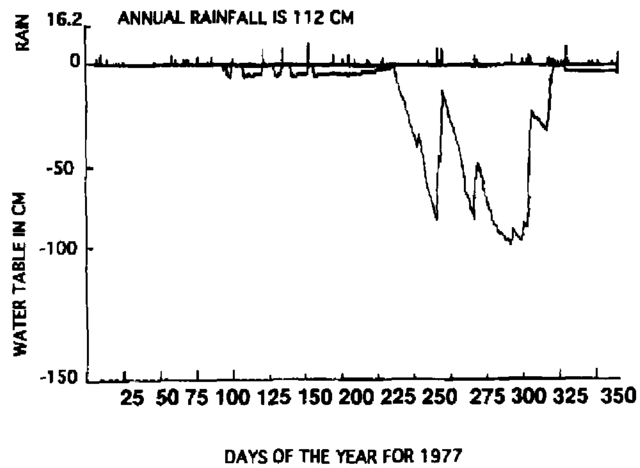

Figure 4. A DRAINMOD simulation of water-table depth for a natural pocosin site on deep peat in coastal North Carolina with mature natural vegetation in 1977.

years of growth (low cover percentage and ET of only 78 cm/yr) and during increased biomass and closed canopy conditions (increased ET of 87 cm/yr) were 42.7 cm/yr (1.7 × 10^6 m^3/yr) and 34.1 cm/yr (1.3 × 10^6 m^3/yr), respectively. Average early pine plantation runoff was only 2% higher than natural runoff levels, but by year 7, forestry runoff was reduced to 19% of natural projected runoff. The general trends of agriculture land use increasing runoff above natural conditions on Portsmouth sandy loam soils and forest plantations decreasing runoff compared to natural systems were also shown by Skaggs et al. (1991). By comparison, drained pocosin, forest plantation, and agriculture on the mineral Portsmouth soil discharged on average 39.2 cm/yr, 35.6 cm/yr, and 42.1 cm/yr over the 32-year period from 1950 to 1982. However, agricultural runoff was 15% greater than natural outflow, and pine plantations only reduced outflow by 3%. The different results for each land-use scenario relate directly to the variations in ET and water interception among cover types, as well as the physical water flux and storage capacity of peat versus sandy loam soils.

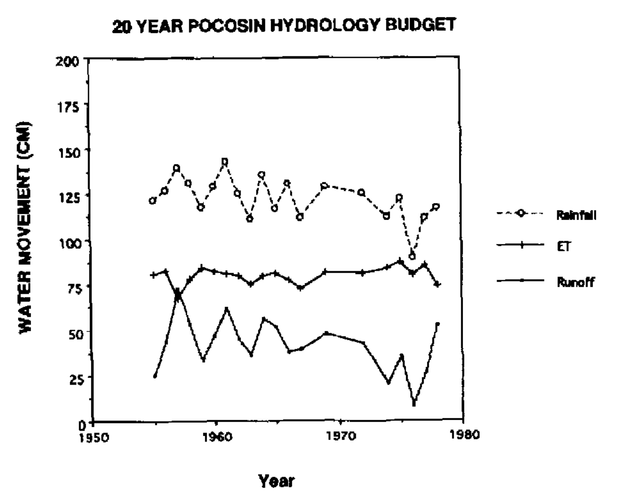

Figure 3. A 20-year DRAINMOD simulation of annual rainfall, evapotranspiration (ET), and runoff for a mature natural area with peat soils in coastal North Carolina.

Monthly Runoff Comparisons by Land-Use Type

A comparison of monthly runoff rates for each block of land for natural, during mining, agriculture, and silviculture land use is shown in Figure 6. The highest simulated runoff for all land-use types occurred during the winter months, and the lowest runoff was during the summer months. The highest runoff in the winter months was from the mining and agriculture land uses. Runoff from mining and agriculture was only 1 to 3 cm above natural site rates during this period. The lowest runoff, < 2.5 cm per month for most of the year, was in the silviculture-reclaimed areas. This suggests that the reclamation of mined areas with forest plantations would result in a significant reduction in total monthly and annual runoff. The next best land-use type in terms of reduced runoff was the natural pocosin area (Figure 6). The highest predicted runoff during the summer months was from the mining sites where ET was significantly reduced. Agriculture sites also showed higher output than natural sites, especially during the fall months. The relatively high runoff during mining would require that outflow in excess of natural conditions be managed in most state water programs due to mining discharge regulations. By contrast, agricultural runoff is not currently regulated in most states.

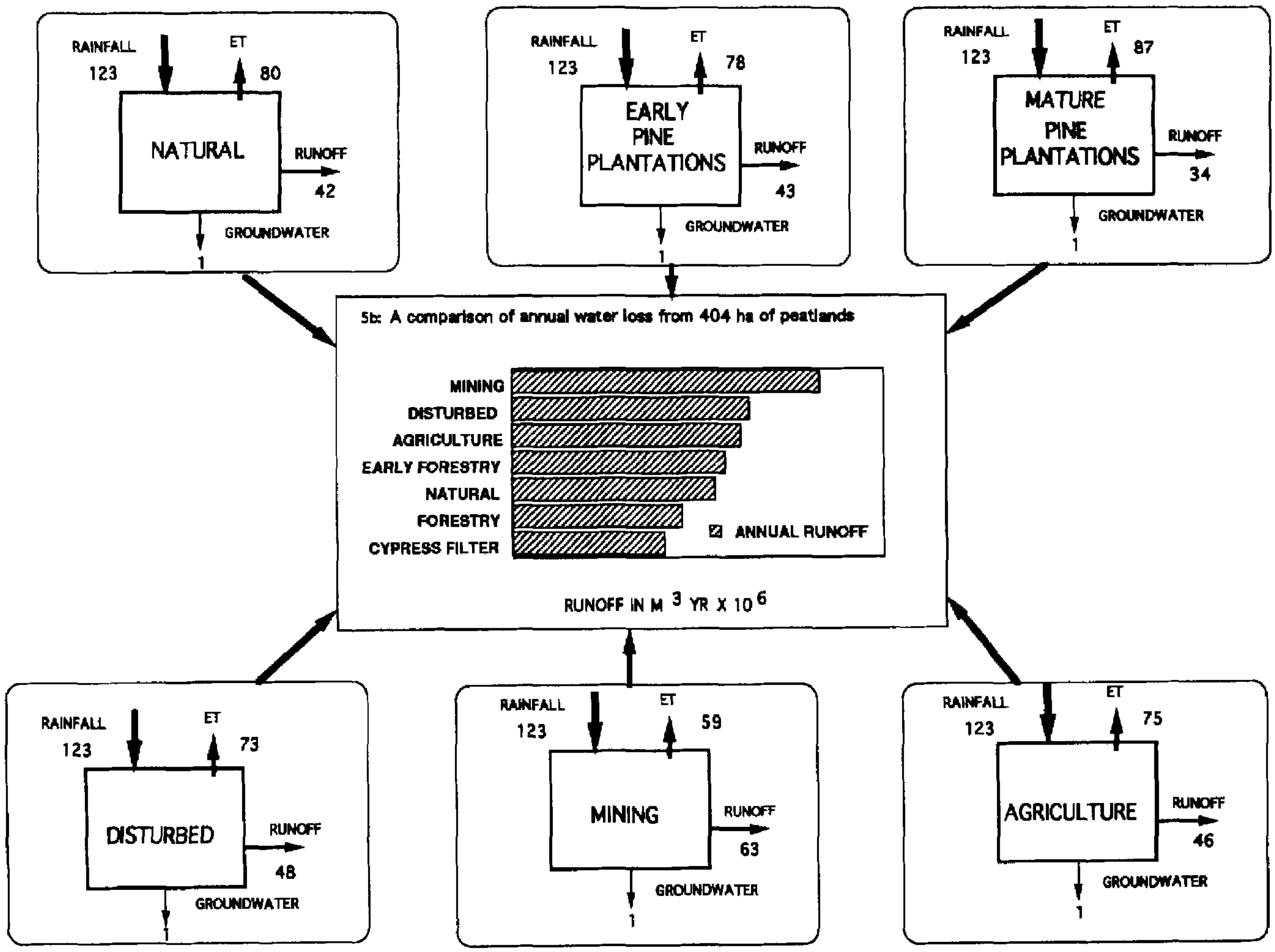

Figure 5. a) Hydrologic inputs and outputs by land-use type in cm/yr. Note: Output values were rounded to nearest whole number and may not exactly match inputs. b) Annual runoff ($m^3 \times 10^6$ yr) from a 404-ha block of peat-based wetlands under several land-use types as simulated for a 20-year period using the DRAINMOD model.

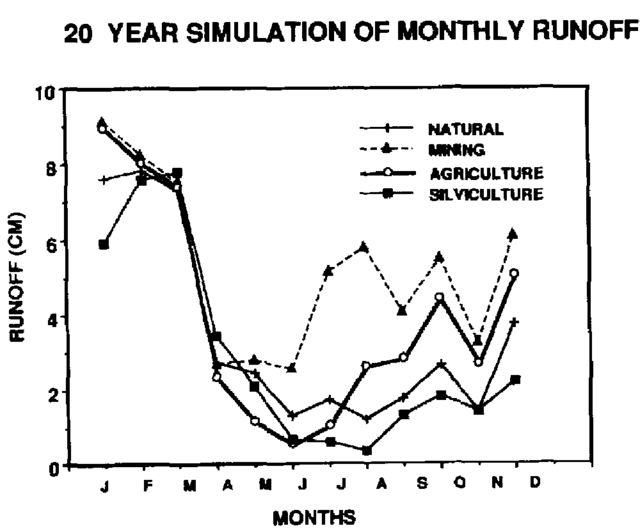

Figure 6. A comparison of simulated monthly runoff levels for natural, mining, agriculture, and silvicultural land use.

Storm Events By Land-Use Types

Flow Duration Curves. While the data presented in Figure 6 are useful for depicting expected monthly runoff, these data provide little indication of peak flows for various land-use conditions. One technique that may be used to estimate the frequency of flows at a given point is the flow duration curve (Dunne and Leopold 1978). The flow duration curves presented in Figure 7 indicate the proportion of the time that a flow rate might be expected to equal or exceed a certain value. High flow periods are an important consideration in water management since periods of high flow are likely to result in soil erosion and increased nutrient loss. Therefore, it is important to develop a quantitative relationship that shows the cumulative frequency of high flow periods.

Data for the flow duration curves were obtained by using DRAINMOD to simulate 20 years of daily unit-

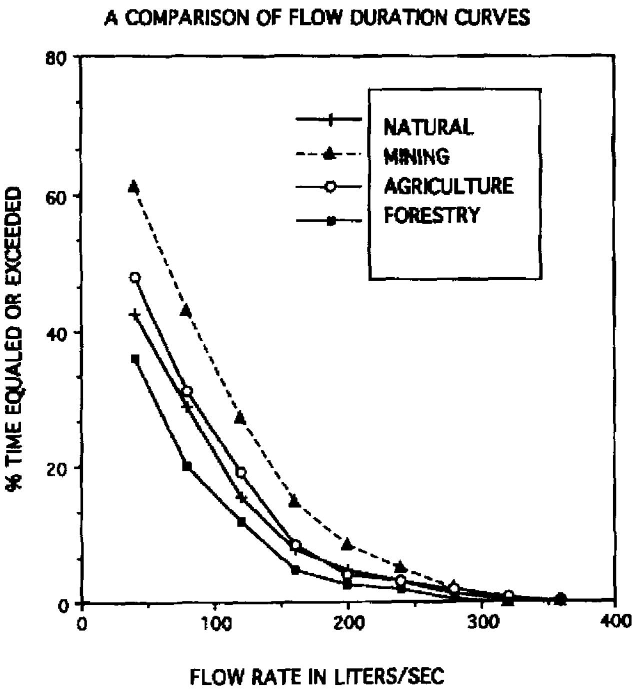

Figure 7. Flow duration curves for four land-use types on peatlands in coastal North Carolina. Data simulated over a 20-year period by DRAINMOD.

area runoff for each of the scenarios listed in the preceding section. The daily unit-area runoff was averaged over the 20-year period of record on a daily basis, yielding 365 observations of average daily runoff. Average daily runoff in centimeters per day was then converted to flow, in liters per second, for a 404-ha tract of land. The procedure described above provided data that could be used to simulate expected canal flow rates (Gregory et al. 1984).

After obtaining average daily flow rates, data were sorted in ascending order, and a frequency histogram was developed. Flow duration curves presented in Figure 7 depict the recurrence interval of exceeding a certain flow for natural, mining, agriculture, and forest management conditions. Flow volumes above 275 liters per second occur roughly 2.5% of the time, regardless of the condition simulated. Hence, for certain periods, high flows may be expected even under natural conditions. Mining conditions displayed higher flows than all other flows simulated. As an example, outflows of 195 liters per second occurred 10% of the time. By comparison, flow volumes of 130 liters per second would be exceeded only 10% of the time when the area is used for silviculture. Possible reasons for the increased flow during the mining phase include removal of natural vegetation, resulting in decreased evapotranspiration (see Figure 5a), and removal of soil layers high in hydraulic conductivity.

Also, the flows under natural conditions and during the agricultural phase of the operation are coincident with flows that may be expected less than 10% of the time, that is, the high flow periods. For more typical rates of flow, that is, flows that may be equaled or exceeded 20 to 50% of the time, flow from agricultural blocks of land only slightly exceeds flow under natural conditions. In addition, at the points where flow during the agricultural phase exceeds that under natural conditions, flows will be under 160 liters per second.

Of all the scenarios that were simulated using DRAINMOD, for any given probability of exceedence, flow under forested conditions was the lowest. As an example, consider flows that may be expected to be exceeded 40% of the time. Under natural, pre-mined conditions, flows of just under 50 liters per second may be expected. Under forested conditions, flows of just under 30 liters per second may be equaled or exceeded 40% of the time.

To summarize, under all conditions simulated, even natural, there is a certain (albeit small) probability that high flows may be expected from the peat-based wetlands. Finally, under forest management, there will be a net reduction in freshwater runoff from the altered wetlands. The peak flows will also be greatly reduced. The specific effects of forest management practices on hydrologic response are reviewed for the conditions shown on Table 1 in the following section.

Case Study of Forest Management Effects on Hydrologic Response for Mineral Soils

Removal of natural vegetation is usually the first activity associated with intensive forest management. If not already in place, a road system is designed and constructed to serve the area. Drainage networks often accompany road system designs. The surface area of these road and drainage systems usually amounts to 1 to 2% of the total land area managed (J. H. Hughes, pers. comm.). In soils with seasonally high water tables, drainage improves soil trafficability for harvest, site preparation, and planting (Terry and Hughes 1978). In addition, soil moisture conditions are typically improved for the newly established seedlings (Figure 8). In many areas with seasonally high water tables, removal of the natural vegetation dramatically reduces evapotranspiration and causes the water table to rise to the soil surface, often making water management a necessity. The magnitude of the rise in water table due to removal of the natural vegetation depends largely on the hydrologic characteristics of the watershed and relative productivity of the removed vegetation. Evapotranspiration and canopy interception increase with an increase in leaf area in the stand (Rutter et al. 1971, Dolman et al. 1988). Leaf area in southern pine stands has been measured to vary up to 180% within

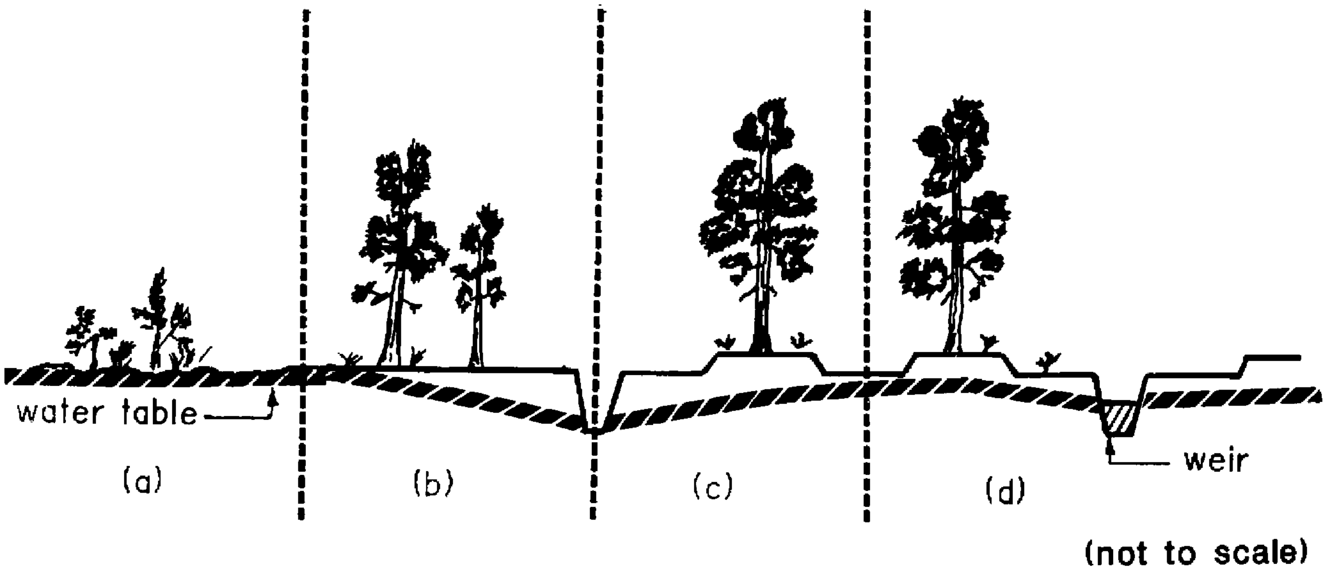

Figure 8. a) Forest productivity can be limited by poorly drained soils with high water tables. b) Drainage provides better soil moisture conditions for tree growth. c) Site preparation, including bedding, further improves soil conditions for tree growth and reduces surface runoff. d) Controlled drainage allows for more regulation and greater flexibility in water management.

a stand on a seasonal basis (Kinerson et al. 1974). The pattern of seasonal variation in leaf area index (LAI) is shown in Figure 9 for the Carteret loblolly pine stand at stand ages 15 to 16. Commerical thinnning reduced LAI by 50%. Seasonal variations in transpiration resulting from variations in leaf area, soil moisture conditions and meteorological conditions, as calculated by the Penman-Monteith equation (Dolman et al. 1988), for the Carteret study site show a two- to four-fold increase in transpiration in the summer months compared to winter months (Figure 10). The 50% decrease in transpiration in summer of 1989 follows the reduction in LAI. Management of sites had significant effects on other components of the hydrologic response for the pine plantations. The following summary of forest management effects is taken from McCarthy (1990), McCarthy et al. (1991, 1992) and Skaggs et al. (1991).

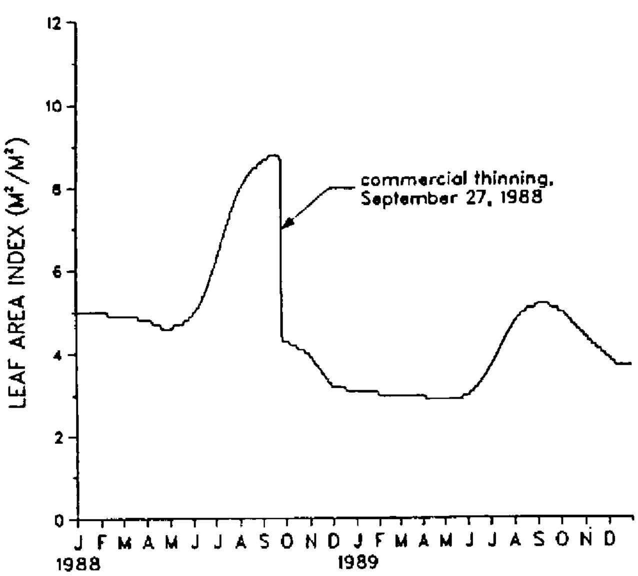

Figure 9. Seasonal variation of Leaf Area Index (LAI) for a loblolly pine stand at stand ages 15 and 16. Values are based on litterfall data collected in the stand. A commercial thinning in September, 1988 reduced LAI by 50% (from McCarthy et al. 1991).

Water management control structures. Adjustable risers and weirs can be integrated into the drainage system to allow greater control over water-table levels and drainage outflow rates. Subsurface drainage maintains available soil-water storage volume, thereby in-

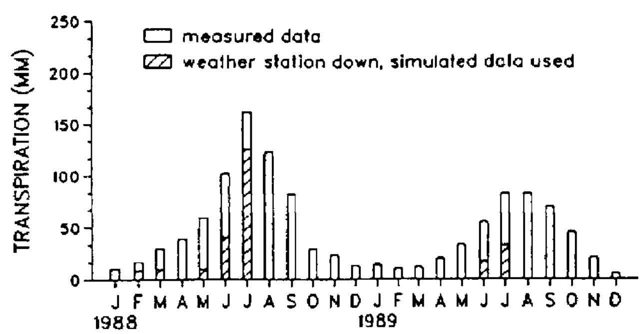

Figure 10. Seasonal variation of dry canopy transpiration for a loblolly pine stand at stand ages 15 and 16. Values are based on the Penman-Monteith equation. Measured hourly meteorological data were used in the calculations except when the weather station was inoperative, in which case simulated meteorological data were used (from McCarthy et al. 1992).

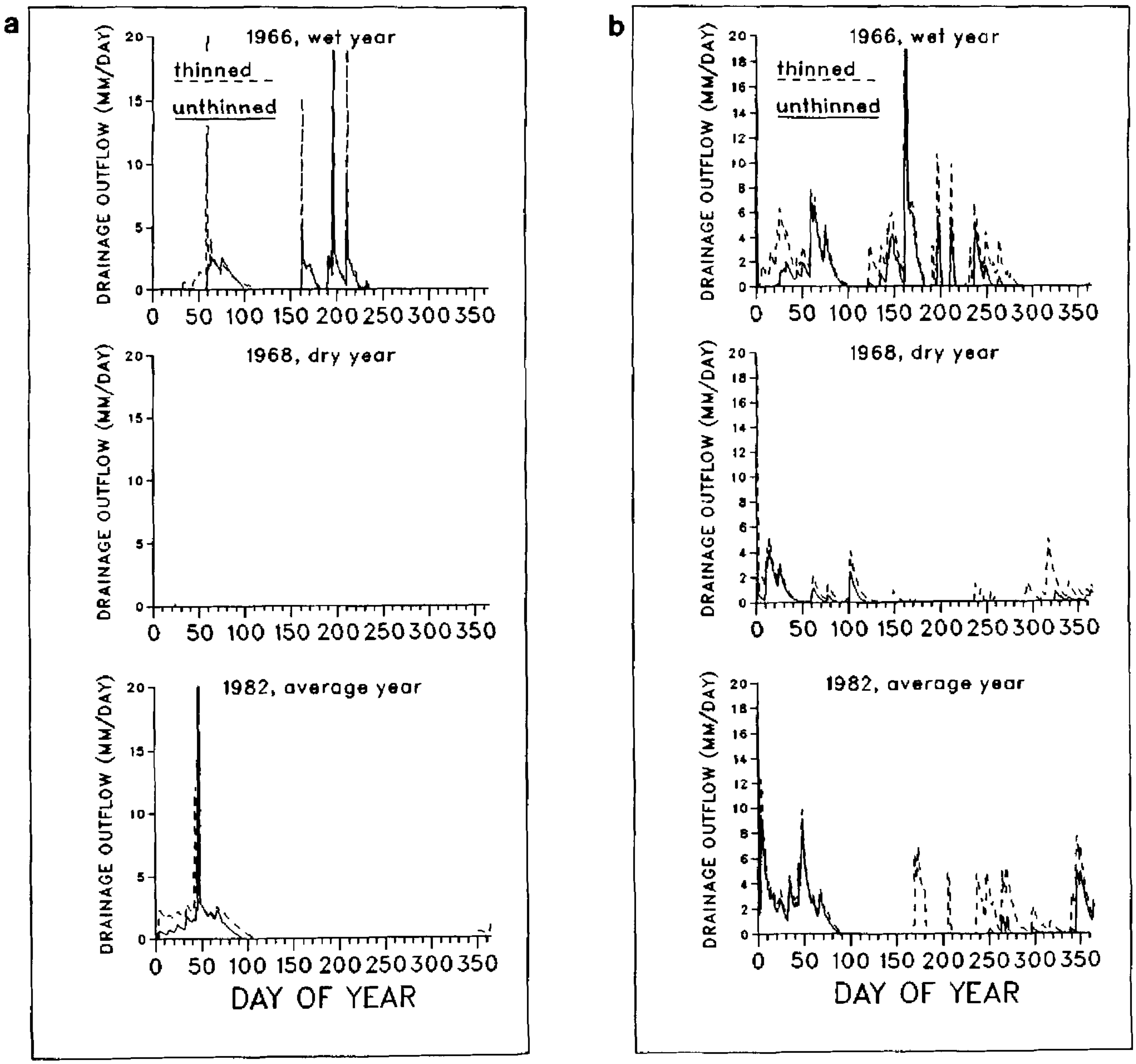

Figure 11. Effects of water management on drainage outflow from a forest watershed. a) No drainage. b) Controlled drainage. Controlled drainage systems can be designed to reduce the frequency of large peak flow rates (for this example, peak flow rates > 10 mm/day). Data presented are DRAINMOD computer simulations. Commercial thinning generally results in higher drainage outflows (McCarthy 1990).

creasing infiltration and decreasing surface runoff. Controlled drainage can substantially reduce the magnitude of peak flows leaving a watershed relative to subsurface drainage. Forest soils typically possess extensive macro-pore networks and have the ability to hold large volumes of infiltrated water (Nelson 1986). With controlled drainage, more infiltration occurs, reducing the frequency of surface runoff. Controlled drainage allows a greater portion of the drainage leaving the site to travel laterally through the soil. Although the total drainage volume leaving the site has the potential to be the same as with no subsurface drainage, peak flow rates are buffered (Figure 11) (McCarthy and Skaggs 1992). Controlled drainage can reduce excessive soil moisture conditions in high water-table soils and was most effective in controlling high flow rates in wet and average years (Figure 11). The average number of flow events over 5 mm/day over a 23-year simulation period ranged from a low of six days under unthinned controlled drainage (weir depth at 0.6 m during March 1-May 31 and 1.0 m below the soil surface the rest of the year) to 26 days with no drainage

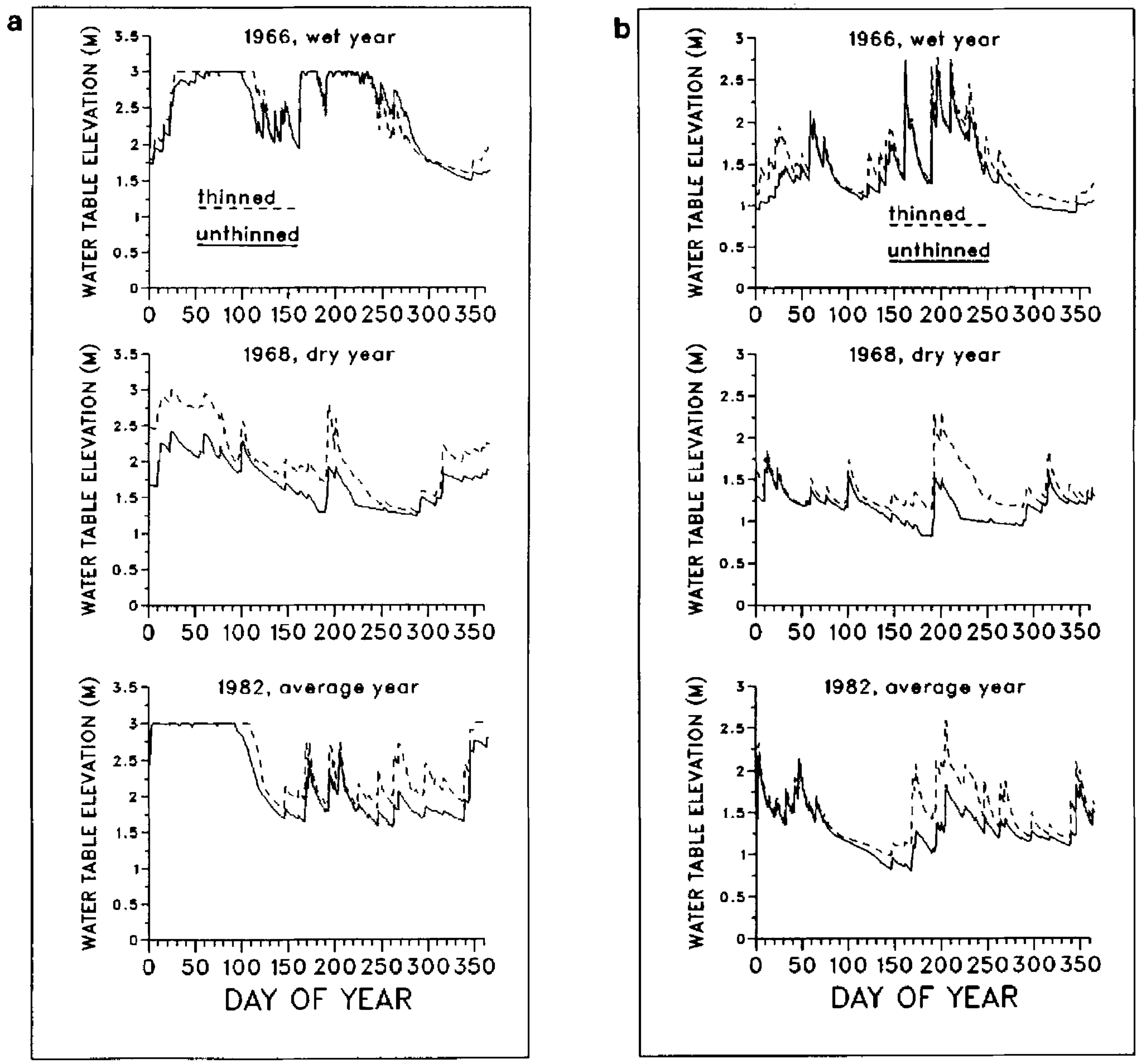

Figure 12. Effects of water management on water-table levels. a) No drainage. b) Controlled drainage. Controlled drainage allows for greater regulation over water-table levels, improving soil moisture conditions for tree growth and forest operations. Soil surface is at 3.0 m. Commercial thinning generally results in higher water tables with no drainage or controlled drainage. Data presented are DRAINMOD computer simulations (McCarthy 1990).

(full LAI and water level maintained at the soil surface), and 86 days with free drainage (full LAI and weir depth at 1.8 m below the surface) (McCarthy and Skaggs 1992). Thinning increased the number of high flow events for all water-management events. By adjusting weir levels on a seasonal basis, water-table levels can be maintained for improved tree growth throughout the year (Figure 12).

Site Preparation. This practice facilitates regeneration efforts and provides favorable conditions for rapid establishment of the future stand. Slash from the previous harvest is often disposed or reduced. Commonly applied methods of slash disposal include piling and burning or chopping. Chopping is a preferred practice since less soil disruption occurs. Such operations often involve the use of heavy machinery and can cause soil compaction. These practices are not recommended on soils with thin fragile "A" horizons. Working or operating on heavy soils during non-optimal soil moisture conditions can result in extensive soil puddling and compaction (Hoag and Steinbrenner 1977). Soil compaction reduces infiltration and increases the potential for surface runoff and erosion.

Bedding. The practice of mounding soil in rows for planting provides improved soil moisture conditions for the root systems of newly planted seedlings during a period when the plants have a low tolerance to excess moisture and the likelihood of high water tables, due to low evapotranspiration rates, is increased. Bedding increases depression storage. In a drained forest system, bedding increases infiltration potential and subsurface drainage and reduces surface runoff. These effects tend to buffer peak flow rates leaving the watershed.

Planting. Planting allows for efficient and uniform establishment of the forest stand. Stocking levels for southern pine plantations typically range from 1,000 to 1,700 trees/ha (400 to 700 trees/acre) depending upon the management objective. Planting often creates stands more dense and productive than would occur with natural regeneration, resulting in higher canopy interception loss and transpiration (McCarthy 1990).

Stocking Control. Pre-commercial thinning and commercial thinning provide quality control for the stand and improve spatial distribution of the crop trees. These practices create short-term decreases in canopy closure and leaf area, thereby reducing canopy interception loss and transpiration. The magnitude of the resulting change is proportional to the level of thinning. Removal of 50% or more of the stand basal area is not uncommon in a commercial thinning. The resulting effect on LAI for a commercial thinning at stand age 15 on the Carteret study site is shown in Figure 9. This effect typically persists for three to five years, until the canopy has expanded to occupy available growing space. Figures 11 and 12 illustrate the effect of commercial thinning on drainage outflow rate and water table for a 15-year-old stand. Due to lower canopy interception loss and transpiration directly after thinning, peak outflow rates and water-table levels are generally higher for thinned conditions.

Fertilization. This is a commonly applied practice used to improve tree growth. Nutrients are added to the soil, usually in the form of granular phosphate and urea. Increases in available nutrients yield a more dense canopy, resulting in increased canopy interception loss and transpiration.

Harvesting. Harvesting reduces forest cover. Clear-cutting removes all of the crop trees in a single operation, creating a dramatic decrease in evapotranspiration and canopy interception loss. This often causes the water table to rise substantially in undrained conditions.

Forest Stand Development

As the forest stand develops and changes with age, so does the hydrology (Figure 13). For example, computer simulations showed that after planting, only 13% of the total rainfall of 135.6 cm was lost as ET, primarily from soil evaporation. Drainage amounted to 85% of water loss from the watershed. At age 35, after two thinnings at ages 15 and 21, ET, drainage, and interception losses were 44% (59.6 cm/yr), 36% (48.8 cm/yr), and 20% (27.1 cm/yr), respectively (McCarthy and Skaggs 1992). Thus, a newly established stand has relatively large drainage volumes leaving the site. As the forest canopy develops and becomes contiguous, canopy interception losses increase. Increases in transpiration and interception result in significant drainage volume decreases. Forest management activities, such as commercial thinning and fertilization, impact the stand development and thus the hydrologic balance. At age 15, the stand was thinnned and the average transpiration, canopy interception, and drainage were 51.5 cm, 22 cm, and 62.1 cm, respectively. By comparison, an unthinned stand had values of 56.3 cm, 24.2 cm, and 55.1 cm for each respective component (McCarthy and Skaggs 1992). As the stand matures, canopy interception loss and evapotranspiration become the major hydrologic components.

SUMMARY AND CONCLUSIONS

Natural peat-based pocosins lose 66% of annual rainfall as ET with 34% leaving as diffuse runoff. Development for agriculture, forestry, and peat mining will result in a shift in the hydrologic output from ET to point source runoff. Agriculture, land clearing, and peat mining simulations suggest that on average these land-use activities will increase annual runoff over natural undrained wetlands by 9%, 13%, and 50%, re-

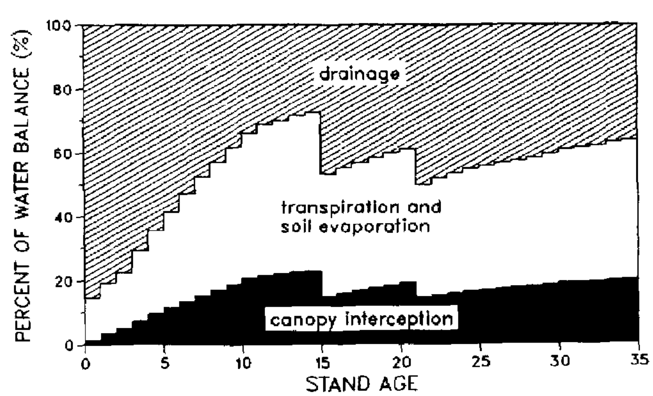

Figure 13. The hydrologic components of the forest change with stand development. Commercial thinnings at stand ages 15 and 21 decrease evapotranspiration and canopy interception and increase drainage (McCarthy and Skaggs 1992).

spectively. Closed canopy forest pine plantations will reduce runoff by 19% over natural conditions. Interception decreases due to forest thinning and harvesting generally increase drainage volumes from the watershed. The opposite is true of forest activities and conditions that increase evapotranspiration and canopy interception. Seasonal changes in leaf area and meteorological conditions also significantly impact the hydrologic components of the water balance. Forest management practices that increase soil infiltration typically buffer peak flow rates leaving the watershed. In high water-table soils, water management provides a means to control drainage outflow and water-table levels. Stand development causes a significant decrease in the hydrologic outflow over time.

A technical challenge lies ahead in developing watershed management methodology and techniques that reduce significant alterations of long-term hydrologic behavior on the landscape. The potentially negative effects of wetland development on hydrologic response must be addressed as a landscape issue, rather than a site-specific problem. This paper hopefully provides some management guidelines as well as estimates of the changes in hydrologic functions of wetlands under varying land use and forestry practices.

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