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ABSTRACT. — The eastern portion of the loblolly pine ecosystem generally receives adequate precipitation (45-55 inches/year), although summer deficits may occur. About 30-40 inches of this precipitation is either evaporated or transpired, with the remaining 10-20 inches available for streamflow or to recharge soil and groundwater. Silvicultural activities have a major influence on the quantity and quality of water. Practices such as clearcutting reduce evapotranspiration which increases soil moisture, reduces moisture storage opportunity, increases stream and stormflow, and raises the water table. Runoff from flood-producing rainfalls is not greatly affected by careful harvesting. Intensive forestry may decrease water yield also, e.g., conversion of hardwood stands to loblolly pine decreases streamflow unless compensated for by shorter rotations and more frequent thinnings. Sediment is the major pollutant from silvicultural activities. Erosion rates from undisturbed loblolly pine stands are less than 0.05 ton/acre/year. Practices that leave a protective ground cover have less impact than those that expose a high percentage of bare soil. Following mechanical site preparation (KG shearing and disking) of small Piedmont catchments, average annual soil loss may be as high as 4 tons/acre. Roadbuilding also has great potential to increase sedimentation. With proper planning and supervision, impacts of forestry activities on water quality can be minimized.

ADDITIONAL KEYWORDS: water quality, water yield, sediment, soil moisture, ground water, water table, silviculture, evapotranspiration.

INTRODUCTION

Loblolly pine (Pinus taeda L.) is one of the most intensively managed species in the United States. Stands are often regenerated by clearcutting and planting. Sites are commonly prepared for regeneration by mechanical methods or using high intensity fires. Cultural practices include thinnings and burning. These practices affect not only stand growth and composition but also water and other resources. The effect of management activities on the water resource of the loblolly pine ecosystem in the Piedmont and Atlantic Coastal Plain from Georgia to Maryland is the subject of this paper.

Both the Piedmont and Coastal Plain are blessed with ample water. Precipitation averages between 45-55 inches annually and is generally well distributed through the year. If there is a dry season, it tends to be during the fall months. The region has a high solar energy load and high potential
evapotranspiration. Annual water yield, the difference between annual precipitation and evapotranspiration, varies from 10 to 20 inches, averaging about 16 inches.

Forest management has little, if any, effect on distribution and quantity of precipitation received in the Southeast (Hewlett 1982). It does affect surface, soil, and ground water quantity and/or quality. Because loblolly pine occupies such a large portion of the forested area of the South, its management plays an important role in the timing, quantity, and quality of water flow in the region.

HYDROLOGIC PROCESSES

The Runoff Process

Streamflow from forest land is composed of a baseflow and stormflow component. Streamflow averages about 30 percent of annual precipitation in the loblolly pine forest type. In hardwoods, because of less evapotranspiration, streamflow will be somewhat greater (Douglass 1982). In upland streams draining loblolly pine land, about 80 percent of total streamflow is baseflow, i.e., flow between storms, and about 20 percent is stormflow. Baseflow results from discharge from ground water aquifers and from slow drainage of unsaturated flow.

Direct runoff, or stormflow, is that resulting from channel precipitation, overland flow, and subsurface stormflow (Hewlett 1982). A small percentage of precipitation actually falls directly into the stream channel and contributes to runoff. Stream channel area increases during prolonged storms as normally dry channels begin to flow. In the Piedmont, these channels are often old gullies in varying stages of stabilization. Often they are crossed by man-made terraces which provide storage capacity and help to regulate ephemeral flow (Douglass and Van Lear 1983b).

Overland flow is water which runs over the surface without having ever infiltrated the soil. In undisturbed loblolly pine forests, even under eroded Piedmont conditions, overland flow is seldom observed because the rate of infiltration normally exceeds the rate of precipitation. However, overland flow is common on compacted areas such as logging roads, skid trails, and where the entire surface soil has been eroded away leaving a slowly permeable surface. Overland flow allowed to accumulate and gain velocity is capable of eroding large quantities of soil. Foresters should attempt to prevent those conditions which increase overland flow to protect water quality and maintain site productivity.

Subsurface stormflow refers to rapid underground movement of water to streams. It is considered a part of the storm hydrograph, i.e., the plotted stream discharge during and following storms. Subsurface flow is the major component of stormflow and is composed of both saturated and unsaturated flow through soils in expanding and contracting source areas adjacent to perennial and ephemeral stream channels (Hewlett 1982).

Stormflow is a relatively small proportion of total streamflow from perennial streams, especially on watersheds with deep permeable soils, i.e., good storage capacity. Stormflow, however, varies widely among and within
physiographic regions. Only about 4 percent of precipitation falling on the deep permeable soils of the Sandhills and Upper Coastal Plain of Georgia is yielded as stormflow. In the steeper and more eroded Piedmont in mixed land use, about 15 percent is stormflow (Hewlett 1967) although watershed characteristics cause wide fluctuations. For example, in the upper Piedmont of South Carolina, Douglass and Van Lear (1983b) measured stormflow from small undisturbed loblolly pine watersheds that ranged from 5 to 17 percent of annual precipitation. Stormflow increased with the length of the deeply incised uninterrupted channel. Watersheds with the lowest percentage of stormflow were those with well developed terraces which intercepted and stored significant moisture. Watersheds with greatest stormflow were those with highest drainage densities caused by severe past gullying.

Evapotranspiration

Evapotranspiration includes moisture intercepted and evaporated from vegetative, forest floor, and soil surfaces, as well as transpiration (Hewlett 1982, Helvey 1971). Transpiration is the vaporization of water from the living cells of plant tissues. Pines transpire more water than hardwoods on an annual basis, primarily because of greater foliage surface area and year-round foliage retention (Swank and Douglass 1974).

Interception by loblolly pine plantations in the Piedmont of South Carolina is between 14 and 22 percent of annual precipitation (Swank et al. 1972) or a maximum of about 10 inches/year, including litter interception. Although rainfall interception and evaporation are a sizeable percentage of gross annual rainfall, interception does not play a significant role in reducing flood peaks in large storms, e.g., storms larger than 2 inches (Hoover 1962).

Interception is greater by pine than by hardwood stands (Helvey 1971), because of greater foliage surface area in summer and winter. Average annual interception for hardwood stands, although highly variable, averages about 6 inches or 11 percent of precipitation (Helvey and Patric 1965), about 4 inches less than for pine (Douglass 1982).

Greater interception and transpiration by pine can reduce streamflow from watersheds converted from hardwood to pine. Swank et al. (1972) estimated that conversion of Piedmont hardwood stands to loblolly pine could lower streamflow by 25 percent (about 4 inches) due to interception losses alone. Water yield reductions from large scale conversions of hardwoods to pine could reduce water resources of the Southeast (Douglass 1974), unless compensated by intensive cultural practices and shorter rotations.

Rainfall not evaporated from the crowns and boles of trees reaches the forest floor as either throughfall or stemflow. Throughfall falls through or drips from the crowns and is the major avenue for precipitation reaching the forest floor. Swank et al. (1972) estimated that throughfall in Piedmont loblolly pine plantations was 73 to 85 percent of precipitation. Throughfall is greater in older thinned stands than young stands because of openings in the canopy. The amount of precipitation reaching the forest floor as throughfall is not always closely related to basal area or stand age (Swank 1968). Spatial distribution of the canopy and characteristics of rainfall, such as rate, frequency, and duration, are probably more related to throughfall than basal area per se.
Precipitation may also reach the forest floor as stemflow. In storms of short duration or low intensity, there may be no significant stemflow in loblolly pine stands because the rough bark absorbs moisture as it moves down the boles. Stemflow accounted for only 2 percent of gross annual precipitation in a 30-year-old thinned loblolly plantation and about 9 percent in younger unthinned plantations between 5 and 20 years old (Swank et al. 1972).

MANAGEMENT EFFECTS ON WATER YIELD

Water Yield

Streamflow.--Water yield is that portion of precipitation not used in the evapotranspiration process. The excess either leaves the watershed as streamflow or recharges soil and ground water. When loblolly pine stands are harvested or thinned, evapotranspiration is reduced and soil moisture is increased. Because soil moisture is higher following cutting, there is less storage opportunity for rainfall. As a result, a harvested watershed is more responsive to precipitation and streamflow is increased. However, regrowth of vegetation causes evapotranspiration to increase with a concomitant return of streamflow to preharvest levels (Nutter and Douglass 1978, Ursic and Douglass 1979).

Increases in water yield following harvest have been demonstrated around the world (Hibbert 1967). Clearcutting loblolly pine may increase first year water yields by up to 16-18 inches (Anderson et al. 1976). Hewlett (1979) found that clearcutting a large loblolly pine stand in the Piedmont of Georgia, followed by roller chopping and machine planting, increased stormflow volumes from small storms by 27 percent and doubled peak flows. Stormflow volumes and peak flows were much less affected by large storms, i.e., stormflows greater than 2 inches. This supports the premise that clearcutting is unlikely to affect flooding from major storms. Water yield was increased by 10 inches the first year after harvest. The increase in peak flows and stormflow volumes was attributed to reactivation of partially healed gullies, exposure of mineral soil by roads and machine planting, and increased soil moisture on lower slopes.

Clearcutting loblolly pine watersheds on four small watersheds in the Piedmont of South Carolina increased peak flows of average storms (those having peak rates greater than 10 csm) by 55-150 percent and total stormflow volumes up to 100 percent (Douglass and Van Lear 1983a). Hydrologic responses from these small upland basins varied because of soil conditions, i.e., surface soil depth, storage capacity, and differences in channel characteristics. Responses observed on these small basins are considerably larger than those measured on larger pine watersheds, probably because of differences in storage opportunity.

These findings imply that water yields could be increased on a region-wide basis by planned harvesting. Such ideas are attractive because, although water supplies are adequate in the Southeast at present, degradation of water quality and an increasing population could result in future shortages. Also, forest management can reduce water yield under certain circumstances (Douglass 1974). Successful manipulation of water yields to best meet society's needs requires greater planning and coordination among all forest ownerships than exists today.
Soil Moisture-Ground Water.—Soil moisture reaches a maximum in the spring of each year. Moisture in the soil is nearly always moving under a suction gradient or because of gravitational forces (Schultz and Hewlett 1978). Tischendorf (1969) showed that soil moisture depletion under loblolly pine stands in the Georgia Piedmont paralleled evapotranspirational patterns. Soil moisture peaked in March but because of the slow downward unsaturated flow, maximum moisture content below 12 feet lagged 5 months behind that of the surface layers. These patterns suggest that deep-rooted trees can take advantage of moisture beyond the reach of shallow-rooted crops or seedlings.

Patric et al. (1965), in fact, showed that when deep-rooted loblolly pine trees are stressed by drought, a large portion of their moisture requirements can be met from the 6-10 foot soil depth. During the early part of the growing season, absorption is greatest from the shallow soil depths; but as the surface layers are depleted of moisture, the lower soil depths become increasingly important in satisfying water needs. Because of their ability to absorb moisture deep in the soil profile, large trees rarely are killed from drought.

Harvest and site preparation affect soil moisture through compaction and reduced infiltration (Nutter and Douglass 1978). Harvesting commonly disturbs between 20 and 40 percent of the logged area. Porosity and infiltration are low in ruts and compacted areas such as log decks, and overland flow and erosion often occur at such sites. Logging and site preparation activities that impact nearly all of the site are especially damaging during wet weather on fragile, sloping landscapes and fine-textured soils. Effects of soil compaction on seedling growth and soil moisture may last for decades (Nutter and Douglass 1978).

In steep terrain, increased streamflow or stormflow is the most obvious response to harvesting forested watersheds. However, in flat terrain such as the lower Coastal Plain, the most obvious response to harvest is a rise in the water table. Williams and Lipscomb (1981) noted a water table rise even with light cutting on sandy soils in the Coastal Plain of South Carolina. Generally, however, the water table rise will be greatest when clearcuttings are made on fine textured soils, especially when the water table prior to logging is relatively deep. Trousdell and Hoover (1955) observed that the water table of a clearcut loblolly pine-hardwood stand on a poorly drained Bladen silt loam soil in the North Carolina Coastal Plain averaged about 3.5 feet higher than that of a lightly cut selection stand in the first year following cutting.

In the lower Coastal Plain, the water table is near the soil surface and watershed boundaries are difficult to distinguish. In fact, their boundaries are often man-made features, such as dikes, or cut material from drainage ditches. Near the coast, the surface aquifer transmits water to streams, ocean, or to deeper aquifers. Groundwater flow to the ocean is estimated to be an order of magnitude less than that attributed to streamflow (Williams 1979).

Removal of excess water from poorly drained sites in the lower Coastal Plain has been a common practice since colonial times. However, drainage has been used by timber companies in recent years as a prerequisite for logging activities, for site preparation, and to improve growth in established pine
plantations (Terry and Hughes 1978). About 25 years ago, Miller and Maki (1957) showed that drainage of pocosin soils in North Carolina markedly improved growth response of loblolly pine. Drainage also extends the logging season and reduces soil damage during harvest. In contrast to the Sandhills and Piedmont where water may be in short supply, the main water problem associated with timber harvest in the lower Coastal Plain is an excess of water.

MANAGEMENT EFFECTS ON WATER QUALITY

Sediment

If trees could be harvested without disturbing the forest floor, erosion from the land surface would not be significant, although a minor increase in channel cutting would be expected from the greater flow after harvest. However, when harvesting disturbs large portions of a cut area, increases in overland flow and erosion are inevitable. If the areas of exposed soil are discontinuous and randomly distributed, much of the displaced soil is deposited in depressions and behind litter and does not reach the stream. Herbaceous vegetation rapidly stabilizes disturbed soils and provides protection against raindrop impact.

Sediment is generally considered the major water pollutant from forest activities (Yoho 1980, Ursic and Douglass 1979). About 65 percent of the South is forested and most of this land produces little sediment to stream channels. Douglass and Van Lear (1983b) measured sediment yields of about 0.01 ton/acre/year from undisturbed 37-year-old loblolly pine plantations in the South Carolina Piedmont. Because overland flow was not observed, sediment probably came from channel erosion in established gullies. Hewlett (1979) estimated sediment export from an undisturbed loblolly forest in Georgia's Piedmont to be about 0.04 tons/acre/year. Thus, the evidence indicates that erosion rates under undisturbed loblolly pine stands in the highly erodable Piedmont are less than 0.05 ton/acre/year.

Disturbance influences sediment delivery to streams to varying degrees depending upon the characteristics of the land, nature of the disturbance, climatic factors, and the care taken to prevent sedimentation. Low-intensity prescribed fires, for example, have a negligible effect on sedimentation in the Piedmont. Douglass and Van Lear (1983b) found no increase in sediment levels of ephemeral Piedmont streams following two prescribed fires. About two-thirds of the forest floor remained after the second burn and less than 1 percent mineral soil was exposed by either burn. Brender and Cooper (1968) also noted no adverse hydrologic effects of burning in the Piedmont when some decomposed forest floor material remained to protect the soil. These results indicate that low-intensity prescribed fires can be used in loblolly pine stands on relatively steep slopes (10-20%) and fragile soils. In the Coastal Plain, Richter, et al. (1982) also found that low intensity fires had little impact on soils, nutrient cycling, or water quality. The impacts of high intensity site preparation fires on water quality, however, has received little study.

At the other extreme is mechanical site preparation that exposes a high proportion of mineral soil (Ursic and Douglass 1979). Douglass and Goodwin (1980) measured soil losses for three years after mechanical site preparation
treatments were applied in the North Carolina Piedmont. Annual soil loss was related to percent ground cover and runoff and ranged from .005 tons/acre for undisturbed forests to 4 tons/acre for watersheds that were KG bladed, windrowed with windrows burned, and disked. Percent cover, i.e., litter, herbaceous material, wood, or stone, was the most important factor determining soil loss. In another Piedmont study, Hewlett (1979) measured sedimentation rates of 1.8 tons/acre/year for 2 months after harvesting, site preparation (chopping), and planting. Rates dropped thereafter so that total sediment delivery for the year was about 1 ton/acre. Sediment production from road building and channel area damage was not included in these figures.

Douglass and Goodwin (1980) observed high rates of sediment loss when slash and soil were pushed into ephemeral stream channels and burned. Since channels are the primary source of sediment even in undisturbed stands (Ursic and Douglass 1979), great care should be exercised not to aggravate these already unstable sites.

Hewlett (1979) observed lower sediment yields from clearcutting followed by chopping in the Piedmont of Georgia than cited by Douglass and Goodwin for KG and disking operations. This variance may reflect increased channel storage opportunities in larger watersheds, less disturbance by the chopping and planting technique, and differences in slope and soil erodibility between the two studies. But the method of site preparation is probably the main reason for the variation. From the standpoint of reducing non-point source pollution, site preparation treatments that minimize exposure of mineral soil are most desirable, especially for steeper Piedmont and upper Coastal Plain sites.

Sediments eroded from roads are the major water quality problem in forested regions around the country. Dissmeyer (1976) estimated that road surfaces in the South contribute about 40 tons of sediment per acre of road surface. Hewlett (1979) calculated that 90 percent of the sediment export over a 30-year pine rotation came from poor roading and channel damage from site preparation and planting equipment. Sediment rates exceeded 3.5 tons/acre/year for a short period following road construction and channel damage during planting.

Because roads are such major contributors to sedimentation, Kochenderfer's (1970) precautions for roads in steep terrain bear repeating. Keep logs and equipment out of streams. Keep roads to a minimum and away from streams. Use bridges or culverts for stream crossings. Winch logs upslope away from stream channels. Avoid road grades over 10 percent. Construct water-bars on skid trails and unused truck roads after logging, and sow grass on steeper slopes and near streams.

**Herbicides**

Herbicides have great potential as a non-sediment producing method of site preparation (Nutter and Douglass 1978), but their hydrologic effects have received little study. Herbicide application would result in little or no soil compaction and would not disturb the protective litter layer. Thus, overland flow should not be increased appreciably. Herbicides could themselves become pollutants if carried by drift or runoff into streams. However, careful applications of Tordon-10K to ridges and upper slopes did not
produce significant pollution of streams in the Southern Appalachians (Neary et al. 1979). Another herbicide hexazinone (Velpar) was broadcast by hand over four small watersheds in the Georgia Piedmont. Residues of hexazinone and its metabolites were detected in the second order perennial stream water samples, but could not be detected in aquatic invertebrates and macrophytes. No major changes were observed in the aquatic insect community (Mayack et al. 1982).

**Nutrients**

Although sediment is the major water pollutant associated with forestry activities, water quality may be altered by nutrients in solution or nutrients attached to sediment. Dissolved minerals in stream and stormflow are typically low in Piedmont streams. Hewlett (1979) found nitrate from mixed agricultural and forest land (0.38 ppm) in the Georgia Piedmont was four times that from the pine forest itself (0.09 ppm). Harvest and regeneration activities did not change baseflow concentrations of nutrients, but because water yield increased, there were small increases in nutrient export for three years.

Douglass and Van Lear (1983b) also found low nutrient concentrations in stormflow from undisturbed loblolly pine plantations in the South Carolina Piedmont. Concentrations of $NO_3^-N$, $NH_4^+N$, and $PO_4^-P$ averaged 0.03, 0.05, and 0.01 ppm, respectively. Cation concentrations in the ephemeral stormflow ranged from 0.43 ppm for Mg to 0.85 ppm for K. Two low intensity prescribed fires had no significant effect on nutrient concentration or exports.

In light of the low base-line levels of dissolved minerals in streams draining loblolly pine watersheds, and the small and temporary nature of increases following site disturbances, it is doubtful that elevated nutrient levels will be a pollution concern.

**Temperature**

Little information is available to evaluate effects of cutting on water temperature in the Piedmont. However, studies elsewhere indicate that increases in temperature must be expected if the stream channel is exposed to direct sunlight. Summer maximum temperatures were increased from 68°F to 79°F by clearcutting a loblolly pine stand in the Georgia Piedmont (Hewlett 1979). A thin line of buffer trees along the stream channel did not provide adequate shade to prevent stream temperature increases. But other studies indicate temperature increases can be controlled through proper use of buffer strips. These strips could be selectively harvested and still allow adequate shade to prevent elevated stream temperatures. In addition, these strips also filter out eroded soil before it reaches the stream channel.

**DISCUSSION**

The practice of silviculture will always affect in varying degrees the water resource. As the term ecosystem implies, all components of the system are interrelated. More than ever, it is essential for foresters to understand and anticipate effects of silviculture prescriptions on water and other resources. While nearly all practices associated with intensive pine management have the potential to change water yield and degrade water quality,
proper advance planning and close supervision can minimize the adverse and maximize the beneficial effects.

Water yields can be increased or decreased by intensive forest management. Harvesting and intermediate cuttings increase soil moisture because evapotranspiration is reduced. This in turn increases streamflow and ground water storage, or both. This increase in water yield will become increasingly important as demand for this limited resource increases. But it is unlikely that careful management will have much impact on regional flooding. To begin with, the area cut and yielding extra water is usually a small percent of the total land area. Secondly, flood producing storms are those which substantially exceed storage capacity of the soil, and the presence or absence of forests have a limited effect on such floods.

Today, except for a few municipal watersheds, forests are not managed for the purpose of increasing water yield. They are managed to yield high quality water. Yet in the future when the gap between supply and demand becomes critical, an understanding of how forest management can be used to augment water supplies will be important. Models have already been developed to predict water yield increases from management of both conifers and hardwoods (Douglass 1982). Thus, foresters and hydrologists have much of the information in hand for future debates concerning the balancing of water and timber needs for the public good.

Because loblolly pine intercepts and transpires more water than hardwoods, conversion of millions of acres of poor quality hardwood sites to pine could significantly reduce regional water yields. However, through modeling it can be demonstrated that water yield depends upon the intensity of management. Although pines use more water than hardwoods in the unmanaged situation, the potential difference declines as rotation age is shortened. Thus, pine forests may yield less or more water than hardwoods, depending on the specific management practices applied. The question foresters will have to answer is how to supply the needs of society for wood and water, not just wood. Foresters in the future will have to adjust to produce a mix of benefits from forest land, rather than a single crop.

The water quality parameter most impacted by silviculture is sediment content. Intensive mechanical site preparations in the Piedmont can cause high rates of soil loss, especially from those treatments which expose a high percentage of bare soil. Conversely, practices which leave most of the forest floor intact, such as low-intensity prescribed burning, have a negligible effect on sedimentation. Water quality, as well as site quality, can be protected in steep terrain by leaving as much of the forest floor and logging debris on site as possible. For this reason, chopping is much preferred in steeper terrain to such practices as root raking and disking. In the lower Coastal Plain, erosion is not as great a concern because of the flat terrain.

The best available model that predicts sedimentation from forestry operations is Dissmeyer and Foster's (1980) modification of the Universal Soil Loss Equation (USLE). It indicates that the cover management factor is the most important factor associated with soil loss. The modified USLE equation is a valuable decision-making tool for forest management in the Southeast.
Under Section 208 of P.L. 92-500, the land manager is mandated to control non-point source pollution. Land managers must understand the hydrologic processes that contribute to sedimentation in order to comply with the intent of the law. Presently, compliance is voluntary. Information is rapidly becoming available concerning potential impacts of various practices on water quality which will enable the forestry community to improve water quality.

Forestry has both ethical and economic incentives for improving water quality. Ethically, it is good for society and future generations to conserve the land, which means keeping soil in place and out of streams. Economically, soil loss is a reflection of potential declines in site quality and productivity. Good soil management is good water management.

LITERATURE CITED


