WATER YIELD AND HYDROLOGY

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Abstract—Few studies have sought to examine the effects of fuel load reductions on hydrologic responses. Because of this lack of direct information, in this chapter we describe water table, water yield, and other hydrologic changes primarily resulting from other types of vegetation manipulations. The reader then can apply these results to various levels of fuel reductions. Often the vegetation manipulations have been more intensive than activities that would be used simply for reducing fuel loads; consequently, many of the hydrologic responses reported probably are larger or more extreme. Regardless of the region involved, hydrologic changes result primarily from changes in evapotranspiration when basal area is reduced. Soil condition, such as antecedent moisture levels, porosity and compaction, and extent of exposure, also substantially influence hydrologic responses. These same factors largely will control hydrologic changes from reducing fuels, although additional research specifically involving fuels reduction is needed so hydrologic changes can be predicted more accurately.

INTRODUCTION

Investigations of hydrologic responses resulting from reducing vegetation density are fairly common throughout the East. While most studies have focused on the potential for increasing water yields or documenting effects from intensive practices that far exceed what would be done for fuel reduction, data are available from some less intensive manipulations (e.g., thinnings, understory removals, and controlled burns for seedbed establishment) that are more easily related to fuel reduction activities. In this chapter, findings from the entire range of available manipulation intensities are presented so the reader can apply the results to various levels of fuel reductions. Even though site preparation is a silvicultural technique and is not traditionally considered in the context of fuels reduction, activities such as shearing, roller chopping, and windrowing are included in this review because they affect the architecture, mineralization rates, and surface area of materials left on site and thus have relevance to combustibility and fuels management.

The ways and extent to which hydrologic responses from vegetation manipulation occur depend upon whether they are expressed as surface flows (e.g., streamflow) or changes in water table elevations. Surface flows typically are associated with uplands (Sun and others 2004) because the steeper terrain results in rapid runoff, which encourages the concentration of water and channel formation (Jackson and others 2004). Hydrologic expression via water table changes typically is associated with flat or depressional terrain (Sun and others 2004) because the lack of slope slows water movement and limits channel network formation and the presence of surface flows (Grace and others 2003, Jackson and others 2004). Surface flow in wet flatlands in the Southeast occurs primarily within drainage ditches created to make lands more amenable to forest plantation or agricultural growth (Amatya and others 1996, Lebo and Herrmann 1998). Water contributing to these ditches comes principally from saturated or nearly saturated lateral subsurface flow (Amatya and others 1996, 1997; Sun and others 2004); to reflect that this source water results from situations that differ from typical streamflow, drainage in these ditches is sometimes referred to as outflow (Amatya and others 1997, 2002; Grace and others 2006; Lebo and Herrmann 1998).

The various hydrologic responses are described by similar equations. Streamflow in a given time period is described and predicted by the water balance equation:

$$\text{Streamflow} = \text{Precipitation} - \text{Evapotranspiration} \pm \Delta\ \text{Soil Moisture Storage} - \text{Deep Seepage} \qquad \text{eq. 1}$$

Often deep seepage losses are assumed to be approximately zero, which simplifies the equation for calculations on a water year basis. Changes in soil moisture storage can be substantial in the short term or seasonally, but over a water year, this term generally is assumed to approach zero. Thus, annually the equation further simplifies so that total streamflow is determined by how much incoming precipitation is lost to evapotranspiration (ET), which is the cumulative losses of evaporated canopy interception, soil evaporation, and vegetative transpiration. Obviously, climate is a dominant term in controlling ET, but in forest land ET can be substantially affected by differences in

species composition, vegetative density, and microclimate resulting from forest management activities; consequently, streamflow also can be substantially affected by these differences.

Equation 1 can be used to predict total stream discharge in the short term, but if changes in soil moisture are included because they are important in controlling streamflow yields. By contrast, the shape of the storm hydrograph cannot be predicted from only the water balance equation; in fact, hydrograph behavior is extremely difficult to predict accurately because precipitation events are unique and random, and physical factors of the watershed affecting the timing of water delivered to stream channels are not constant with time.

Streamflow or outflow in channels or drainage ditches supplied primarily by saturated lateral water movement is similarly described, with one additional component to account for lateral seepage across watershed boundaries (Amatya and others 1996):

$$\text{Streamflow} = \text{Precipitation} - \text{Evapotranspiration} \pm \text{Lateral Seepage} \pm \Delta\ \text{Soil Moisture Storage} - \text{Deep Seepage} \qquad \text{eq. 2}$$

The deep seepage term for many wet flat lands also is considered to be approximately zero because many of the soils involved are poorly drained (e.g., Amatya and others 1996; Grace and others 2003, 2006; Riekerk 1989).

The change in the height of a wetland water table for a given time period is described by the equation (Sun and others 2001):

$$\Delta\ \text{Water Table Height} = (\Delta\ \text{Inflow} - \Delta\ \text{Outflow} - \Delta\ \text{Evapotranspiration}) / (\text{Soil Specific Yield}) \qquad \text{eq. 3}$$

Inflow and outflow rates can have large effects on water table height, but if water exchange is slow, ET becomes the dominant factor in controlling water table height. Soil specific yield, also known as drainable soil porosity, is the ratio of the volume of water that drains from a saturated soil due to lowering the water table relative to the volume of that soil. Its value ranges between 0 and 1, but it is not actually a constant and depends upon position of the water table, rate of water table change, and soil characteristics (Hillel 1982). Fuel reduction activities primarily would affect the variables in the numerator of equation 3 (Sun and others 2001).

For changes in water table responses to be measured and interpreted accurately, it is critical that measurement wells be at least as deep as the lowest water table levels expected during monitoring. If the well is not sufficiently deep, a water table may rise or fall, but it will be impossible to document the change. In these instances, "no measured effect" should not be interpreted as "no effect."

HYDROLOGIC GROUPINGS OF PROVINCES

Hydrologic studies of vegetation manipulation have been performed in all the major regions of the Eastern U.S. Commonly, the study areas have been experimental forests operated by either the U.S. Forest Service or universities, although in the South and mid-South studies have been applied fairly broadly, particularly on industrial lands in the Coastal Plain.

For consistency throughout this eastern document, our approach is to classify and describe responses by ecological divisions and provinces (Figure X Chapter X, this volume) to the extent possible. Ecological divisions and provinces, respectively, are defined by criteria based upon "regional climatic types, vegetational affinities, and soil order," and "dominant potential natural vegetation, and highlands or mountains with complex vertical climate-vegetation-soil zonation" (U.S. Department of the Interior 2003). As a result, these boundaries do not fall strictly along those that largely define hydrologic behavior, such as the commonly used physiographic region boundaries defined by geology and topography (U.S. Department of the Interior 2003). Thus, in an effort to keep to the ecological division/province approach as much as possible, we have defined groups of provinces with fairly similar hydrologic characteristics (Table 1) and present subsequent discussions based on those groupings. However, because most groupings include provinces from different divisions, these groupings have been assigned more traditional physiographic or regional names (North Central, Northeast, Ozarks and Ouachita Plateau, Central and Southern Appalachians, Piedmont, and Coastal Plain) because these can be more concisely described and easily understood. The results and interpretations from the reviewed literature should be generally applicable throughout the area encompassed by the respective provinces within the grouping. The principal exception to grouping by distinct

ecological province is the separate consideration of the Piedmont and Coastal Plain. Hydrologically, these two regions behave very differently from one another, but the boundaries of the ecological provinces involved (Figure X Chapter X, this volume) do not coincide with the boundaries of the Coastal Plain and Piedmont physiographic regions (Fig. 1). Consequently, the Southeastern Mixed Forest province within the Subtropical division is included in both the Piedmont and Coastal Plain regions (Table 1).

No hydrologic response data applicable to province 251 (Prairie Parkland Temperate) were found in the literature, so this province is not included in the review. Likewise, province 411 (Everglades) is not included, but fuel reduction activities are not applicable to this area, making it a moot point.

HYDROLOGIC RESPONSES

Regions are discussed in order from north to south in subsequent sections so that responses from similar climates are grouped closely. When data exist, water yield and water table results are presented by season (growing and dormant) as well as by year. Storm event responses also are described where data were available. The terms quickflow and stormflow are used interchangeably in this chapter to define the volume of flow composed of the sum of precipitation falling directly into the channel, surface (overland) flow reaching the channel, and precipitation delivered to the channel by subsurface flow during and immediately following precipitation or snowmelt events (Hewlett and Hibbert 1961). Peakflow is defined as the instantaneous maximum magnitude or rate of discharge during a precipitation or snowmelt event.

North Central

This region is characterized by two different types of sites: those that have unsaturated mineral soils (often uplands) and those that are lowland bogs with organic (peat) soils. Often the elevational or topographic differences between the two are not great, but they are large enough to result in different soil characteristics that substantially affect hydrologic responses. Hydrologic changes from vegetation manipulation in organic soils usually are measured as water table fluctuations, and those in mineral soils usually are measured as streamflow changes.

Streams can exist in lowland bogs, but hydrologic expression in them is generally more tempered than in water tables because peatland soils tend to transmit water laterally very slowly (Boelter and Verry 1977). For example, strip cutting followed later by clearcutting black spruce in a lowland bog on the Marcell Experimental Forest in northern Minnesota did not change streamflow yields (Table 2), partially because of the low hydraulic conductivity (Verry 1981). However, the type of peat soil present in the area of harvesting substantially influences hydrologic responses in streams, if present, or water tables. Water moves laterally fairly freely and rapidly in poorly decomposed peats and very slowly in well-decomposed peats, making these soils hydrologically quite responsive. On the other hand, well-decomposed organic soils, which are most common in the North Central region, have many small pores that hold water tightly because of extremely low hydraulic conductivities, so losses from these organic soils are primarily as evapotranspiration (Boelter and Verry 1977).

Water table responses also are affected by the type of ground water involved. If the harvested stand is over a ground water-fed water table, removing or reducing the evapotranspirational draft will have little effect on water table fluctuations or levels because regional aquifer supplies greatly exceed precipitation inputs. By contrast, harvesting over perched water tables can result in measurable changes in water table levels. If precipitation frequency is adequate, water tables in harvested areas will rise because interception losses are reduced. If precipitation is infrequent, the water table will drop after harvesting because there is increased evapotranspiration due to winds and increasing transpiration by sedges that can access deeper moisture than many other plants (Boelter and Verry 1977). This is the type of water table response that Verry (1981, 1986) reported in the 4 years after clearcutting a bog. Water tables rose 100 mm during wet periods (Table 2), because interception was reduced by approximately 170 mm (30 percent), thereby adding that much more precipitation to the peat soils. Conversely, during dry periods water tables fell by as much as 190 mm after clearcutting due to high levels of evapotranspiration attributable to greater wind, solar radiation, higher surface temperatures, and rapid herbaceous vegetation growth (Verry 1981). Water tables also fluctuated to a greater degree after clearcutting during years of higher-than-average or lower-than-average precipitation compared to before clearcutting.

Harvesting on mineral soils can increase soil moisture (Blackmarr and White 1964, Verry 1972) and/or water table levels (Urie 1971), but because mineral soils transmit water to streams quickly, measurements of hydrologic change often are focused on streamflow. Many harvests in areas with mineral soils cover a greater percentage of total

watershed area than those on organic soils, further contributing to the degree of hydrologic change that may be observed in mineral soils. Upland clearcutting of aspen over two-thirds of watershed 4 on the Marcell Experimental Forest resulted in significant increases to annual runoff for 9 years following harvesting (Hornbeck and others 1993, Verry 1987), with approximately 50 percent of the 9-year change occurring during harvesting and the 3 following years (Table 2). Changes during those 3 years were 40 to 70 percent above those when trees were present on the watershed. Most of the annual stream augmentation occurred during the growing season (Verry 1972, 1987). No change in annual yield was reported after clearcutting an oak hickory stand in a 0.67-ha watershed at Rose Lake Wildlife Experiment Station in southern Michigan, and evapotranspiration was estimated to have returned to pre-treatment levels within 5 years after the clearcut (Blackmarr and White 1964).

Stormflow effects in the North Central states tend to be a function of whether snowmelt or rainfall is involved and how much of the stand is harvested. Harvesting only about 50 percent of watershed 4 of the Marcell Experimental Forest reduced peak runoff during spring snowmelt by 35 percent because the melt in the forest and open areas became desynchronized (Verry 1972, Verry and others 1983). But increasing the area harvested to approximately two-thirds of the watershed increased spring snowmelt peaks from 11 to 143 percent for 7 years (Verry and others 1983), although effects may have lasted for as many as 15 years (Verry 1986). The increases presumably occurred from less desynchronization of snowmelt due to the greater heat transfer to the snow pack from solar radiation and re-radiation of longwave radiation to the snowpack by the regrowing sprouts (Verry 1986, Verry and others 1983). Consequently, snowmelt peak discharges began 3 to 5 days earlier (Verry 1972, Verry and others 1983); however, none of the changes to snowmelt peaks resulted in significant increases in total snowmelt volumes (Verry and others 1983).

By contrast, stormflow volumes from rain events increased by 100 percent or more the first 2 years after harvesting two-thirds of the watershed, but they were not significantly affected by the third year. Rainfall-induced peakflow rates were significantly higher for 8 years – the increases during the first 3 to 5 years were about double pre-harvest levels. Increases in rainfall-associated peakflows were due to reductions in soil moisture deficits after harvesting (Verry and others 1983). Peakflow rates from the annual series for 2-year and 10-year events, respectively, increased by about 1.5 and 2.5 times over pre-harvest levels (Verry 1986, Verry and others 1983). Similarly, flow duration curves showed that average daily flows increased across all ranges of flow rates except the very highest flows associated with maximum snowmelt peaks (Verry 1972).

Northeast

Most of the studies in the Northeast involve clearcutting or whole-tree harvesting (Table 3). First-year water yield increases from these intensive harvests generally were in the range of 150 to 350 mm (20-40 percent) (Table 3), although occasionally higher percentage increases were reported from whole-tree harvests (Pierce and others 1993). Small single harvests or small sequential harvests (e.g., progressive strip cuts) yielded substantially lower annual discharges (Hornbeck and others 1987, Mrazik and others 1980). Regardless of the amount of augmentation, increases were short lived, lasting no longer than 6 years (Table 3), and after 10 to 15 years, water yields commonly fell to levels less than pre-treatment (Table 3). This result may be because regenerating species had higher transpiration rates than the original stand (Hornbeck and others 1987).

With one exception (Mrazik and others 1980), seasonal data show that annual augmentation in the Northeast was almost entirely the result of increased discharge during the growing season, and water yield changes during the dormant season were very small (Table 3). Water yield increases of ≥ 300 percent have been reported from a clearcut during the first one to two growing seasons (Hornbeck and others 1970). Thus, as growing season augmentation diminished, so did annual water yields. Mrazik and others (1980) found that percentage increases in streamflow were greater during the growing season, but the actual volumes of streamflow augmentation during the growing and dormant seasons were similar (Table 3). They attributed the lack of seasonal differences to the milder climate in central Massachusetts compared to other study sites in New England, such as Hubbard Brook.

Increases in streamflow were expressed primarily during low flows. Shifts in flow frequency curves for Caldwell Creek, MA, and watersheds 2, 4, and 5 at Hubbard Brook indicated increases in the numbers of days of occurrence across all flows, but the greatest displacement of the curves was at the lowest flows (Hornbeck and others 1997, Mrazik and others 1980) primarily during the growing season (Hornbeck and others 1997). This same pattern was observed for basal area reductions ranging from about 35 percent (Mrazik and others 1980) to 100 percent of the watershed, although curve displacement was greatest when herbicide applications followed clearcutting (Hornbeck

and others 1997). For example, average daily growing season flows equaling or exceeding 1 mm occurred on an average of 26 days before clearcutting watershed 2 at Hubbard Brook. After clearcutting and herbicide applications, growing season flow equaled or exceeded 1 mm on 116 days.

Removing overstory vegetation by clearcuts, block cuts, and strip cuts resulted in changing the timing of spring snowmelt, but it did not change the overall volume of spring discharge (Hornbeck and Pierce 1970; Hornbeck and others 1970, 1987, 1997; Pierce and others 1970, 1993). More extensive and continuous overstory removal resulted in slightly earlier snowmelt peaks than light cuts that had substantial residual shade from edge vegetation (Hornbeck and others 1987). On all of the harvests at Hubbard Brook, peakflow from spring snowmelt occurred an average of 4 to 8 days earlier than from a fully forested watershed, although during one year there was a shift forward of 17 days on one watershed due to clearcutting (Hornbeck and Pierce 1970, Pierce and others 1970). Resulting streamflow and peakflow were higher than normal during these earlier periods of snowmelt and lower than predicted later in the snowmelt season. Snowmelt also ended 2 to 4 days earlier in a clearcut watershed than in an uncut watershed with the same aspect (Hornbeck and Pierce 1970).

Reducing vegetation can result in other hydrograph responses, but the limited results reported in the literature from the Northeast indicate that changes to peakflow and stormflow were small even after clearcutting an entire watershed (Table 4). No changes in average peak discharges were observed for 3 years at Dickey Brook, MA, after 32 percent of the basal area was removed using a combination of clearcutting and thinning (Bent 1994). High flows ($> 0.2\ m^3\ s^{-1}\ km^{-2}$) increased by an average of 13 percent during the first 3 years after clearcutting and herbicide applications on watershed 2 at Hubbard Brook (Hornbeck and others 1970). The average annual increase in stormflow during the first 3 years was 21 percent (Hornbeck and others 1970), but the largest relative increases in storm peaks and the greatest increases in stormflow volumes have been reported primarily during the largest events (Hornbeck 1973, Mrazik and others 1980) during the growing season (Table 4). Average annual stormflow on Hubbard Brook watershed 2 increased by 99 mm during the first 3 years, with two-thirds of that occurring during the growing season (Table 4). Dormant season stormflow increases were restricted primarily to spring melt events, because snowmelt was concentrated in one or a few short periods. Individual stormflow totals during these spring melts can be much greater than during other parts of the year. For example, the maximum increase in spring stormflow from Hubbard Brook watershed 2 was 50 mm, compared to a maximum summer stormflow increase of 30 mm (Hornbeck 1973). By contrast, changes to mean peak discharge at Caldwell Creek, MA, were distributed relatively evenly between growing and dormant seasons during the first 4 years after deadening or harvesting approximately 35 percent of the watershed (Mrazik and others 1980).

Ozarks and Ouachita Plateau

Unlike the other regions described in this chapter, available discharge data from the Ozarks and Ouachita Plateau focus on stormflows and peakflows rather than annual yields, because runoff data have been collected primarily from ephemeral channels.

In the Ozarks, clearcutting one-third of a 6.6-ha oak watershed did not change stormflow even though half of the harvested area was cut using a logger's choice method and soil disturbance was substantially greater than what would have occurred with best management practices (BMPs) (Settergren and others 1980). The lack of change was attributed to the limited area that was harvested and the confinement of disturbance to the ephemeral headwaters. Had the harvest been performed in lower portions of the watershed closer to the non-ephemeral portions of the channel, stormflow increases via reductions in soil infiltration and subsequent overland flow may have occurred as a consequence of the extensive soil disturbance. For example, mechanical removal of litter significantly reduced infiltration rates of four soil series in the Missouri Ozarks by 11 to 25 percent, with an average reduction of 18 percent (Arend 1941). Annual burning of the hardwood litter layer for 5 to 6 years across a variety of soils in the Ozarks exposed mineral soil and reduced soil infiltration by 20 to 62 percent; the average reduction was 38 percent (Arend 1941).

Even though no changes to stormflow were observed by Settergren and others (1980) after clearcutting one-third of a watershed, some local soil moisture augmentation may have occurred due to reductions in transpiration. Substantial differences were observed in soil moisture deficits between clearcut and forested plots on the Koen Experimental Forest in the Ozark Mountains (Rogerson 1976). Average maximum soil water deficits in the clearcut plots were 78 mm, only 29 percent of the average maximum deficits of 267 mm in the forested plots. Soil moisture deficits in the clearcut plots were present only during summer and fall; recharge occurred earlier than in the forest

because summer deficits grew only at an average daily rate of 0.6 mm in the clearcut plots compared to 2.1 mm in the forest.

The soil disturbance associated with site preparation following clearcutting of shortleaf pine (*Pinus echinata* Mill.) substantially affected hydrology in three small watersheds in the Ouachita Mountains of Oklahoma (Miller 1984). Site preparation following clearcutting included roller chopping, burning, and contour ripping of the subsoil. The resulting soil disturbance increased roughness and detention storage in the furrows and cut off soil macropores connected to ephemeral channels. Precipitation then became routed into the subsoil rather than laterally to streamflow. As a result, average stormflow in the clearcut watersheds fell to levels below the uncut controls (Table 5) even though transpiration and probably interception losses were reduced greatly by harvesting and site preparation. Only during the second year after treatment, which was unusually dry, were the reductions in evapotranspiration in the clearcut watersheds enough to significantly increase stormflows. Annual average peakflow rates also were not affected by harvesting and site preparation.

In the Ouachita Mountains of Arkansas, stormflow responses resulting from clearcutting followed by roller chopping and burning were compared to those from selection harvesting with no site preparation, and uncut controls (Miller and others 1988). The large average annual stormflow increases that were observed (Table 5) indicated that stormflow increased roughly proportionally to the amount of harvesting and site disturbance; however, the increases were not significant because there was substantial variability in responses across the replicated sites. One of the three replicated sites in both harvesting treatments consistently yielded much greater annual stormflow volumes than the other replicates, presumably because it had more lateral moisture movement through the soil (Miller and others 1988). Hydrologic increases calculated from those sites provide a measure of high-end responses that could be expected: the average stormflow value for the clearcut/site prepared watershed would have been 98 mm greater than the average reported for year 1 in Table 5 and 100 mm greater than in year 2. By contrast, selection harvest values from the first 2 years would have been little changed (-5 and 0 mm different). These greater stormflow values suggest that all clearcut/site prepared watersheds (including those dominated by vertical soil moisture) had substantial short-term reductions in transpiration and interception compared to the selection harvests. The changes in soil moisture from all clearcut and selection harvest watersheds were large enough to increase the number of stormflow events that occurred the first 2 years after harvesting and to lengthen the time that stormflows, albeit small volumes, were present. After harvesting, periods of stormflow extended further into the summer and began earlier in the fall. Peakflow increases also were related to the intensity of treatment, but peakflows were not significantly different among the treatments and the controls.

In other nearby watersheds in the Ouachita Mountains, clearcutting and thinning pine followed by 3 years of herbicide applications to control hardwood regrowth also decreased soil water deficits, which, in turn, increased discharge from ephemeral channels (Rogerson 1985; Table 5). In the first growing season following thinning and clearcutting, soil water deficits were reduced by as much as 51 to 76 mm and 76 to 102 mm, respectively, on the clearcut and thinned watersheds. Elevated soil moisture levels continued for at least another six growing seasons. Dormant season soil moisture was not affected by either harvesting treatment. Resulting first-year water yield increases for both types of harvests were substantial, but those from the clearcut were about 2.5 times as great, both as volume and percentage increases, as from the thinned watershed (Table 5). Water yields over the 7-year study increased by an average of 23 percent from thinning and 67 percent from clearcutting, and more than half of those volume increases occurred during the growing seasons (thinned 52 percent, clearcut 61 percent).

Clearcutting with mechanical site preparation in the Athens Plateau of Arkansas increased stormflow significantly the first and third years after treatment (Beasley and others 1986), but clearcutting followed by chemical site preparation did not increase streamflow during any of the 3 years following treatment (Table 5) because vegetation deadening was incomplete, stump sprouting was common, and there was less overall disturbance to watershed soils. Thus, more soil moisture augmentation was needed before stormflow could be generated. Stormflow increases in year 2 were very large because that year was unusually wet with several large rainfalls; however, stormflow was not statistically different from pre-treatment because of substantial variability in responses among replicate watersheds attributable to variable soil depths. The Athens Plateau is an area of transition between the Ouachita Mountains and the West Gulf Coastal Plain, and watershed replicates in the West Gulf Coastal Plain had deeper soils than the replicates in the thinner rocky soils of the Ouachita Mountains. As a result, there was almost no stormflow discharge in the former area except during the unusually wet second year, while replicates in the Ouachita Mountain soils yielded much more stormflow.

Central and Southern Appalachians

The central and southern Appalachians cover a fairly extensive north-to-south range. In the northern portions, snow is an important component of the hydrologic cycle, although snowpacks are typically not continuous throughout most winters (U.S. Department of Agriculture 1987). In the southern portion, snow makes up only a small percentage of the hydrologic budget (Hewlett and Hibbert 1961). Most of the available data for this region is from the Fernow Experimental Forest in north central West Virginia and the Coweeta Hydrologic Laboratory in western North Carolina. Limited amounts of data also are available from central Pennsylvania and the Cumberland Plateau. Studies in this region provide data from a wide variety of experiments, including thinnings, other partial harvests, and understory removal/reduction experiments.

In general, more intensive levels of harvesting in this region result in greater augmentation of annual flows (Table 6), and first-year water yield increases are proportional to the basal area removed (Hewlett and Hibbert 1961, Kochenderfer and others 1990). Thinnings in which only small percentages of the basal area were removed typically resulted in small, nonsignificant changes in annual discharges, whereas with few exceptions clearcutting most or all of a watershed increased annual water yields by at least 100 mm (and often more) during the first year or two following harvesting. Site preparation following clearcutting at Clover Run watershed (Kochenderfer and Helvey 1989) and Coweeta watershed 6 (Hibbert 1969) did not increase annual water yields more than from clearcutting alone (Douglass and Swank 1972, Hewlett and Helvey 1970, Hoover 1944, Johnson and Kovner 1954, Kochenderfer and others 1990, Kovner 1956, Lull and Reinhart 1967, Meginnis 1959) (Table 6). However, vegetative reductions do not have to be restricted to the overstory to increase annual discharge. Removal of a thick understory of mountain laurel (*Kalmia latifolia* L.) and rhododendron (*Rhododendron maximum* L.) that accounted for 22 percent of the basal area of Coweeta watershed 19 resulted in significant, although short-term, increases in annual yields (Table 6).

In the Appalachians, yields typically decline quickly due to rapid regrowth and restoration of evapotranspiration encouraged by high precipitation levels and relatively long growing seasons. For example, after clearcutting at Fernow, Leading Ridge, and Coweeta, discharges returned to pre-treatment levels in 5 to 10 years (Hornbeck and Kochenderfer 2001, Hornbeck and others 1993, Swank and others 2001). After recovery, streamflow can fall below that of the uncut stand due to changes in species composition or leaf area index of the regrowing stand (Swank and others 2001).

More severe deforestation treatments using herbicides to kill residual vegetation and prohibit regrowth (Fernow watersheds 6 and 7) resulted in greater annual increases than from clearcutting alone (Table 6). This result was likely because nearly all the transpiration on the watersheds ceased from the deadening, whereas in traditional clearcuts substantial live vegetation remains in residual saplings and understory plants. Because the denudation lasted several years and regeneration occurred primarily by seed sources rather than by root or stump sprouts (Hornbeck and others 1993), the effects lasted about 15 years, which is substantially longer than harvest-only studies at Fernow (Table 6). Annual cutting for almost 15 years to eliminate regrowth on Coweeta watershed 17 also elevated streamflow during the entire period (Johnson and Kovner 1954). The annual discharge levels were similar to initial levels from clearcutting other north-facing watersheds at Coweeta (Table 6).

High road density and/or a lack of BMPs had little effect on annual water yields. Fernow watershed 1 had both a high density (7.3 percent of watershed area) of skidroads and no BMPs applied during or after harvesting (Reinhart and others 1963), but annual stream discharge there was similar to other clearcut watersheds on the Fernow (Table 6). Likewise the lack of BMPs in Kentucky resulted in only slightly higher annual water yields (~30 mm) than in a nearby watershed that had the same cutting treatment and BMPs were applied (Arthur and others 1998) (Table 6). Coweeta watershed 28 had a high road density with 66 percent of BA removed, but lower yields than watershed 37, which has a similar aspect and only 50 percent basal area removed (Hewlett and Helvey 1970).

A major difference between watershed responses on Fernow and Coweeta is the influence that aspect has on annual water yields following clearcutting and other intensive treatments. Aspect at Fernow did not affect annual discharge, while at Coweeta annual increases from watersheds with a northerly aspect were almost always greater than those with a southerly aspect (Hewlett and Hibbert 1961). Discharges from most south-facing clearcut catchments at Coweeta were similar to those from clearcut watersheds at Fernow (Table 6) and were typically 100 to 200 mm less than north-facing Coweeta watersheds the first 1 to 2 years after clearcutting. Complete reduction of the forest on north-facing slopes yielded an average of 400 mm of discharge the first year following harvest. Removing 50

percent of the basal area correspondingly reduced yields by about half (200 mm) on Coweeta watershed 22 (Hewlett and Hibbert 1961). South-facing Coweeta watershed 7 was the exception to the aspect differences. For unknown reasons, it had first- and second-year increases that were similar to those of north-facing watersheds at Coweeta (Swank and others 1982, 1988). Aspect responses could not be evaluated from the Pennsylvania or Kentucky data because in both cases harvesting was not performed on multiple aspects.

The causes for the differences in runoff between north- and south-facing aspects at Coweeta have not been definitively identified. Hewlett and Hibbert (1961) initially suggested that the differences may be due at least partially to soil depth, watershed configuration, and aquifer characteristics that may differ with aspect. However, a more likely reason is that substantially different solar energy inputs affect north- and south-facing slopes (Douglass 1983). First-year streamflow yield increases from the Appalachians are explained primarily by basal area removed and incoming energy–the former being positively related and the latter being negatively related to water yield changes (Douglass 1983, Douglass and Swank 1975). South-facing hillsides receive more radiation year round than north-facing ones, so that changes in evapotranspiration, and subsequently discharge, after harvesting on the south-facing slopes may not be as dramatic as on north-facing slopes. Sites in the central Appalachians may not experience aspect differences because the watersheds are not as steep and elevational ranges are not as large (Hibbert 1966), so all aspects may receive more similar energy inputs.

Aspect differences at Coweeta also influence the way that water yield increases are expressed seasonally. Clearcuts on north-facing watersheds tend to have their largest quantitative augmentation of flow during the late dormant season (e.g., January-April) (Hewlett and Hibbert 1961), due to the lag that results from the time needed for these deep soils to recharge (Kovner 1956, Meginnis 1959). South-facing clearcut watersheds at Coweeta tend to express most of their water yield increases during the late growing season (Hewlett and Hibbert 1961) because reductions in evapotranspiration caused by harvesting elevate soil moisture, which subsequently becomes streamflow (Swank and others 2001). Lower intensity treatments at Coweeta tend to display associated water yield increases during the growing season (Hewlett and Hibbert 1961), but seasonal expression of flow is less consistent and predictable. Riparian clearing in Coweeta watershed 6 created only small water yield increases restricted to the growing season (Dunford and Fletcher 1947), while understory removal on watershed 19 produced small increases distributed throughout the year (Johnson and Kovner 1956).

At both Leading Ridge and Fernow, water yield increases during the first 1 to 3 years after clearcutting predominantly occur during the growing season (Table 6) (Kochenderfer and others 1990, Lynch and others 1972, Reinhart and others 1963, Reinhart and Trimble 1962). Significant dormant season increases also can occur during those first years, but the magnitude of increase is usually substantially less than during the growing season. Typically, growing season yields return to pre-clearcut levels after only 5 to 7 years at both Leading Ridge and Fernow (Table 6), but dormant season increases at Fernow tend to last much longer (Kochenderfer and others 1990). For example, growing season yields for Fernow watershed 3 returned to pre-harvest conditions in about 5 years, while dormant season yields remained elevated for all but 2 years during 18 years of post-harvest monitoring (Kochenderfer and others 1990). Delaying regrowth with herbicides following clearcutting extended the duration of both growing and dormant season responses on Fernow watersheds 6 and 7. On watershed 6, significant increases for both growing and dormant seasons lasted about 20 years, reaching similar levels during both seasons 8 years after the first-half clearcutting. On Fernow watershed 7, most of the growing season increase disappeared after 10 years, but the dormant season increase lasted at least another 15 years (Kochenderfer and others 1990).

Low intensity thinnings on Fernow watersheds 2 and 5 had small but significant effects on augmenting growing season flows, but these lasted only a year or two (Table 6). Even the second thinning on watershed 2 that removed only 12 percent of the basal area increased growing and dormant season streamflow significantly for 2 years. However, dormant season flow behavior became somewhat erratic in subsequent years, so it is unknown if the changes from such a light thinning actually were attributable to the treatment (Kochenderfer and others 1990).

Regardless of location and seasonality of streamflow increases, most measurable increases in water yields occur during periods of low flow in the Appalachians (Douglass and Swank 1975). Flow frequency curves show shifts in the position of the curves in the low to moderate ranges of average daily flow after treatment compared to pre-harvest conditions at Fernow, Coweeta, and Leading Ridge (Johnson and Kovner 1954, Johnson and Meginnis 1960, Lynch and others 1972, Patric and Reinhart 1971, Reinhart and Trimble 1962), indicating these lower end flows occurred more frequently after harvesting (Table 7). Changes in high-end flows were much smaller or nonexistent.

For clearcut Coweeta watersheds 13 and 17, there were no significant shifts in the flow frequency curves for flows > 50 L s^{-1} km^{-2} (Johnson and Meginnis 1960). Curve positions for flows ≥ 55 L s^{-1} km^{-2} were not shifted during either half or total watershed clearcutting + herbicide applications on Fernow watersheds 6 or 7 (Patric and Reinhart 1971). Following riparian clearcutting and control of sprouting at Leading Ridge watershed 2, flow frequencies during growing and dormant seasons were not changed for flows > 8.7 L s^{-1} km^{-2} (Lynch and others 1972). The actual changes in the volumes associated with the low flows are each relatively small (Table 6), but because these flows occur so frequently, their accumulated totals over a year or a season are quite sizable and much greater than the small increases to moderate or higher flows. In general, the greater intensity of vegetation removed, the greater the shift in the frequency curve (Reinhart and Trimble 1962) for a given site.

Excluding clearcut Fernow watershed 3, Table 7 shows that all of the other harvested Fernow watersheds had much greater percentage increases of low flows than Coweeta; this is true even for thinned Fernow watersheds 2 and 5, which were cut much less heavily and treated less intensively than clearcut Coweeta watersheds 13 and 17. However, the data are not fully comparable, because the Coweeta values represent average responses over 7 years and the Fernow data are average responses over only the first 2 growing seasons. Even with this longer "averaging time," the median absolute increase from Coweeta watershed 13 was about double that from the Fernow watersheds (Table 7). This result is expected due to the lower absolute increases observed across the Fernow watersheds compared to north-facing Coweeta watersheds.

Supplements to low flows can measurably decrease the number of days in which low flows or no flow exists in Appalachian headwater channels (Table 8). Streams on clearcut + herbicided Fernow watersheds 6 and 7 always dried up at least one month each year before deforestation, but when each watershed was only half deforested streamflow never dropped below 0.55 L s^{-1} km^{-2}. When each watershed was fully deforested, flows were always ≥ 3.3 L s^{-1} km^{-2}. (Patric and Reinhart 1971). Clearcutting on Fernow watersheds 1 and 3 and thinning on Fernow watersheds 2 and 5 reduced the number of days that streamflow was < 0.55 L s^{-1} km^{-2} (Troendle 1970). Discharge was doubled on clearcut Coweeta watershed 7 during low flow months (Swank and others 2001). Cutting only the riparian zone on Coweeta watershed 6 added 10 to 13 m^3 of extra water daily to the stream during rainless days in the first growing season after treatment and 4 to 8 m^3 in the second growing season (Johnson and Kovner 1954). More intensive harvests tend to result in a greater reduction in the number of low flow days (Trimble and others 1963) and greater loss of the diurnal fluctuations in streamflow that are typically observed during low flows (Dunford and Fletcher 1947). A reduction in low flow days helps prolong ground water depletion rates during baseflow hydrographs, at least for watersheds subject to intensive harvests (Table 9). For example, clearcutting Coweeta watershed 17 lengthened the time by 25 days needed for flow to decrease from 20 L s^{-1} km^{-2} to 4.7 L s^{-1} km^{-2} (Johnson and Meginnis 1960).

Fewer years of stormflow data and analyses are available for the Appalachians compared to annual and seasonal analyses. However, the available results are consistent, showing that changes to most hydrograph components are small and nonsignificant (Tables 10 and 11). Even though clearcut Coweeta watersheds 13 and 17 had the largest annual augmentation of streamflow of any watersheds shown in Table 6, neither experienced significant annual changes in peakflow rates or quickflow volumes (Table 10); thus, streamflow increases were almost entirely from baseflow (Kovner 1956). Coweeta watershed 37 had only a 7-percent increase in average annual peakflows and an 11-percent increase in average annual quickflow for the 30 largest storms during the first 4 years after clearcutting (Hewlett and Helvey 1970), so even large events were affected little. The largest increase in stormflow volume for a single storm on watershed 37 was 25 percent (Hewlett and Helvey 1970). Generally changes to quickflows at Coweeta only occur for larger storms, because the moisture storage associated with the deep soils prohibits changes to quickflow volumes that are < 25 mm (Hewlett and Helvey 1970). Clearcut Coweeta watershed 7 had the most consistent responses to larger precipitation events across all variables, although the increases to stormflow components were fairly small (Tables 10 and 11). The small magnitudes of the change were attributable to the lack of disturbance to the soil surface during harvesting and low road density resulting from proper pre-planning (Swank and others 1982, 2001). The principal changes to Coweeta watershed 7 hydrographs were to the recession limbs (Swank and others 2001).

The largest percentage changes to peakflow and stormflow at Coweeta were on watershed 28 (Table 10), which was conventionally clearcut to remove 66 percent of the basal area but had a high density of roads, to which these changes were attributed (Swank and others 1988). Clearcut Fernow watershed 1 also had a high density of poorly located roads (Reinhart and others 1963), but only responses for events in the top 23 percent of runoff events were

examined. For these high flow events, growing season peakflows and quickflows increased by 21 and 24 percent, respectively; there was little change annually and almost no change during the dormant season (Table 10). Although changes to Fernow watershed 1 storm hydrographs were not large, Reinhart (1964) observed sharp, short-duration peaks at the start of some larger storm hydrographs. These first peaks were attributed to contributions of overland flow directly to the stream from the poor road layout and drainage from the road, which was exacerbated by road interception of subsurface flows. Trimble and others (1963) noted that the location and number of roads in a watershed can affect stormflow responses, because roads can direct concentrated flow directly to stream channels. The higher the road density and the closer roads are to streams, the more that hydrograph components, including peakflow, can be expected to change. However, even with the presence of roads, total streamflow increases in Fernow watershed 1 primarily were due to decreased soil moisture deficiencies from harvesting, and road-induced changes were small (Reinhart 1964).

The greatest absolute and percentage changes to stormflow occurred on Leading Ridge watershed 2 (riparian clearcut) and Fernow watersheds 3 (clearcut) and 6 (clearcut + herbicide). On each of these catchments, mean peak discharge during the growing season increased by more than 300 percent (Table 10). While the 300-percent increase on Fernow watershed 3 was significant, it represented only moderate peakflow increases (Patric 1980). Growing season quickflow on Leading Ridge watershed 2 also increased by 171 percent, but the increases were associated with storms with relatively low initial flow rates (Lynch and others 1972).

Activities applicable to fuels reduction in the central and southern Appalachians have primarily involved mechanical actions, and few investigations have examined the hydrologic effects of controlled fires. This may be partially attributable to the fact that the Appalachians are fairly moist (Swift and others 1993), making the severity of fires (i.e., the ground conditions) relatively light even when the burn is high intensity (Van Lear and Kapeluck 1989). Following commercial clearcutting in the southern Appalachians of South Carolina, separate plots with standing residuals and with felled residuals were burned in a high intensity fire. Post-burn soil infiltration rates (183 and 157 cm hr^{-1}, respectively) were not different from unburned clearcut plots (179 cm hr^{-1}) (Van Lear and Danielovich 1988). Even though the burn was intense, a substantial amount of organic matter remained on the surface and soil macropores in the deep soils were not changed by the burning; thus, soil infiltration rates remained high (Van Lear and Danielovich 1988) and soil hydrophobicity did not develop (Van Lear and Kapeluck 1989).

Swift and others (1993) also found that soils did not become hydrophobic following a low intensity fire that was applied after a fell (both overstory and understory) and burn practice on a poor quality site in the southern Appalachian Mountains of western North Carolina. Humus and some charred litter were present over much of the area after burning so relatively little soil became exposed. Consequently, although infiltration rates were not measured, they apparently were not changed much because there was no evidence of increased overland flow. The lack of change to soil infiltration allowed soil moisture levels to increase in the top 60 cm of soil in late summer immediately after harvesting and even somewhat further in fall after burning. Soil moisture increases were present consistently during the second growing season in the top 30 cm of soil, but they were only about half of what they had been the previous summer and fall. Most of the soil moisture increases were attributed to reductions in transpiration from the combination of cutting and burning, and augmentations were greatest in the headwaters of ephemeral channels, making it likely that stormflow increased (Swift and others 1993).

Piedmont

The history of the Piedmont includes widespread agricultural activities that have resulted in extensive and often severe erosion. The current expressions of this past erosion are shallow soils, incised stream channels, and gullies that also serve as channels for runoff (Hewlett 1979, Van Lear and others 1985). Shallow soils and denser and incised channel networks reduce the potential for soil moisture storage by increasing the potential for soil moisture to reach channels, and allow channels to intersect water tables at deeper levels (Hewlett 1979). These characteristics mean streamflow in Piedmont watersheds can be highly responsive to even moderate changes in the other variables in the water balance equation (eq. 1).

Hewlett (1979) found that clearcutting 32 ha of loblolly pine (*Pinus taeda* L.) in the Georgia Piedmont followed by double roller chopping increased water yields by 254 mm the first year after harvest and site preparation and by 126 mm the second year (Table 12). Similarly, after harvesting and site preparation using a KG blade and disking in North Carolina, average runoff increased by 345 mm in the first year and by more than 200 mm in both the second and third years (Table 12; Douglass and Goodwin 1980). Replanting with grass following those same treatments

apparently influenced infiltration and evapotranspiration substantially, because runoff was 6 to 7.5 times less during those same 3 years on planted plots. Using shearing without disking resulted in runoff values that were between the other two treatments, but generally closer to the lower values for planted grass.

For much less intensive, short-term treatments, annual water yields do not change. In the upper Piedmont of South Carolina, water yields did not change when one low intensity controlled fire was applied annually for 3 years in each of three pine stands before harvest (Van Lear and others 1985). But, harvesting, coupled with a high severity burn in the Georgia Piedmont, is believed to have increased runoff, even though it was not measured directly (Van Lear and Kapeluck 1989). A network of gullies formed in the 0.35-ha watershed after treatment, which acted as channels. These apparently were intercepting and conveying significant amounts of soil water and/or local ground water because gully sides were eroding, due in part to flowing water. The gullies were expected to continue to grow in length and width for several years. While infiltration also was not measured, the authors discounted the probability that a hydrophobic layer had formed, based upon other fire/soil research results.

By contrast, very temporary hydrophobic conditions (i.e., lasting only a few minutes) were observed during simulated rain applications to plots that were cut and burned in the Georgia Piedmont (Shahlaee and others 1991). The hydrophobicity was present only when unburned organic material at the soil surface was dry. However, elevated runoff attributable to hydrophobicity was observed only on the steepest plots (30-percent slope) and for only the higher of the two rainfall application rates (~102 mm hr^{-1}). Plots with 10- and 20-percent slopes also displayed hydrophobicity, but runoff from the same rain intensity during the initial period of water repellency was much less than for the steeper conditions. Mean depth of runoff across all slopes for a 30-minute period averaged 1.11 mm for high intensity applications and only 0.78 mm for low intensity applications (71 mm hr^{-1}), and the maximum runoff for any plot was 5.97 mm over 30 minutes. So even with initial hydrophobic conditions, actual runoff volumes were low because the forest floor was not fully consumed by burning.

The degree of disturbance similarly influences the extent to which storm hydrographs are affected by treatments. Clearcutting alone increased peakflow by 55 to 60 percent and increased stormflow significantly in South Carolina, but blading the slash from the watershed increased average peak discharge by 150 percent and doubled average stormflow (Douglass and others 1983) (Table 13). Stormflow volumes before and after the peak increased, but time to peak and event length did not change. Clearcutting with road construction, roller chopping, and machine planting increased stormflow by only 27 percent, but peakflows < 1.1 $m^3 s^{-1} km^{-2}$ increased by 100 percent (Hewlett 1979). Peakflow changes were attributed largely to channel extension during storms by reactivation of old gullies and rills (Hewlett and Doss 1984). Peakflows occurring during wet antecedent conditions were most susceptible to change, increasing by as much as 35 to 50 percent during large events (Hewlett 1979), whereas stormflows occurring during moderate to dry antecedent conditions were most commonly changed (Hewlett and Doss 1984). The percentage of precipitation that became stormflow during the first year after clearcutting, roller chopping, and machine planting was 31 percent compared to 22 percent during pre-treatment (Hewlett and Doss 1984). On four 1-ha watersheds in the upper Piedmont of north Georgia, clearcutting overstory vegetation after a ground herbicide application approximately doubled average stormflow for 2.5 years (Neary and others 1986). Controlled fires applied in the absence of other disturbances or treatments have had little effect on hydrograph responses in the Piedmont of South Carolina. Three consecutive years of controlled burning did not change average peak discharges or stormflow (Douglass and others 1983).

Coastal Plain

The Coastal Plain covers a large area, with a fairly broad range of precipitation and temperature regimes. The Southeastern states tend to have more rain in the growing season than in the dormant season, while the mid-South (Arkansas, Texas, Mississippi, Louisiana) generally is wetter in the dormant season and drier in the growing season (Langdon and Trousdell 1978). Hydrology in these regions is expressed in terms of water table levels and/or surface flows. Water table measurements are most common in flatter terrain in the lowlands (Grace and others 2003), although surface flows also can be present, particularly in humanmade structures, such as drainage ditches, dikes, and canals with single outlets. Water is present and can be measured using weirs and other devices in these ditches when water tables rise and intersect the bottoms of these structures (Riekerk 1983b). In these situations, outflows strongly depend on precipitation events so total annual water yields may be close approximations of total annual stormflow. Streamflow, in its traditional sense, primarily occurs in some areas of the upper Coastal Plain in which greater topographic relief exists.

Increases in water table levels are the most common hydrologic responses reported following harvesting of southern forests growing on soils with shallow water tables (Aust and Lea 1992, Bliss and Comerford 2002, Lockaby and others 1997a, Sun and others 2001, Trousdell and Hoover 1955, Williams and Lipscomb 1981, Van Lear and Douglass 1982, Xu and others 2000). Although typically short lived (Lockaby and others 1997c; Xu and others 2000, 2002), average annual water table increases of at least 100 mm can be expected during at least the first 2 to 3 years after harvesting (Table 14). They are short lived (Table 14) because revegetation is very rapid in these warm, long growing seasons (Beasley and others 1986) and reductions in evapotranspiration control water table fluctuations (Amatya and others 2006b, Aust and Lea 1992, Riekerk 1989, Xu and others 1999). Evapotranspiration is the dominant output term in the hydrologic budget throughout most Coastal Plain forests, making up 60 to 80 percent of the annual hydrologic budget (Amatya and others 2002, 1996, 1997; Chescheir and others 2003; Skaggs and others 1991; Sun and others 1998). As a result, water table augmentation from harvesting most often is expressed during the growing season when changes to evapotranspiration are most marked (Grace and others 2006; Lockaby and others 1997c; Xu and others 1999, 2000).

Even though evapotranspiration reductions are responsible for creating post-harvest water table increases, antecedent water table levels and precipitation characteristics are the most important factors in determining the amount of change that ultimately occurs (Langdon and Trousdell 1978, Williams and Lipscomb 1981). Water table increases are greatest and most easily detectable during dry years or periods when water tables have space to rise in the soil column (Amatya and others 2006b, Langdon and Trousdell 1978, Riekerk 1989). In four studies in the lower Coastal Plain of South Carolina in which longleaf or loblolly pine and mixed hardwoods were harvested, Williams and Lipscomb (1981) reported similar average first-year water table rises (Table 14) from the lightest cuts and the heaviest cuts (18 and 67 percent basal area, respectively). Little water table rise was detected because the heavy cut was made when the water table was near the ground surface. Thus, only small rises could occur before the water reached the soil surface and was no longer ground water (Riekerk 1983b, Williams and Lipscomb 1981). The presence of more wet days one winter and early spring resulted in only half the water table increase (61 mm) compared to that present during the same time period under drier conditions a year earlier (133 cm) in a harvested and site prepared watershed in North Carolina (Amatya and others 2006b).

Small to moderate water table rises can result from soil damage, such as compaction or rutting by skidder operation in wet conditions, although the changes are usually short lived (Aust and others 1993, 1995; Blanton and others 1998; Grace and others 2007; Perison and others 1997; Xu and others 1999). Average water table increases during the year after harvesting in wet conditions were 210 mm compared to only 140 mm for dry weather harvesting, but most of the increase was confined to the growing season (Xu and others 2000; Table 14). The mechanism for water table increases is typically an increase in bulk density, particularly through losses of larger soil pores, which reduces saturated hydraulic conductivities and drainable porosities and disrupts lateral or vertical subsurface drainage (Grace and others 2007, Skaggs and others 2006, Sun and others 2004). Thinning alone reduced saturated hydraulic conductivities from 100 cm hr^{-1} to 32 cm hr^{-1} in an organic soil in North Carolina (Grace and others 2007). Because water drainage or movement is retarded, water table levels remain elevated (Grace and others 2007, Skaggs and others 2006, Sun and others 2004), at least within the local area of soil damage (Aust and others 1993, 1995). Aust and others (1995) and Xu and others (2000) suggested that better drained soils may be more vulnerable to soil damage than poorly drained soils, so that changes to water table levels may be much greater on damaged better drained soils than on damaged poorly drained soils. However, better drained soils typically have longer periods of drier soil conditions and shallower damage, making any needed mitigation easier to accomplish (Aust and others 1995).

Some forest management practices have lowered water table levels. Both conventional bedding and mole-plow + bedding site preparation in poorly drained soils in the South Carolina Coastal Plain temporarily reduced water table depths about 150 to 180 mm lower than in nonbedded harvested sites (Xu and others 2000). However, 2 years after planting, the water table elevations of the bedded sites were only 10 to 50 mm below the nonbedded ones. There also was little difference in effects to water table levels or duration of effects whether the initial harvesting occurred during wet or dry conditions. Lockaby and others (1994, 1997b) observed similar water table reductions from clearcutting bottomland hardwoods in the upper Coastal Plain of Alabama using two types of systems: helicopter and feller buncher-skidder. Water table elevations were significantly lower (e.g., ~0.2 m) beneath harvest blocks during July than outside the harvest boundaries, but data were not separated by harvest type, so it is impossible to determine if soil disturbance from the feller buncher-skidder operation influenced the water table response. In this study, water table lowering was attributed to increased evaporation caused by increased wind speeds and

temperatures in cut areas, even though only modest soil temperature increases of 2 to 4 ºC have been reported in clearcuts elsewhere in the Coastal Plain (Aust and Lea 1991, Messina and others 1997).

Outflow and streamflow increases following harvesting in the Coastal Plain are related to the amount of forest vegetation harvested (Beasley and others 2000), again, because these increases are largely controlled by reductions in evapotranspiration (Amatya and others 2006b, Riekerk 1989, Sun and others 2000). Neary and others (1982) found that first-year water yield increases in the Coastal Plain typically were < 0.4 mm for every 1 percent of basal area removed. However, at least some of the sites included in that analysis also involved site preparation, which may affect measured changes. It often is difficult to separate harvesting and site preparation effects, especially in the Coastal Plain, because very few harvest-only studies have been done. Summer and others (2006) noted that streamflow increased significantly following clearcutting and thinning of the streamside zone in two watersheds in the Coastal Plain of southwestern Georgia, but the amounts of increases were not specified. Studies in which harvesting and site preparation are separated sufficiently in time provide evidence that water yield increases originate primarily from harvesting. For example, Swindel and others (1981) did not observe a secondary increase in outflows after intensive site preparation following mechanized logging. But due to the dearth of harvest-only studies in the Coastal Plain, it is probably more correct to state that changes in discharges are related to the level of devegetation and site disturbance (Riekerk 1983a).

Clearcutting followed by intensive mechanical site preparation that included shearing on three watersheds in the Coastal Plain of southeast Arkansas increased first-year water yields by 122 mm (Table 15), or thirteen fold increase (Beasley and Granillo 1988, Grace 2005). Outflow increases did not extend beyond that first year (Beasley and Granillo 1988). Much less intensive selection harvests and deadening of the residual hardwoods on three other watersheds increased mean annual water yields five fold, but the actual increase was only about 41 mm, which was not significant (Beasley and Granillo 1988, Grace and others 2003). Beasley and others (2000) reported similar first-year increases (120 mm) from harvesting and shearing in east Texas, while harvesting with roller chopping in the same location resulted in outflows (57 mm) that were only slightly greater than from harvesting and deadening in Arkansas (41 mm) (Beasley and Granillo 1988; Table 15). In an analysis of harvesting followed by two different intensities of site preparation, termed minimum disturbance (clearcutting pine, roller chopping, bedding, and planting) and maximum disturbance (clearcutting pine, stump removal, burning, windrowing, harrowing, bedding, and planting) in the Florida Coastal Plain, the maximum intensity treatment resulted in significant first-year outflow increases of 152 mm or 150 percent compared to an nonsignificant 30-mm increase (23 percent) from the minimum intensity treatment (Riekerk 1989; Table 15). The maximum treatment left almost no residual vegetation, while the minimum left some intact vegetation and allowed sprouting (Riekerk 1983a). Overall, increases to first-year outflows for the watershed with maximum disturbance were exhibited soon after treatment was completed, and they were well distributed over all seasons and weather conditions. Subsequent changes to outflows from the maximum disturbance watershed diminished in the second year (Riekerk 1983a, b). By contrast, most of the first-year increase to outflows from the minimum disturbance watershed was primarily from precipitation during only one wet month; other increases that contributed to the first-year augmentation were small, intermittent, and strongly dependent upon precipitation and season (Swindel and others 1981, 1982). Lebo and Herrmann (1998) reported that increases in outflows in several drained watersheds in North Carolina lasted only about 1 year following site preparation involving shearing, burning, and bedding. Site preparation at all sites occurred within a year of clearcutting the pine overstory. The outflow increases were seasonal–mostly during the summer. The largest summer increases ranged from 70 to 110 mm, which were equivalent to increases of 56 to 95 percent but still represented only about 33 percent of precipitation totals for the same time period. Amatya and others (2006b) reported longer lived outflow increases from harvesting followed by site preparation and bedding activities in coastal North Carolina. Increased outflow in a drained watershed was measurable for 4 to 5 years (Table 15) until planted regeneration sufficiently re-established evapotranspiration rates that reduced soil moisture storage.

Prescribed burning, regardless if done before or after harvesting, is the one site preparation technique that generally has little or no effect on surface flows. One reason may be that controlled burns may not completely combust the organic layer, so soil infiltration rates are retained (Mohering and others 1966, Shahlaee and others 1991). Burning 20 percent of a watershed in the Santee Experimental Forest in the Coastal Plain of South Carolina did not increase streamflow (Amatya and others 2006a). An additional 60 percent of the watershed was burned during the next 3 years and also did not increase streamflow. A later prescribed fire covering 84 percent of the watershed was followed by 2 years of increased outflows (64 percent in the first year and 70-percent in the second year), suggesting a delayed increase in flow from the burn. However, this burn followed salvage harvesting after Hurricane

Hugo and understory mowing, so some of the effect may have been due to the combination of reduced evapotranspiration from burning understory vegetation and those previous disturbances rather than just the fire (Amatya and others 2006a). Even long-term applications of burning have had limited effects on watershed hydrology. Neither the time required for surface runoff to begin nor the soil infiltration capacity was changed by 20 years of biennially burning on sandy loam plots or by biennial burning for 10 years, or by annual burning for 10 years in silt loams plots supporting longleaf pine (*Pinus palustris* Mill.)(Dobrowolski and others 1992).

Augmentation of streamflow and outflow volumes that result from harvesting and site preparation can increase the number of days in which flow is present in nonperennial systems. In a 23-ha mostly hardwood clearcut in North Carolina, flow began 2 weeks earlier than in an adjacent control, and the duration of surface flow was extended (Grace and others 2003). Over the 16-month period following clearcutting, the number of days during which streamflow occurred (190 days) was nearly double that of the control (99 days). Little analysis of flow frequencies has been done in the Southeast and mid-South because surface flows tend to be ephemeral or intermittent at best and typically storm driven. However, examination of flow frequencies from the harvesting plus maximum site preparation reported by Riekerk (1983a) showed that the resulting water yield increases, which were equivalent to only 2.54 mm of daily flow, came primarily from intermediate-size storms that occurred about 2 percent of the time.

Like overall water yields, storm hydrograph components also are affected differentially by various combinations of harvesting and site preparation operations. In flatter portions of the Coastal Plain, operations that involved clearcutting, shearing, and windrowing had greater increases in stormflow and peakflow responses compared to other clearcutting and site preparation techniques (Table 16). First-year increases in peakflow and stormflow in east Texas were 49 L s^{-1} and 146 mm, respectively (Blackburn and others 1986), and in southeast Arkansas they were 14 L s^{-1} and 125 mm, respectively (Beasley and Granillo 1983, 1988). Peakflows and stormflow volumes remained somewhat elevated for several more years, but these later increases typically were much less than those during the first year (Table 16). While the shearing component of site preparation apparently was important to increasing annual yields, windrowing was the most important variable related to the changes in peakflow when windrows were oriented toward the stream (Swindel and others 1983). Presumably the windrows directed surface runoff to the drainages (Riekerk 1989).

By contrast, in steep Coastal Plain terrain (30- to 50-percent slope) there was little difference in stormflow responses resulting from various site preparation techniques (Beasley 1979). Regardless of whether the site preparation involved brush chopping, shearing and windrowing, or bedding on the contour, first-year average increases in stormflow were well over 400 mm, and even second-year values in steep terrain remained above first-year increases in flat terrain (Table 16). Topographic influences controlled storm runoff and overrode any effects of site preparation (Beasley 1979).

Applying herbicide to kill the overstory in the upper Coastal Plain in Mississippi (Ursic 1970, 1982) had larger effects on peakflow the first 3 years than harvests with intensive site preparation (Beasley and Granillo 1983, 1988; Blackburn and others 1986; Table 16). However, the watersheds on which the herbicide was applied were very small (each ~ 0.86 ha), and small watersheds have less moisture storage capacity, particularly if the soils are shallow, which can result in large responses to a given disturbance (Douglass and others 1983, Van Lear and others 1985). Where clearcutting was followed by herbicide applications on 7.99- and 8.5-ha watersheds, the peakflow and stormflow responses were small or in most cases were less than predicted (Wynn and others 2000), particularly from the combination of herbicide applications and burning (Table 16).

Regardless of location, increases in stormflow translate to increases in the percentage of precipitation that becomes stormflow. In flat Coastal Plain areas, 11 to 12 percent of precipitation became stormflow after clearcutting plus shearing, compared to 5 to 6 percent after clearcutting with roller chopping and selective harvesting with herbicide applications (Beasley and Granillo 1983, Blackburn and others 1986). In steep terrain in the Coastal Plain, between 33 and 37 percent of precipitation became stormflow during the first year after harvesting with various mechanical site preparation techniques, and second-year values ranged from 19 to 28 percent (Beasley 1979). In the absence of treatment in all these Coastal Plain watersheds, only 1 to 3 percent of precipitation became stormflow (Beasley 1979, Beasley and Granillo 1983, Blackburn and others 1986).

REGIONAL COMPARISONS

Forest hydrology research related to stream responses from harvesting has been ongoing for at least a half century in parts of the East (Ice and Stednick 2004). By contrast, investigations into how wetland water tables are affected by harvesting or similar activities are relatively new so much less information has been compiled from wetland dominated watersheds (Sheperd et al. 1993). One of the oldest wetland studies focusing on harvesting effects on water table levels in the East is from the Marcell Experimental Forest in northern Minnesota (Verry 1981). Studies of wet flatlands in the South and Southeast are much newer–rarely present before the 1980s and increasing markedly beginning in the 1990s (Sun and others 2001).

Even with these vastly different amounts of available information, one characteristic common to both wetland and stream systems is that augmentation of water table levels and water yields occurs primarily due to reducing evapotranspirational losses from the watershed. Because forest evapotranspiration is greatest during the growing season, hydrologic changes caused by reducing vegetation generally are expressed during the growing season. However, changes to streamflow or water table levels may not be measurable during the growing season if soil moisture deficits are large due to dry antecedent conditions. Most precipitation inputs will go toward fulfilling soil moisture storage needs before water is released to ground water or stream water. Conversely, if soil moisture is very high in the growing season and precipitation remains above normal, water yields or water table levels may not differ much between harvested and unharvested sites, and treatment effects may be undetectable.

Hydrologic changes from treating only a small percentage of the vegetation on a watershed are more difficult to detect than from larger reductions. Overstory vegetation treatments also typically result in greater hydrologic changes than understory removals, probably because overstory trees transpire at faster rates and intercept more water because of greater leaf area indexes than understory vegetation. But when understory vegetation makes up a substantial percentage of the basal area removed (e.g., Johnson and Kovner 1956, Meginnis 1959), hydrologic changes are observable, although these tend to be much smaller and shorter lived than those occurring with heavy or complete reductions in overstory vegetation. Overall, literature from throughout the East most commonly is focused on more intensive harvest and soil disturbance practices, which have the most potential for creating the most extreme hydrologic changes. The vastly greater number of hydrologic studies involving clearcutting or clearcutting + site preparation makes these most usable for comparing responses across regions.

While data from the North Central region are limited, they suggest that water table elevations there increase much less in response to harvesting than in the Coastal Plain (Tables 2 and 14, respectively), although in the Coastal Plain additional disturbances associated with site preparation often accompany harvesting. The difference is attributable to the higher evapotranspiration rates in the Coastal Plain. Net radiation is low in northern latitudes because cold soils act as sinks for the heat. Because evapotranspiration depends on net radiation, transpiration rates are lower in the North (Verry 1997), which contributes to smaller water table changes from harvesting. Evapotranspiration from peatlands in the Marcell Experimental Forest averaged 63 percent (50.5 cm) of precipitation (80 cm) (Verry and Timmons 1982), compared to as much as 60-80 percent in the Coastal Plain, and overall rainfall levels tended to be higher in the Coastal Plain (Amatya and others 2002, 1996, 1997; Chescheir and others 2003; Skaggs and others 1991; Sun and others 1998).

In the South, when water table responses were measured, in almost all cases the change due to harvesting was an increase in water table elevations. The studies of Lockaby and others (1994 and 1997b) and Xu and others (2000) were the exceptions to this finding in the Coastal Plain. They reported decreases in water table elevations, which they attributed to increasing wind exposure and ground temperatures after harvesting. In wetlands in the North Central region, Verry (1981) reported similar decreases in water tables during dry years following harvesting, due to increased evaporation from increased wind exposure and solar radiation, and elevated transpiration by understory vegetation. In wet years, water table levels could increase because higher precipitation inputs offset any changes in these other losses.

Aspect played a major role in affecting runoff from harvesting only at Coweeta in the southern Appalachians. In general, discharges from northern aspects following clearcutting exceeded those found elsewhere in the East. However, despite the colder climate and lower evapotranspiration rates (450 mm) in the Northeast (Likens and Bormann 1995) compared to the southern Appalachians (704 mm) (Kovner 1957), runoff from whole-tree harvesting (Table 3) rivaled some of the more moderate increases associated with northern aspects at Coweeta (Table 6). Annual discharges after clearcutting from south-facing watersheds in the southern Appalachian Mountains were similar to those from clearcutting watersheds in the central Appalachians and clearcutting uplands

in the North Central region (Tables 2 and 6). Northeastern responses were similar to these levels (Tables 2 and 6) only when partial cutting was used (Table 3).

Annual discharges from clearcutting and site preparation in the Ouachitas and Ozarks (using stormflow totals because the monitored streams are ephemeral) are comparable to those from the central Appalachians, south-facing slopes in the southern Appalachians, and the North Central region (Tables 2, 5, and 6). However, because streamflow comes as stormflow in the Ozarks and Ouachitas, the increases are expressed during much shorter periods of time than in the Appalachians and elsewhere, where the dominant expression of harvest effects is during growing season baseflow. That harvesting effects are expressed over vastly different time periods and during different flow regimes is evident in the magnitude of stormflow responses from the Ozarks and Ouachitas (Table 5) compared to those from the Appalachians (Table 10). It should be noted that the watersheds treated in Ozark and Ouachita studies tend to be much smaller than those elsewhere in mountainous areas; thus, while the area-depth figures (i.e., mm) are comparable across sites, the total annual runoff volumes (L) from the Ozarks and Ouachitas are much smaller.

There was a tremendous amount of variability in annual discharge in the few available Piedmont studies that involved site preparation following clearcutting (Table 12). Runoff ranged from values similar to high values in the southern Appalachians to low values reported elsewhere in the central Appalachians (Table 6). By comparison, the Piedmont is generally more susceptible to streamflow changes from disturbances than the Coastal Plain, even if the disturbance is more extensive in the Coastal Plain. For example, harvesting without site preparation in the Piedmont resulted in first-year flow increases (Hewlett and others 1984; Table 12) that exceeded those with even the most intensive site preparation in the Coastal Plain (Table 14). And even though roller chopping is considered less disturbing to a site than shearing (Blackburn and others 1986), first-year increases in water yield in the Piedmont (Table 12) were substantially more than those associated with clearcutting and shearing in the Coastal Plain (Table 14). The more deeply incised/gullied channels and thinner, eroded soils of the Piedmont account for these differences (Hewlett 1979) and probably explain much of the hydrologic variability observed after harvesting across various Piedmont sites. The contrasting responses between the Coastal Plain and Piedmont provide good examples of how secondary factors, such as physical channel characteristics and land management practices, interact with the primary drivers of hydrologic responses (precipitation, antecedent soil moisture conditions, evapotranspiration, land cover, and topography) in all regions to influence outflow and streamflow responses (Amatya and others 2006a, Douglass and others 1983, Grace 2005, Miwa and others 2003, Riekerk 1983a, Young 1968).

APPLICATION TO FUEL REDUCTION PRACTICES

The vast majority of literature reviewed in this chapter involves activities in which fuel sources were reduced for purposes other than reduction of hazardous fuels for wildfire suppression. However, the results still are applicable to fuel reductions because hydrologic responses are a function of on-the-ground actions, not the purpose of the activity. As noted previously, most available studies have involved harvesting intensities that far exceed what would be done during typical fuel management in forests, except for large-scale salvage harvests. If harvesting follows soon after the event that led to salvage logging, the total change in annual, seasonal, and/or storm hydrology will be similar to that from clearcutting. If salvage logging is done in stands where much of the overstory is already dead, most of the hydrologic changes will be associated with the decline, not the removal, of that dead, standing fuel (e.g., Douglass and Van Lear 1983, Van Lear and others 1985). Overstory removal will reduce only the interception component of evapotranspiration, which has been reported to range between 10 and 26 percent of annual precipitation in the East, depending upon species and stand age (Helvey 1967, Lull and Reinhart 1966, Swank and others 1972). But these figures are for trees with leaves, so the crown condition of the overstory (such as in salvage logging) will determine the importance of interception. However, interception will not go to zero after harvesting because slash on the ground, residual vegetation, and litter all intercept precipitation (Helvey 1967, Lull and Reinhart 1966).

Eastwide, a minimum of 20 to 30 percent of a watershed's basal area must be removed before measurable changes in annual water yields occur (Hornbeck and Kochenderfer 2001, Hornbeck and others 1997). Fuel reductions solely to suppress fire (other than salvage logging) normally would affect a small percentage of basal area in a watershed and be widely dispersed, thereby retaining a substantial proportion of antecedent interception and transpiration from adjacent vegetation (Lull and Reinhart 1966). Therefore, little change in hydrologic response would be expected in most cases, and changes that did occur should be short lived, particularly in forests of the Southeast and mid-South, because changes there usually last only a year or two. This is fortuitous, because the Coastal Plain and lower Piedmont are the regions where fuel reduction activities most likely may be a regular part of land management

activities because wildfire regimes are more frequent there than in other forested landscapes in the East (Van Lear and Harlow 2002).

Overall, where researchers have studied hydrologic responses of prescribed fires in the East, they have found little effect to hydrology. Low fire intensity may be partially responsible for the lack of hydrologic response (Cushwa and others 1970, Mohering and others 1966, Shahlaee and others 1991), but fire also can stimulate herbaceous growth and seed production (Lewis and Harshbarger 1976), which can quickly restore litter to the soil surface and promote root growth. However, high severity controlled burns can affect hydrology. Changes most commonly result from reductions in soil infiltration and soil moisture storage when the litter and duff layers are completely combusted and soil becomes exposed (Wells and others 1979). Reductions in infiltration rates in the East appear to be caused primarily by pore clogging from fine soil particles once soil is exposed (Arend 1941, Wells and others 1979) rather than physicochemical changes to soil that result in water repellency (DeBano 1966) because hydrophobicity is rarely reported and very short lived in the East.

Particular care should be taken when burning in the Piedmont, because this region is perhaps the most susceptible to major hydrologic changes from soil disturbance. Relatively dry soils from warm temperatures in the Piedmont, coupled with thin organic layers overlaying thin soils, can make this region more susceptible to gullying and erosion than even steeper areas typically thought to be more highly erodible (Van Lear and Kapeluck 1989). Gullies can change hydrologic responses and increase runoff in the long term. In both the Piedmont and Coastal Plain, special care also should be taken when using practices that increase fuel loads on the soil surface before burning or that increase soil temperatures during burning. Practices such as felling and burning or shearing and burning increase the fuel load in contact with the soil surface. Likewise, windrowing or piling concentrates fuels so that soil temperatures from burning become elevated much more than from burning dispersed materials (Cromer and Vines 1966, Robert 1965, Well and others 1979). These activities increase the probability that soil will be damaged and hydrology changed.

It is clear from the studies reviewed in this chapter that antecedent soil conditions and the degree of soil disturbance or damage can play an important role in controlling hydrologic responses. Therefore, fuel management plans should consider those factors when estimating potential hydrologic changes. Because fuel reduction activities typically can be planned and applied during more appropriate conditions compared to wildfire suppression, it should be possible to keep most soil disturbance at or below the levels at which hydrologic change will occur.

Soil disturbance by new fire line construction may be one of the biggest long-term impacts of fuel reduction activities to watersheds. Hand-constructed firebreaks will have little if any effects because litter can quickly be restored to the surface from wind action and annual leaf fall. Soil infiltration rates also should not be substantially affected by hand-constructed fire lines. By contrast, mechanically constructed fire lines (e.g., bulldozed lines) are more like roads, or at least skid roads, and may have some of the same potential effects, such as intercepting subsurface flows, increasing bulk densities and reducing soil hydraulic conductivity, concentrating overland flow, and diverting overland flow to streams. While fire lines lack the repeated trafficking that roads have, and tracked equipment that often is used to construct fire lines exerts lower pressures on the soil than comparable wheeled equipment, the largest proportion of soil compaction occurs after just a few equipment passes (Jansson and Johansson 1998, McNabb and others 2001, Wang and others 2005). As a result, significant compaction and other changes to soil physical properties can occur during fire line construction. Many fire lines are subjected to all-terrain and other vehicle use during prescribed fires, which can result in further compaction. Therefore, the same care needed for road planning, construction, and closure should be used for fire line construction. Appropriate best management practices also should be applied, particularly those that focus on proper location, water control, and soil protection and coverage.

From the perspective of cumulative watershed effects, the influence of fuel reduction activities on hydrology probably will be small assuming the landscape is reforested and not converted to another land use. In the literature, the primary hydrologic cumulative effect from harvesting that has been raised as a possible concern is downstream flooding. Downstream flooding results from the simultaneous accumulation of large volumes of water from upstream sources (Hewlett 1982). But even in watersheds where substantial vegetation has been removed, stormflow volumes from each subwatershed are desynchronized, thereby reducing the risk of downstream flooding (Hewlett and Doss 1984). Furthermore, most of the hydrologic change from harvesting anywhere in the East occurs during growing seasons and/or low flows, when flooding is least likely to occur. Consequently, the overwhelming

consensus within the scientific literature is that contemporary forest management practices do not increase the risk of downstream flooding (Hewlett 1982, Hewlett and Doss 1984, Hornbeck and others 1997, Rogerson 1976, Verry 1972, Woodruff and Hewlett 1970).

RESEARCH NEEDS

In this chapter, studies involving harvesting or other types of vegetation reductions have been used as a proxy for understanding how hydrology might change from reducing fuels in the East. This approach was needed because information specifically pertaining to fuels reduction in this region is largely missing from the literature. Most of the available investigations have involved much larger reductions of evapotranspiration than would occur for controlling fuels, so we have information predominantly about upper end or "worst case" effects. However, from the standpoint of being able to accurately describe and disclose expected effects from fuel reduction activities in environmental documents required by such legislation as the National Environmental Policy Act of 1969 (NEPA), there is a need to perform studies specifically focused on fuel reduction activities and their effects on soil and water resources. The public would be better served by including data used in these documents that are fully applicable to the proposed activities so that direct and cumulative effects could be more accurately assessed.

Furthermore, our knowledge about the effects of controlled burns is extremely limited despite the increased use of burning as a management tool. Controlled burns in forests usually are used to reduce dead, downed fuels and possibly reduce the density of understory brush, while limiting the damage to standing trees (Biswell 1975). The intensities and severities of burning to control only understory fuels may be quite different from those associated with fell and burn activities or as part of site preparation following harvesting; if so, the effects may be different. However, until a body of scientific evidence shows that the effects from understory burning are small, it is not appropriate simply to make that assumption based on current limited data; the effects or lack thereof should be determined in scientific, replicated studies. It is now particularly important to perform these types of studies because (1) there is new interest in using controlled burns during the growing season (Outcalt and others 2006) when soil moisture is lower and potential effects on soil condition and hydrology may be greater than the traditional application of fires during the dormant season, (2) repeated burning is being used or considered for a variety of uses (e.g., Bowles and others 2007), and (3) burning is being considered where it has long been excluded, which can result in initially severe burns (Knapp and others 2007). These new applications may have effects that are measurably different from what one might conclude based only on currently available, sparse datasets.

CONCLUSION

The initial foundation of what we know about forest management effects on water balance and overall hydrologic expression in the East comes primarily from studies at Coweeta and Fernow Experimental Forests. These sites have the most comprehensive sets of long-term hydrology studies related to vegetation management, including a variety of low-intensity vegetation removals that have not been performed elsewhere but are applicable to fuel reduction activities. However, substantial data also have been collected from other sites and provide additional, valuable information to further complete the current base of knowledge in the East.

While biological, physical, and climate conditions are quite varied throughout the East, the similarity of results among study sites is striking. In general, water yield increases from reducing vegetation do occur when the level is greater than approximately 20 to 25 percent of the watershed basal area. Larger percentages of basal area removals result in proportional increases in annual water yields, but they primarily augment low and moderate flows. Water yield changes from reducing vegetation typically are short lived, although retarding vegetative regrowth mechanically or chemically prolongs the time during which yields are elevated. Storm hydrograph components also can change, but these are primarily associated with small and moderate runoff events. Aspect is important in controlling total annual yields only in mountainous areas that are steep and have great relief. Aspect becomes unimportant in controlling the amount of water yield in less steep mountains or forests with lower topographic relief. The timing of the spring snowmelt hydrograph can be changed by varying the size of harvested sites and character of the opening and associated regeneration. Wetland soil characteristics in both the northernmost and southernmost parts of the East play a large role in controlling how hydrologic responses will be expressed in flatlands: hydraulic conductivities largely determine the degree of influence of evapotranspiration on water table levels. On steep hillsides, the extent of water delivery to channels at least partially depends on the characteristics of the channel network, such as density, length, and degree of incision. These and other commonalities among vastly different regions illustrate the broad transferability and application of findings, particularly when adjusted for differences in precipitation, climate, topography/relief, soils, and species composition.

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FIGURE CAPTIONS

Figure 1—Piedmont and Coastal Plain boundaries.

Table 1—Groupings of ecological divisions and provinces that are expected to have similar hydrological responses to fuel reduction treatments. To simplify discussions in the text, these groupings are assigned regional titles

Region	Division and provinces
North Central	210 Warm continental 212 Laurentian mixed forest 220 Hot continental 222 Midwest broadleaf forest
Northeast	210 Warm continental 211 Northeastern mixed forest M210 Warm continental – Mountains M211 Adirondack – New England mixed forest – Coniferous forest – Alpine meadow 220 Hot continental 221 Eastern broadleaf forest (northern portion only)
Ozark Mountains and Ouachita Plateau	M220 Hot Continental – Mountains M223 Ozark broadleaf forest M230 Subtropical – Mountains M231 Ouachita mixed forest meadow
Central and Southern Appalachian Mountains	M220 Hot continental – Mountains M221 Central Appalachian broadleaf forest – Coniferous forest meadow 220 Hot continental 221 Eastern broadleaf forest (southern portion only)
Piedmont	230 Subtropical 231 Southeastern mixed forest
Coastal Plain	230 Subtropical 231 Southeastern mixed forest 232 Outer coastal plain mixed forest 234 Lower Mississippi riverine forest 250 Prairie 255 Prairie parkland (subtropical)

Table 2—Water yield and water table responses to harvesting treatments in the North Central region. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time period	Annual changes to water yields	Changes to water table			Reference
					Annual	Wet periods	Dry periods	
Marcell Expt. Forest, MN watershed 1	33.2 ha, no aspect given, mineral soil uplands, peat soils central bog	Strip cut 43% of spruce in bog, strips run NW-SE	Years 1-5	NS[a]	NS			Verry 1981
		Year 6 clearcut remaining spruce in bog (total harvested = 8% of watershed)	Years 6-10	NS		100 mm*	-190 mm*	
Marcell Expt. Forest, MN watershed 4	34.8 ha, flat topography, sandy loams overlaying clay loams in uplands and peat soils in lowlands	Clearcut aspen 3 m and taller in uplands on 25.3 ha, no harvesting in lowlands 9.5 ha	During harvest	90 mm* (42%)				Hornbeck and others 1993, Verry 1972, 1987
			Year 1	85 mm* (39%)				
			Year 2	117 mm* (58%)				
			Year 3	88 mm* (70%)				
			Year 4	38 mm* (20%)				
			Year 5	77 mm* (34%)				
			Year 6	34 mm* (45%)				
			Year 7	51 mm* (34%)				
			Year 8	52 mm* (21%)				
			Year 9	40 mm* (15%)				
			Year 10	19 mm (18%)				
			Year 11	6 mm (3%)				
			Year 12	-22 mm (-8%)				
			Year 13	-9 mm (-9%)				
			Year 14	33 mm* (16%)				
			Year 15	12 mm (4%)				
			Year 16	56 mm* (26%)				
			Year 17	-1 mm (0%)				
			Year 18	-25 mm* (-8%)				
			Year 19	1 mm (0%)				
			Year 20	-12 mm (-10%)				
			Year 21	-4 mm (-4%)				
Sand Plain, northwestern lower MI	40 ac blocks, no aspect given, sands	2 replicate 16 ha blocks, strip cut 50% of pines, strips SE-NW orientation	Years 1-3		66 mm[b] (20-30% under strips)			Urie 1971

[a]NS = nonsignificant change indicated, but no value was given
[b]Significance/nonsignificance information was not provided for this result

Table 3—Water yield responses to harvesting treatments in the Northeast. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time period	Changes to water yields			Reference
				Annual	Growing	Dormant	
Hubbard Brook Expt. Forest, NH watershed 2	15.8 ha, S, sands and sandy loams	Winter clearcut primarily northern hardwoods, trees left in place, herbicide stumps and ground cover	Year 1	347 mm* (40%)	315 mm* (344%)	25 mm	Hornbeck and others 1970, 1993, 1997, Pierce and others 1970
			Year 2	278 mm* (29%)	231 mm* (310%)	36 mm	
			Year 3	240 mm* (26%)			
			Year 4	200 mm* (22%)			
			Year 5	146 mm* (17%)			
			Year 6	44 mm* (6%)			
			Year 7	12 mm (1%)			
			Year 8	52 mm (4%)			
			Year 9	67 mm* (8%)			
			Year 10	3 mm (0%)			
			Year 11	4 mm (5%)			
			Year 12	64 mm* (6%)			
			Year 13	- 13 mm (-1%)			
			Year 14	- 13 mm (-2%)			
			Year 15	-34 mm (-4%)			
			Year 16	-41 mm* (-3%)			
			Year 17	-70 mm* (-8%)			
			Year 18	-62 mm* (-6%)			
			Year 19	-64 mm* (-9%)			
			Year 20	-44 mm* (-5%)			
			Year 21	-80 mm* (-9%)			
			Year 22	-82 mm* (-10%)			
			Year 23	-56 mm* (-8%)			
			Year 24	-34 mm (-3%)			
			Year 25	-48 mm* (-4%)			
Hubbard Brook Expt. Forest, NH watershed 5	22 ha, no aspect given, sandy loam	Whole-tree clearcut of northern hardwoods applied to 20 ha	Year 1	152 mm* (23%)		-49 mm*[a]	Hornbeck and others 1997
			Year 2	47 mm (5%)		-46 mm*[a]	
			Year 3	-15 mm (-2%)			
			Year 4	-11 mm (-1%)			
			Year 5	4 mm (1%)			
			Year 6	46 mm (5%)			
			Year 7	51 mm* (5%)			
			Year 8	66 mm* (8%)			
			Year 9	47 mm (6%)			
			Year 10	20 mm (2%)			
			Year 11	21 mm (4%)			
			Year 12	46 mm (4%)			

Location	Area, aspect, soils	Treatment description	Time period	Changes to water yields			Reference
				Annual	Growing	Dormant	
Great Northern Paper Co., ME[b]	47 ha, aspect not given, sandy loam	Spruce-fir whole-tree harvest	Year 1	310 mm (63%)			Pierce and others 1993
			Year 2	290 mm			
			Year 3	210 mm			
Success, NH[b]	7 ha, aspect not given, sandy loam	Northern hardwoods whole-tree harvest	Year 1	220 mm (45%)			Pierce and others 1993
			Year 2	160 mm			
			Year 3	170 mm			
Chester, CT[b]	6 ha, aspect not given, sandy loam	Central hardwoods whole-tree harvest	Year 1	270 mm (22%)			Pierce and others 1993
			Year 2	100 mm			
			Year 3	70 mm			
Hubbard Brook Expt. Forest, NH watershed 4	36 ha SE, sandy loams	Northern hardwoods progressive strip cutting in east-west orientation	Year 1	22 mm (3%)	28 mm*	-4 mm	Hornbeck and others 1987, 1997
			Year 2	46 mm* (4%)	36 mm*	-5 mm	
			Year 3	114 mm* (8%)	91 mm*	14 mm	
			Year 4	67 mm* (8%)	38 mm*	33 mm	
			Year 5	55 mm8 (4%)	81 mm*	33 mm	
			Year 6	81 mm* (9%)	38 mm*	-22 mm	
			Year 7	69 mm* (7%)	27 mm*	34 mm	
			Year 8	-14 mm (-2%)	2 mm	42 mm*	
			Year 9	-30 mm* (-4%)	6 mm	-15 mm	
			Year 10	-27 mm* (-3%)	0 mm	-35 mm	
			Year 11	-18 mm (-2%)			
			Year 12	-45 mm* (-5%)			
			Year 13	-33 mm* (-3%)			
			Year 14	-21 mm* (-3%)			
			Year 15	-44 mm* (-5%)			
			Year 16	-67 mm* (-8%)			
			Year 17	-29 mm (-4%)			
			Year 18	-59 mm* (-8%)			
			Year 19	-42 mm* (-4%)			
			Year 20	-63 mm* (-5%)			
			Year 21	-42 mm* (-5%)			
			Year 22	-60 mm* (-6%)			
			Year 23	-30 mm* (-3%)			
			Year 24	-36 mm* (-6%)			
			Year 25	-23 mm (-2%)			

Location	Area, aspect, soils	Treatment description	Time period	Changes to water yields			Reference
				Annual	Growing	Dormant	
Hubbard Brook Expt. Forest, NH watershed 101	12 ha, SE, sandy loam	Northern hardwoods block cuts	Year 1	278 mm (36%)	237 mm	8 mm	Hornbeck and others 1987
			Year 2	155 mm	140 mm	41 mm	
			Year 3	92 mm	85 mm	15 mm	
			Year 4	39 mm	45 mm	7 mm	
			Year 5	41 mm	36 mm	-6 mm	
			Year 6	20 mm	22 mm	5 mm	
			Year 7	15 mm	10 mm	20 mm	
			Year 8	8 mm	6 mm	15 mm	
			Year 9	1 mm	5 mm	5 mm	
			Year 10	4 mm	5 mm	1 mm	
Caldwell Creek watershed, central MA	163 ha, S, sands and sandy loams	49% riparian overstory mixed oaks and northern hardwoods and understory vegetation chemically deadened, 21% of upland pine plantations chemically deadened, harvesting uplands in patch clearcuts. 34.4% of basal area in watershed deadened or harvested	Year 1	103 mm* (21.6%)	56 mm* (38.4%)	53 mm* (16.1%)	Mrazik and others 1980
			Year 2	155 mm* (22.5%)	89 mm* (43.9%)	76 mm* (15.9%)	
			Year 3	91 mm* (19.7%)	47 mm* (30.9%)	50 mm* (16.6%)	
			Year 4	79 mm* (13.5%)	31 mm* (21.0%)	53 mm (12.2%)	
			Year 5	133 mm (14.1%)	66 mm* (20.0%)	89 mm (14.9%)	
			Year 6	72 mm (10.9%)	49 mm* (20.9%)	36 mm (8.5%)	
			Year 7	36 mm (5.7%)	8 mm* (4.2%)	38 mm (8.8%)	

[a]Based on snowmelt runoff only
[b]Significance/nonsignificance information was not provided for this site

Table 4—Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the Northeast. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time period	Hydrologic changes						Reference
				Mean peak discharge			Stormflow			
				Annual	Growing	Dormant	Annual	Growing	Dormant	
Hubbard Brook Expt. Forest, NH watershed 2	15.8 ha, S, sands and sandy loams	Winter clearcut, trees left in place, herbicide stumps and ground cover	Years 1-3[a]	13%	118%*	0%				Hornbeck 1973, Hornbeck and others 1970
			Years 1-3[a]				21%	197%*	13%	
			Years 1-3 for all storms				99 mm*	64 mm*	28 mm*	
Dickey Brook watershed, New Salem, MA	308 ha, W, fine sandy loam and sandy loam	9% watershed whole-tree harvest clearcut and 5% thinned; 32% basal area removed	Years 1-3[b]	NS[c]						Bent 1994
Caldwell Creek watershed, central MA	163 ha, S, sands and sandy loams	49% riparian overstory mixed oaks and northern hardwoods and understory vegetation chemically deadened, 21% of upland pine plantations chemically deadened, harvesting uplands in patch clearcuts. 34.4% of basal area in watershed deadened or harvested	Years 1-4		0.12 m^3 s^{-1} km^{-2}* (50%)					Mrazik and others 1980
Hubbard Brook Expt. Forest, NH watershed 5	22 ha, no aspect given, sandy loam	Whole-tree clearcut of northern hardwoods applied to 20 ha	Year 1		18%	15%				Hornbeck and others 1997[d]
			Year 2		63%	-2%				
			Year 3		31%	-2%				
			Year 4		19%	-30%				
			Year 5		15%	10%				
			Year 6			-12%				
			Year 7		29%	-2%				
			Year 8			-13%				
			Year 9		28%	-30%				
			Year 10			-40%				
			Year 11			-14%				
			Year 12			-13%				

[a]For storms with peaks > 1.5 m^3 s^{-1} km^{-2} or storms with stormflows > 1.5 m^3 s^{-1} km^{-2}
[b]For storms with 2-day precipitation totals > 25.4 mm
[c]NS = nonsignificant change indicated, but no value was given
[d]Changes to mean peak discharge in this study were calculated from only statistically significant peaks that were > 10 mm day^{-1}

Table 5—Water yield responses (as stormflow volumes) to harvesting treatments in the Ozark Mountains and Ouachita Plateau. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Acreage, aspect, soils	Treatment description	Time period	Stormflow changes	Reference
Ouachita Mtns., OK	1.6-4.2 ha, SW, loam overlaying silt clay	Three replicate watersheds, clearcut, roller chop, burn, contour soil ripping (subsoiling), hand plant	Year 1 Year 2 Year 3 Year 4	-94 mm 49 mm* -11 mm -17 mm	Beasley and others 2000, Miller 1984
Ouachita Mtns., AR	4.08, 5.11, and 5.91 ha, N, SE, and NW, loam overlaying clay	Three replicate watersheds, clearcut and roller chop, burn, hand plant	Year 1 Year 2 Year 3	101 mm 92 mm 193 mm	Beasley and others 2000, Miller and others 1988
	4.15, 4.35, and 5.74 ha, N, S, and W, loam overlaying clay	Three replicate watersheds, selection harvest	Year 1 Year 2 Year 3	101 mm 74 mm 149 mm	Beasley and others 2000, Miller and others 1988
Ouachita Mtns., AR	0.52 ha, NE, stony silt loams	Overstory pine thinned, 57% BA removed, mixed hardwood understory herbicided annually for three years	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6 Year 7	109 mm*[a] (79%) 57 mm 82 mm 66 mm 0 mm 49 mm 41 mm	Rogerson 1985
	0.59 ha, NE, stony silt loams	Overstory pine clearcut, mixed hardwood understory herbicided annually for three years	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6 Year 7	259 mm*[a] (193%) 141 mm 113 mm 135 mm 143 mm 160 mm 102 mm	Rogerson 1985

Location	Acreage, aspect, soils	Treatment description	Time period	Stormflow changes	Reference
Athens Plateau, AR	2-5 ha, aspect not given, fine sand or fine loam	Three replicate watersheds, clearcut, shear, windrow, plant	Year 1 Year 2 Year 3	166 mm* 388 mm 237 mm*	Beasley and others 1986, 2000
	2-5 ha, aspect not given, fine sand or fine loam	Three replicate watersheds, clearcut, chemical site prep, plant	Year 1 Year 2 Year 3	-3 mm 176 mm -4 mm	Beasley and others 1986, 2000

[a]Significance/nonsignificance for this study was specified only for year 1

Table 6—Water yield responses to harvesting treatments in the central and southern Appalachians. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Robinson Forest, KY watershed B	Acreage not reported, E, loams and fine loams	Clearcut hardwoods and pines > 35.5 cm dbh, cut and left stems < 5 cm, BMPs employed	During clearcutting	NS[a]			Arthur and others 1998
			First 17 months	178 mm* (123%)			
			Year 8	15%[b]			
			Years 1-8	37%[b]			
Robinson Forest, KY watershed C	Acreage not reported, E, loams and fine loams	Clearcut hardwoods and pines > 35.5 cm dbh, cut and left stems < 5 cm, no BMPs employed	During clearcutting	NS			Arthur and others 1998
			First 17 months	206 mm* (138%)			
			Year 8	12%[b]			
			Years 1-8	48%[b]			

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Leading Ridge, PA watershed 2	42.9 ha, SE, silt loams, stony loams, and cobbly loams	Riparian clearcut ~1/ 3 of watershed (8.6 ha), herbicides to control stump sprouts during next 3 summers	Year 1	70 mm*	53 mm*	-27 mm	Hornbeck and others 1993, Lynch and others 1972
			Year 2	32 mm* (11%)	23 mm*	-5 mm	
			Year 3	63 mm* (16%)	25 mm*	40 mm*	
			Year 4	73 mm* (14%)	42 mm*	26 mm	
			Year 5	50 mm* (10%)			
			Year 6	94 mm* (10%)			
			Year 7	79 mm* (17%)			
			Year 8	132 mm* (25%)			
			Year 9	61 mm* (9%)			
			Year 10	193 mm* (32%)			
			Year 11	239 mm* (35%)			
			Year 12	138 mm* (21%)			
			Year 13	63 mm* (9%)			
			Year 14	73 mm* (28%)			
			Year 15	-25 mm (-4%)			
			Year 16	-37 mm (-7%)			
			Year 17	49 mm* (9%)			
			Year 18	22 mm (4%)			
			Year 19	56 mm* (11%)			
			Year 20	64 mm* (11%)			
			Year 21	-28 mm (-7%)			
			Year 22	26 mm (6%)			
			Year 23	36 mm* (6%)			
			Year 24	27 mm (3%)			
Leading Ridge, PA watershed 3	104.0 ha, SE, silt loams, stony loams, and cobbly loams	Commercial clearcut hardwoods on 44.5 ha with BMPs	Year 1	137 mm*	146 mm*	-31 mm	Lynch and Corbett 1990
			Year 2	39 mm	27 mm*	10 mm	
			Year 3	-61 mm*	25 mm*	-89 mm*	
			Year 4	51 mm*	1 mm	60 mm*	
			Year 5	-37 mm	-33 mm	-11 mm	
			Year 6	-20 mm	0.5 mm	-20 mm	
			Year 7	17 mm	8 mm	1 mm	
			Year 8	8 mm	2 mm	6 mm	
			Year 9	22 mm	3 mm	7 mm	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Fernow Expt. Forest, WV watershed 1[d]	29.9 ha, NE, silt loams	Commercial clearcut hardwoods > 13 cm dbh, no BMPs employed; 74% BA removed	Year 1[c]	56 mm*	30 mm*	26 mm	Kochenderfer and others 1990, Lull and Reinhart 1967
			Year 2	130 mm*	107 mm*	16 mm	
			Year 3	86 mm*	76 mm*	19 mm	
			Year 4	89 mm*	44 mm*	44 mm*	
			Year 5	61 mm	2 mm	9 mm	
			Year 6	46 mm*	30 mm*	29 mm	
			Year 7	36 mm	-25 mm*	19 mm	
			Year 8	28 mm	-10 mm*	26 mm	
			Year 9	20 mm	8 mm	42 mm	
			Year 10	15 mm	8 mm*	8 mm	
			Year 11	13 mm	2 mm	14 mm	
			Year 12		16 mm*	7 mm	
			Year 13		14 mm*	4 mm	
			Year 14		-4 mm	-0.2 mm	
			Year 15		5 mm	19 mm	
			Year 16		-27 mm*	14 mm	
			Year 17		-11 mm*	28 mm	
			Year 18		-5 mm	27 mm	
			Year 19		4 mm	15 mm	
			Year 20		3 mm	10 mm	
			Year 25		-10 mm*	2 mm	
			Year 30		26 mm*	41 mm*	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Fernow Expt. Forest, WV watershed 2[d]	15.4 ha, S, silt loams	43-cm diameter limit cut 1958, 32% BA removed 43-cm diameter limit cut 1972, 12% BA removed	Year 1[c]	25 mm	18 mm*	5 mm	Kochenderfer and others 1990, Reinhart and others 1963, Reinhart and Trimble 1962, Trimble and others 1963
			Year 2	64 mm*	46 mm*	20 mm	
			Year 3	36 mm*	18 mm*	22 mm	
			Year 4		-5 mm	15 mm	
			Year 5		9 mm	33 mm	
			Year 6		-22 mm*	18 mm	
			Year 7		2 mm	34 mm*	
			Year 8		5 mm	39 mm*	
			Year 9		6 mm	30 mm*	
			Year 10		6 mm	19 mm	
			Year 11		11 mm*	5 mm	
			Year 12		-1 mm	26 mm	
			Year 13		10 mm	30 mm	
			Year 14		-4 mm	27 mm	
			Year 15		6 mm	34 mm	
			Year 16		26 mm*	37 mm	
			Year 17		14 mm	53 mm*	
			Year 18		1 mm	31 mm	
			Year 19		8 mm	15 mm	
			Year 20		9 mm	31 mm*	
			Year 21		-6 mm	60 mm*	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Fernow Expt. Forest, WV watershed 3[d]	34.4 ha, S, silt loams	Intensive selection harvests 1958 13% BA removed	Year 1[c]	-3 mm	-14 mm	8 mm	Kochenderfer and others 1990, Reinhart and others 1963, Reinhart and Trimble 1962, Trimble and others 1963
		1963 8% BA removed	Year 2	8 mm	8 mm	-0.3 mm	
			Year 3		10 mm	25 mm*	
			Year 4		-3 mm	8 mm	
		0.2-ha patch cuts 1968 6% BA removed	Year 5		3 mm	9 mm	
			Year 6		-17 mm*	17 mm*	
			Year 7		0.2 mm	15 mm	
		Clearcut 1968 to 2.5-cm dbh 91% BA removed	Year 8		-2 mm	21 mm*	
			Year 9		8 mm	32 mm*	
			Year 10		9 mm	17 mm	
		Riparian buffer cut 1972 9% BA removed	Year 11		7 mm	22 mm*	
			Year 12		35 mm*	21 mm*	
			Year 13		171 mm*	56 mm*	
			Year 14		64 mm*	27 mm*	
			Year 15		36 mm*	36 mm*	
			Year 16		45 mm*	40 mm*	
			Year 17		29 mm*	53 mm*	
			Year 18		9 mm	40 mm*	
			Year 19		2 mm	17 mm	
			Year 20		21 mm*	38 mm*	
			Year 25		11 mm	32 mm*	
			Year 30		-17 mm*	36 mm*	
Fernow Expt. Forest, WV watershed 5[d]	36.4 ha, NE, silt loams	Extensive selection harvest 20% BA removed 1958	Year 1[c]	25 mm*		-3 mm	Kochenderfer and others 1990, Lull and Reinhart 1967, Reinhart and others 1963, Trimble and others 1963
			Year 2	18 mm	36 mm*	-15 mm	
			Year 3		-8 mm	8 mm	
			Year 4		0 mm	-18 mm	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Fernow Expt. Forest, WV watershed 6[d]	22.3 ha, SE, silt loams	1964 clearcut lower half, removed 51% BA; herbicide through 1969; 1967-68 clearcut upper half, removed 49% BA; herbicide through 1969	Year 1[c]		30 mm	20 mm	Hornbeck and others 1993, Kochenderfer and others 1990, Patric and Reinhart 1971
			Year 2		79 mm*	86 mm*	
			Year 3		107 mm*	36 mm*	
			Year 4		99 mm*	15 mm (2nd ½ cut)	
			Year 5		201 mm*		
			Year 6		228 mm*	58 mm*	
			Year 7		130 mm*	31 mm*	
			Year 8		116 mm*	54 mm*	
			Year 9		64 mm*	55 mm*	
			Year 10		49 mm*	31 mm*	
			Year 11		78 mm*	44 mm*	
			Year 12		61 mm*	57 mm*	
			Year 13		85 mm*	73 mm*	
			Year 14		94 mm*	50 mm*	
			Year 15		90 mm*	72 mm*	
			Year 16		90 mm*	104 mm*	
			Year 17		49 mm*	45 mm*	
			Year 18		132 mm*	81 mm*	
			Year 19		142 mm*	57 mm*	
			Year 20		60 mm*	45 mm*	
			Year 21		85 mm*	71 mm*	
			Year 22		86 mm*	47 mm*	
			Year 23		57 mm*	58 mm*	
			Year 24		20 mm	56 mm*	
						31 mm	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Fernow Expt. Forest, WV watershed 7[e]	24.3 ha, E, silt loams	1963 clearcut upper half, 49% BA removed; herbicide through 1969 1966-67 clearcut lower half 51% BA removed; herbicide through 1969	Year 1[c]	165 mm* (23%)	91 mm*	64 mm*	Hornbeck and others 1993, Kochenderfer and others 1990, Patric and Reinhart 1971
			Year 2	142 mm* (36%)	74 mm*	71 mm*	
			Year 3	157 mm* (23%)	124 mm*	25 mm* (2nd ½ cut)	
			Year 4	251 mm* (38%)	218 mm*		
			Year 5	258 mm* (40%)	191 mm*	33 mm*	
			Year 6	246 mm* (33%)	217 mm*	71 mm*	
			Year 7	224 mm* (33%)	149 mm*	21 mm	
			Year 8	175 mm* (20%)	118 mm*	66 mm*	
			Year 9	164 mm* (16%)	93 mm*	48 mm*	
			Year 10	157 mm* (17%)	74 mm*	69 mm*	
			Year 11	187 mm* (20%)	81 mm*	82 mm*	
			Year 12	104 mm* (17%)	36 mm	104 mm*	
			Year 13	65 mm (11%)	20 mm	80 mm*	
			Year 14	89 mm* (12%)	28 mm	53 mm*	
			Year 15	112 mm* (11%)	39 mm	62 mm*	
			Year 16	99 mm* (12%)	40 mm	70 mm*	
			Year 17	62 mm* (8%)	21 mm	68 mm*	
			Year 18	61 mm (6%)	12 mm	53 mm*	
			Year 19	109 mm* (14%)	53 mm*	60 mm*	
			Year 20	103 mm* (12%)	30 mm	63 mm*	
			Year 21	71 mm* (8%)	25 mm	68 mm*	
			Year 22	52 mm (5%)	24 mm	55 mm*	
			Year 23	88 mm* (13%)	20 mm	20 mm	
			Year 24	48 mm (9%)	-3 mm	71 mm	
			Year 25	55 mm* (7%)		54 mm	
			Year 26	37 mm (4%)			
			Year 27	-2 mm (0%)			
Clover Run, WV watershed 9	11.6 ha, S, silt loams	Clearcut trees > 15 cm dbh removed; brush windrowed onto contoured roads and along perimeter of watershed, root raking with stumps left intact; trees > 2.5 cm dbh on 1.2 ha of steep land herbicided; buffer strip uncut	Year 1		99 mm*	NS	Kochenderfer and Helvey 1989
			Year 2		71 mm*	NS	
			Year 3		38 mm*	NS	

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Coweeta Hydrologic Lab., NC watershed 1[b]	16.2 ha, S, deep and permeable, (texture not reported)	1954 Cove hardwoods deadened 25% BA; 1956 clearcut 100% BA, no products removed, slash scattered, partial control burn; 1957 planted to pine	Year 1[f] Year 2 Year 3 Year 4[f] Year 5 Year 6 Year 7 Year 8 Year 9	30 mm < 25 mm < 25 mm 145 mm 18 mm 58 mm 41 mm 71 mm 69 mm			Swank and Miner 1968
Coweeta Hydrologic Lab., NC watershed 3[b]	9 ha, S, texture not reported	Clearcut	Year 1	127 mm			Hewlett and Hibbert 1961
Coweeta Hydrologic Lab., NC watershed 6[b]	8.9 ha, NW, deep and permeable (texture not reported)	Riparian area 5 m from stream cut 1941; Clearcut hardwoods 1958; remaining vegetation cut piled and burned; seedbed prepared by burning, grubbing and harrowing; planted to grass; foliar herbicide application subsequent years to control hardwood regrowth; fertilized and limed	1st 17 mo. Year 1[g] Year 2 Year 3 Year 4 Year 5	74 mm -17 mm 47 mm 64 mm 147 mm 149 mm			Hibbert 1969
Coweeta Hydrologic Lab., NC watershed 7[b]	59.0 ha, S, texture not reported	Clearcut and yarded using mobile cable system; < 10 % of watershed area with soil disturbance	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6	260 mm (28%) 200 mm 170 mm 120 mm 40 mm 40 mm			Swank and others 1982, 1988
Coweeta Hydrologic Lab., NC watershed 10[b]	86 ha, S, texture not reported	Commercial clearcut	Year 1	25 mm			Hewlett and Hibbert 1961

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Coweeta Hydrologic Lab., NC watershed 13[b]	16.2 ha, NE, deep and permeable (texture not reported)	Clearcut trees and shrubs, 100% BA cut, no products removed; allowed to regrow	Year 1	367 mm (57%)			Johnson and Kovner 1954, Kovner 1956, Meginnis 1959
			Year 2	277 mm (40%)			
			Year 3	278 mm (31%)			
			Year 4	248 mm (28%)			
			Year 5	200 mm (27%)			
			Year 6	252 mm (28%)			
			Year 7	201 mm (24%)			
			Year 8	185 mm (21%)			
			Year 9	132 mm (15%)			
			Year 10	131 mm (15%)			
			Year 11	145 mm (17%)			
			Year 12	147 mm (15%)			
			Year 13	127 mm			
Coweeta Hydrologic Lab., NC watershed 17[b]	13.4 ha, NW, deep and permeable (texture not reported)	Clearcut all stems > 1.2 cm dbh, 100% BA cut; wood products left on site; little soil disturbance; recut regrowth each growing season for most years during next 15 years	1st 6 mo.	207 mm			Hoover 1944, Johnson and Kovner 1954
			Year 1	425 mm (65%)			
			Year 2	271 mm			
			Year 3	229 mm			
			Year 4	152 mm			
			Year 5	152 mm			
			Year 6	330 mm			
			Year 7	279 mm			
			Year 8	279 mm			
			Year 9	279 mm			
			Year 10	254 mm			
			Year 11	279 mm			
			Year 12	279 mm			
Coweeta Hydrologic Lab., NC watershed 19[b]	28.3 ha, NW, loams, sandy loams, and sandy clay loams	All laurel and rhododendron on 28.3 ha cut close to ground, 22% BA cut; slash left on site, little soil disturbance	Year 1	71 mm	49 mm	36 mm	Johnson and Kovner 1956, Meginnis 1959
			Year 2	64 mm	39 mm	15 mm	
			Year 3	55 mm	30 mm	45 mm	
			Year 4	47 mm	20 mm	22 mm	
			Year 5	39 mm	11 mm	26 mm	
			Year 6	31 mm	1 mm	9 mm	
			Year 7		-8 mm		
			Years 1-6	4%			
Coweeta Hydrologic Lab., NC watershed 22[b]	34.4 ha, N, texture not reported	All vegetation in alternate 10.1-m-wide strip cuts herbicided, 50% BA cut; no products removed	Year 1	198 mm			Hewlett and Hibbert 1961

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields			Reference
				Annual	Growing	Dormant	
Coweeta Hydrologic Lab., NC watershed 28[b]	144.0 ha, NE, deep and permeable (texture not reported)	All trees and shrubs clearcut on 77 ha, cove vegetation thinned on 39 ha, 66% BA removed, 28 ha no harvest; products removed; high road density	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6 Year 7	165 mm 102 mm 79 mm 23 mm 28 mm 81 mm 104 mm			Douglass and Swank 1972
Coweeta Hydrologic Lab., NC watershed 37[b]	43.7 ha, NE, texture not reported	Clearcut watershed, 100% BA cut, no products removed, no roads constructed	Year 1 Year 2 Year 3	264 mm (18%) 91 mm (6%) 94 mm (6%)			Hewlett and Helvey 1970
Coweeta Hydrologic Lab., NC watershed 40	20.2 ha, SE, texture not reported	Commercial logging, selection cut, 22% BA removed	Year 1	0 mm			Hewlett and Hibbert 1961
Coweeta Hydrologic Lab., NC watershed 41[b]	28.7 ha, SE, texture not reported	Commercial logging, selection cut, 35% BA removed	Year 1	51 mm			Hewlett and Hibbert 1961

[a]NS= nonsignificant change indicated, but no value was given
[b]Significance/nonsignificance for this result or watershed was not provided
[c]Includes the harvesting or first harvesting period
[d]Significance/nonsignficance information for published data for this watershed was obtained from Forest Service records
[e]Significance/nonsignificance information for published growing and dormant season data for this watershed after year 5 was obtained from Forest Service records
[f]Year 1 includes deadening, year 4 includes clearcutting
[g]After grass establishment

Table 7—Flow frequency curve results for the central and southern Appalachians. A flow level of 50% represents median flow; 84% represents the median flow plus one standard deviation; 16% represents the median flow minus one standard deviation. Refer to Table 6 for watershed and treatment descriptions

Location	Time period	Flow level equaled or exceeded (%)	Average increase (%)	Volume increase ($L\ s^{-1}\ km^{-2}$)	Reference
Fernow watershed 1	First 2 growing seasons	84	1700	0.9	Reinhart and others 1963[a]
		50	500	4.9	
		16	132	22.3	
Fernow watershed 2	First 2 growing seasons	84	200	0.7	Reinhart and others 1963[a]
		50	221	3.4	
		16	84	15.7	
Fernow watershed 3	First 2 growing seasons	84	20	0.1	Reinhart and others 1963[a]
		50	33	0.3	
		16	0	0.0	
Fernow watershed 5	First 2 growing seasons	84	100	0.4	Reinhart and others 1963[a]
		50	38	1.4	
		16	20	6.5	
Coweeta watershed 13	First 7 years	84	62	7	Johnson and Kovner 1954,
		50	41	8	Johnson and Meginnis 1960
		16	17		
Coweeta watershed 17	First 7 years	84	124		Johnson and Kovner 1954
		50	50		
		16	35		

[a]Volume data were determined from contemporary reconstruction of flow frequency curves presented in Reinhart and others (1963)

Table 8—Decreases in the number of days during which designated low flow levels occurred following harvesting in the central Appalachians. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant. Refer to Table 6 for watershed and treatment descriptions

Location	Flow level ($L\ s^{-1}\ km^{-2}$)	Time period	Decrease in number of days during which low flow occurred	Reference
Leading Ridge watershed 2	< 7.34	Year 1	40*	Lynch and others 1972
		Year 2	5	
		Year 3	61*	
		Year 4	46*	
Fernow watershed 1	< 3.67	Year 1	72*	Reinhart and others 1963, Trimble and others 1963
		Year 2	38*	
		Year 3	63*	
		Year 4	39*	
Fernow watershed 2	< 3.67	Year 1	22*	Reinhart and others 1963, Trimble and others 1963
		Year 2	47*	
		Year 3	27*	
Fernow watershed 3	< 3.67	Year 1	21*	Reinhart and others 1963, Trimble and others 1963
		Year 2	14*	
Fernow watershed 5	< 3.67	Year 1	5	Reinhart and others 1963, Reinhart and Trimble 1962, Trimble and others 1963
		Year 2	13*	
		Year 3	5	

Table 9—Changes in depletion times during low flows following basal area reductions in the southern Appalachians (from Johnson and Meginnis 1960). Refer to Table 6 for watershed and treatment descriptions

Location	Flow depletion ($L\ s^{-1}\ km^{-2}$)	Before clearcut	After clearcut	Resulting streamflow increase (mm)
		Number of days required for depletion to occur		
Coweeta watershed 13	20 to 6	65	82	10
Coweeta watershed 17	20 to 4.7	38	63	14
Coweeta watershed 19	14 to 9	12	27	3

Table 10—Changes in stormflow volumes and peakflow magnitudes following harvesting for the central and southern Appalachians. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant. Refer to Table 6 for watershed and treatment descriptions

Location	Time period	Hydrologic changes						Reference
		Mean peak discharge change			Mean stormflow change			
		Annual	Growing	Dormant	Annual	Growing	Dormant	
Leading Ridge watershed 2	Years 1-3.5[a]	115 L s^{-1} km^{-2}* (118%)	280 L s^{-1} km^{-2}* (351%)		0. 5 mm* (32%)	1.7 mm* (171%)		Lynch and others 1972
Fernow watershed 1[b]	Year 1[c]	4%	21%		7%	24%		Lull and Reinhart 1966, Reinhart 1964, Reinhart and Trimble 1962
	Years 1-4[c]			-4%			2.5%	
Fernow watershed 3	Year 1[d]		300%*	NS[e]	NS			Patric 1980
Fernow watershed 6	Year 1[f]		400%*	NS				Patric and Reinhart 1971
Fernow watershed 7	Year 1[f]		NS	NS				Patric and Reinhart 1971
Coweeta watershed 7	Years 1-3[g]	19 L s^{-1} km^{-2}* (15%)			0.3 mm* (10%)			Swank and others 1982, 1988, 2001
	Years 1-4[g]	17 L s^{-1} km^{-2}* (15%)			0.3 mm* (10%)			
Coweeta watershed 13	Year 1	NS			NS			Meginnis 1959
Coweeta watershed 17	Years 1-2	NS			NS			Hoover 1944, Meginnis 1959
Coweeta watershed 19	Year 1				NS			Johnson and Kovner 1956, Meginnis 1959
Coweeta watershed 28	Years 1-9				17%*			Swank and others 1988, 2001
	Years 1-2	30%*						
Coweeta watershed 37	Years 1-4[h]	65.6 L s^{-1} km^{-2}* (7%)			5.8 mm* (11%)			Hewlett and Helvey 1970, Swank and others 2001

[a]For events with stormflow > 0.025 cm. Annual extends from April through November each year. Growing season includes May through October each year
[b]Significance/nonsignificance information was not provided for this watershed
[c]For storms > 109 L s^{-1} km^{-2}
[d]After clearcutting [e]NS=nonsignificant change [f]After full deforestation
[g]For precipitation ≥ 2 cm [h]For 30 largest events

Table 11—Changes in hydrograph parameters following harvesting in the central and southern Appalachians. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant. Refer to Table 10 for information about changes to peakflow magnitudes and total stormflow volumes. See Table 6 for watershed and treatment descriptions

Location	Time period	Time to peak	Recession time	Stormflow duration	Stormflow before peak	Stormflow after peak	Initial flow	Reference
Coweeta 7[a]	Years 1-4	0%	10%*	5%*	6%*	11%	14%*	Swank and others 2001
Coweeta 37	Years 1-4	NS[b]	NS	NS				Hewlett and Helvey 1970, Swank and others 1988
Leading Ridge 2	Years 1-3.5[c]	-3% during both growing and dormant seasons	4.2 hr (33%)* growing season; no change dormant season				2.54 mm[d] (12%) annually; 5.08 mm[d] (123%) growing season; 1%[d] dormant season	Lynch and others 1972

[a]For precipitation ≥ 2 cm
[b]NS=nonsignificant change indicated, but no value was given
[c]April –Nov. events with stormflow > 0.0.25 cm; annual period extends from April through November; growing season includes May through October; dormant season includes only April and November
[d]Significance/nonsignificance information was not provided for this result

Table 12—Changes to annual stream discharge following site preparation and harvesting in the Piedmont

Location	Area, aspect, soils	Treatment description	Time period	Discharge change	Reference
Piedmont, NC[a]	0.25–0.75 ha, aspect not given, sandy clay loams, sandy clays, clay loams	Site prep using KG blade shearing, windrowing, burning, and disking 4 replicated watersheds	Year 1 Year 2 Year 3	345 mm 242 mm 223 mm	Douglass and Goodwin 1980
	0.43-0.62 ha, aspect not given, sandy clays, sandy clay loams, clay loams, sandy loams	Site prep using KG blade shearing, windrowing, burning 4 replicated watersheds	Year 1 Year 2 Year 3	70 mm 142 mm 71 mm	
	0.33-0.53, aspect not given, clay, sandy clay loams	Site prep using KG blade shearing, windrowing, burning, disking, planting to grass 4 replicated watersheds	Year 1 Year 2 Year 3	46 mm 40 mm 35 mm	
Piedmont, GA[a]	32.4 ha, SW, loam overlaying sandy loam	Harvest, roller chop twice	Year 1 Year 2	254 mm 126 mm	Hewlett 1979, Hewlett and others 1984

[a]Significance/nonsignificance information was not provided for these sites

Table 13—Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the Piedmont. An * indicates a statistically significant change at the alpha level used by the original authors

Location	Area, aspect, soils	Treatment description	Time period	Hydrologic change			Reference
				Mean peak discharge	Mean stormflow	Other parameters	
Piedmont, SC	0.65 and 1.25 ha, aspect not given, sandy loam overlaying clay	Two watersheds with 3 consecutive years of control burns, then clearcut pine, slash left in place	First 21 months	55-60%*	Increased significantly	Nonsignificant change in time to peakflow and event length	Douglass and others 1983
	1.1 ha, aspect not given, sandy loam overlaying clay	One watershed with three consecutive years of control burns, then clearcut pine, slash bladed off with bulldozer	First 21 months	150%*	100%*		

Table 14—Average changes to water table elevations following harvesting or harvesting plus site preparation in the Coastal Plain

Location	Area, aspect, soils	Treatment description	Time period	Average changes to water tables		Reference
				Annual	Growing	
Lower Coastal Plain, SC[a]	Acreage not given, flat topography, sandy loams over sandy clays	Dry weather harvest, no bedding, plant	1st year after cut	140 mm		Xu and others 2000
			1.75 yr after cut	430 mm		
			2.75 yr after cut	280 mm		
			3.75 yr after cut	140 mm		
		Wet weather harvest, no bedding, plant	1st yr after cut	210 mm		
			1.75 yr after cut	450 mm		
			2.75 yr after cut	360 mm		
			3.75 yr after cut	210 mm		
		Dry weather harvest, conventional bedding, plant	After bedding	280 mm		
			Year 1	250 mm		
			Year 2	130 mm		
		Wet weather harvest, conventional bedding, plant	After bedding	270 mm		
			Year 1	280 mm		
			Year 2	160 mm		
		Wet weather harvest, mole plowing + conventional bedding, plant	After bedding	270 mm		
			Year 1	300 mm		
			Year 2	180 mm		
Lower Coastal Plain, SC[a]	No acreage given, flat topography, fine sands	Seed tree cut in pine stand 67% basal area removed	Year 1	100 ± 37 mm[b]	119 ± 43 mm[b]	Williams and Lipscomb 1981
		Selection cut in pine stand 18% basal area removed	Year 1	146 ± 70 mm[b]	155 ± 116 mm[b]	
		Selection cut in pine stand 56.9% basal area removed	Year 1	226 ± 46 mm[b] b	171 ± 91 mm[b]	
		Commercial clearcut of pine and mixed hardwoods 41% basal area removed	Year 1	323 ± 61 mm[b]	219 ± 88 mm[b]	
Coastal Plain, NC[a]	25 ha, flat topography, fine sandy loam	Clearcut pine, site preparation, bedding	Year 1	74 mm		Amatya and others 2006b
			Year 2	107 mm		
			Year 3	146 mm		
			Year 4	30 mm		
			Year 5	22 mm		
			Year 6	-8 mm		
			Year 7	40 mm		
			Year 8	-14 mm		
			Year 9	-50 mm		
			Year 10	-42 mm		

[a]Significance/nonsignificance information was not provided for these sites [b]± 1 standard deviation

Table 15—Changes to annual outflow or stream discharge following harvesting and site preparation in the Coastal Plain. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time period	Outflow or discharge change	Reference
Lower Coastal Plain, FL	67 ha, flat topography, sands overlaying clay	33 ha clearcut pine and pine, chop, bed, plant (low disturbance level)	Year 1	30 mm	Riekerk 1989
			Year 2	40 mm	
			Year 3	0 mm	
			Year 4	-100 mm*	
			Year 5	-180 mm*	
			Year 6	30 mm	
			Year 7	-130 mm*	
	49 ha, flat topography, sands overlaying clay	36 ha clearcut pine, stump removal, burn, windrow, harrow, bed, plant (high disturbance level)	Year 1	150 mm* (150%)	
			Year 2	-60 mm*	
			Year 3	30 mm	
			Year 4	-130 mm*	
			Year 5	80 mm	
			Year 6	100 mm*	
			Year 7	130 mm*	
West Gulf Coastal Plain, AR	2.3 - 4.0 ha, flat topography, silt loams and clays	3 replicates, clearcut mixed hardwoods and pine, shearing, windrowing, burning, hand plant (high disturbance level)	Year 1	122 mm*	Beasley and Granillo 1988
			Year 2	137 mm	
			Year 3	153 mm	
			Year 4	120 mm	
		3 replicates, selective harvest of pine, harvest of all commercial hardwoods, herbicide all remaining hardwoods, plant (low disturbance level)	Year 1	41 mm	
			Year 2	28 mm	
			Year 3	-30 mm	
			Year 4	-36 mm	
Coastal Plain, NC[a]	25 ha, flat topography, fine sandy loam	Clearcut pine, site preparation, bedding	Year 1	91 mm (99%)	Amatya and others 2006b
			Year 2	260 mm (38%)	
			Year 3	207 mm (54%)	
			Year 4	98 mm (13%)	
			Year 5	56 mm (10%)	
			Year 6	-31 mm (-4%)	
			Year 7	8 mm (18%)	
			Year 8	21 mm (5%)	
			Year 9	116 mm (9%)	
			Year 10	-2 mm (-0.5%)	

[a]Significance/nonsignificance information was not provided for this site

Table 16—Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the Coastal Plain. An * indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an * are nonsignificant

Location	Area, aspect, soils	Treatment description	Time period	Hydrologic change			Reference
				Mean peak discharge	Mean stormflow	Other parameters	
Coastal Plain, East Texas	2.57-2.72 ha, aspects not given, fine sandy loam overlaying clay	3 replicates, clearcut pine and mixed hardwoods, roller chopping and burning, plant (low disturbance level)	Year 1	14 L s^{-1}*	57 mm*		Blackburn and others 1986
			Year 2	1 L s^{-1}	24 mm*		
			Year 3	2 L s^{-1}	23 mm		
			Year 4	1 L s^{-1}	21 mm*		
		3 replicates, clearcut pine and mixed hardwoods, shearing, windrowing, and burning, plant (high disturbance level)	Year 1	38 L s^{-1}*	120 mm*		
			Year 2	11 L s^{-1}*	38 mm*		
			Year 3	10 L s^{-1}*	41 mm*		
			Year 4	12 L s^{-1}*	47 mm*		
Coastal Plain, VA	7.9 ha, SE, sandy loams	Clearcut pine and hardwoods with no BMPs, herbicide, moderate intensity burn, hand plant	38 month postharvest	3%	-12%*		Wynn and others 2000
			after site prep.	-6%*	-31%*		
	8.5 ha, SE, sandy loams	Clearcut pine and hardwoods with BMPs, herbicide, moderate intensity burn, hand plant	38 month postharvest	15%*	-21%*		
			after site prep.	4%	-6%*		
Gulf Coastal Plain, AR	2.3 - 4.0 ha, flat topography, silt loams and clays	3 replicates, clearcut mixed hardwoods and pine, shearing, windrowing, burning, hand planting loblolly pine (high disturbance level)	Year 1	14.1 L s^{-1}*	125 mm*		Beasley and Granillo 1983, 1988
			Year 2	8.5 L s^{-1}			
			Year 3	8.5 L s^{-1}			
			Year 4	4.1 L s^{-1}			
		3 replicates, selective harvest of pine, harvest of all commercial hardwoods, herbicide all remaining hardwoods (low disturbance level)	Year 1	0 L s^{-1}	41 mm		
			Year 2	2.8 L s^{-1}			
			Year 3	0 L s^{-1}			
			Year 4	1.4 L s^{-1}			

Location	Area, aspect, soils	Treatment description	Time period	Hydrologic change			Reference
				Mean peak discharge	Mean stormflow	Other parameters	
Northern MS[a]	0.8 ha, NW, sandy loams, silt loams	Harvest, brush chopping	Year 1 Year 2		479 mm 316 mm		Beasley 1979
	1 ha, W, sandy loams, silty clay, silty clay loams	Harvest, shearing and windrowing	Year 1 Year 2		422 mm 252 mm		
	0.7 ha, WSW, sandy loam, silty clay, silty clay loam	Harvest, bedding on the contour	Year 1 Year 2		478 mm 208 mm		
Upper Coastal Plain, MS	0.86 ha, aspect not given, silt loam, sandy loam	Upland hardwoods, slow burned, hand plant pines, deaden overstory > 2.54 cm dbh with herbicides	Year 1 Year 2 Year 3	94 L s^{-1}* (53%) 38 L s^{-1}* (31%) 14 L s^{-1} (13%)	31 mm* (22%) 26 mm* (22%) 47 mm* (54%)		Ursic 1970, 1982
	0.86 ha, aspect not given, silt loam	Upland hardwoods, slow burned, hand plant pines, deaden overstory > 2.54 cm dbh with herbicides	Year 1 Year 2 Year 3	83 L s^{-1}* (33%) 24 L s^{-1}* (15%) 46 L s^{-1} (34%)	69 mm* (22%) 34 mm (16%) 75 mm* (46%)		

[a]Significance/nonsignificance information was not provided for these sites