CHAPTER 11.

Water Yield and Hydrology

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Investigations of hydrologic responses resulting from reducing vegetation density are fairly common throughout the Eastern United States. Although 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 objectives, data from some less-intensive manipulations—such as thinnings, understory removals, and controlled burns for seedbed establishment—that are more easily related to fuel-reduction activities are available. In this chapter, findings from the entire range of available manipulation intensities are presented so that results can be applied 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 onsite, and thus, have relevance to combustibility and fuels management.

The ways and extent to which hydrologic responses from vegetation manipulation occur depend on whether they are expressed as surface flows, such as 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 southeastern wet flatlands 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:

$$\text{Streamflow} = \text{Precipitation} - \text{Evapotranspiration} + \Delta\ \text{Soil Moisture Storage} + \Delta\ \text{Ground Water Storage} \quad (1)$$

Often ground water changes 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 defined as 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.

Equation 1 can be used to predict total stream discharge in the short term, but doing so would require inclusion of changes in soil moisture because these changes 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):

$$\text{Streamflow} = \text{Precipitation} - \text{Evapotranspiration} + \Delta\ \text{Lateral Seepage} + \Delta\ \text{Soil Moisture Storage} - \text{Deep Seepage} \quad (2)$$

The deep seepage term for wet flatlands often also is considered to be approximately zero because the soils involved often are poorly drained (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):

$$\Delta\ \text{Water table height} = (\Delta\ \text{Inflow} - \Delta\ \text{Outflow} - \Delta\ \text{Evapotranspiration})\ /\ \text{Soil Specific Yield} \quad (3)$$

Although inflow and outflow rates can have substantial effects on water-table height, ET becomes the dominant factor in controlling water-table height if water exchange is slow. Soil specific yield, also known as drainable soil porosity, is the ratio of the volume of water that drains from a saturated soil as a result of lowering the water table relative to the volume of that soil. Its value ranges between zero and one, but it is not actually a constant and depends on 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).

To ensure that changes in water-table responses are measured and interpreted accurately, measurement wells must be at least as deep as the lowest water-table levels expected during monitoring. If the well is not deep enough, a water table may rise or fall, but documenting the change will be impossible. 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 landforms of the Eastern United States; commonly, the study areas have been experimental forests operated by either the U.S. Department of Agriculture Forest Service or universities, although in the South studies have been applied fairly broadly, particularly on forest-industry lands in the Coastal Plain.

For consistency throughout this volume on Eastern landscapes, the approach is to classify and describe responses by ecological divisions and provinces (chapter 3) to the extent possible. Ecological divisions are defined by "regional climatic types, vegetational affinities, and soil order"; and provinces are defined by "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 more commonly employed physiographic 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 names (North Central States, Northeastern States, Ozark Mountains and Ouachita Plateau, Central and Southern Appalachian Mountains, 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 our separate consideration of the Piedmont and Coastal Plain. Hydrologically, these two areas behave very differently from one another, but the boundaries of the ecological provinces involved (chapter3) do not coincide with the boundaries of the Coastal Plain and Piedmont physiographic areas (fig. 1). Consequently, the Southeastern Mixed Forest Province within the Subtropical Division (230) is included in both the Piedmont and Coastal Plain (table 1).

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 physiographic titles)

Physiographic area	Division and provinces

North Central States	210 Warm Continental
	  212 Laurentian Mixed Forest
	
	220 Hot Continental
	  222 Midwest Broadleaf Forest

Northeastern States	210 Warm Continental
	  211 Northeastern Mixed Forest
	
	M210 Warm Continental—Mountain
	  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—Mountain
	  M223 Ozark Broadleaf Forest—Meadow
	
	M230 Subtropical—Mountain
	  M231 Ouachita Mixed Forest—Meadow

Central and Southern Appalachian Mountains	M220 Hot Continental—Mountain
	  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)

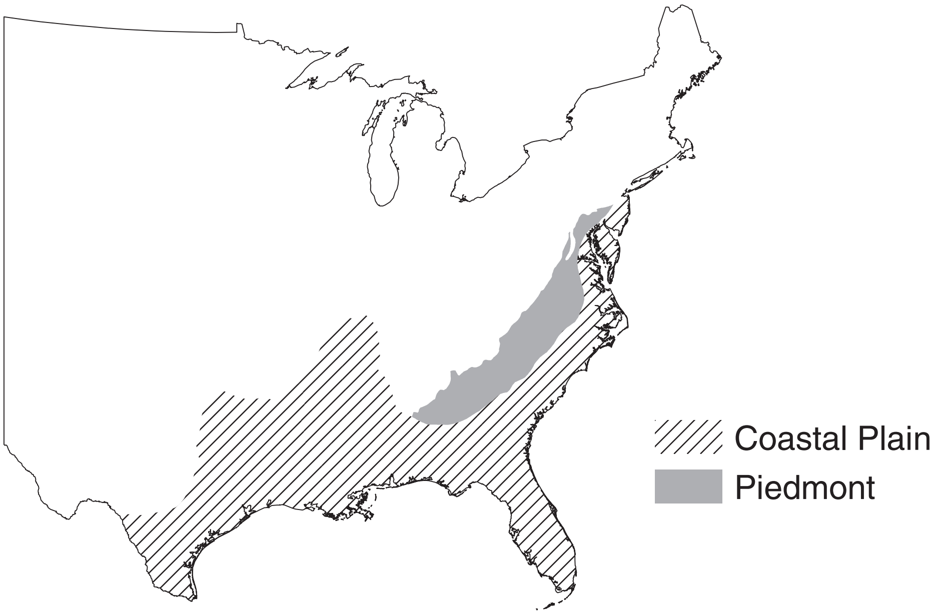

Figure 1. Piedmont and Coastal Plain boundaries.

No hydrologic response data applicable to the Prairie Parkland (Temperate) Province (251) were found in the literature, so this province is not included in our chapter. Likewise, the Everglades Province (411) is not included, but fuel-reduction activities are not being practiced in this area.

Hydrologic Responses

Physiographic areas 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 seasonally (growing and dormant) as well as annually. Storm event responses also are described where data were available. The term stormflow—also called quickflow—is used in this chapter to describe 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 or both events combined (Hewlett and Hibbert 1961). Peakflow is defined as the instantaneous maximum magnitude or rate of discharge during a precipitation or snowmelt event.

North Central States

The North Central States are 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 less demonstrative 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 (*Picea mariana*) 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, making these soils hydrologically quite responsive. Conversely, well decomposed organic soils, which are most common in the North Central States, have many small pores that hold water tightly because of extremely low hydraulic conductivities, so losses from these organic soils are primarily as ET (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 ET will have little effect on water-table fluctuations or levels because 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 ET caused by winds and increasing transpiration by sedges, which 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 lowered by as much as 190 mm after clearcutting—the result of high ET attributable to more wind and 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 preharvest conditions.

Harvesting on mineral soils can increase soil moisture (Blackmarr and White 1964, Verry 1972), or water-table levels (Urie 1971), or both; but because mineral soils transmit water to streams quickly, measurements of hydrologic change often are focused on streamflow. Harvests in areas with mineral soils often cover a higher percentage of total watershed area than those on organic soils, further contributing to the degree of hydrologic changein mineral soils. Upland clearcutting of aspen (*Populus tremuloides*) over two-thirds of watershed 4 on the Marcell Experimental Forest in Minnesota resulted in significant increases to annual runoff for 9 years following harvesting (Hornbeck and others 1993, Verry 1987), with approximately half of the 9-year change occurring during harvesting and the 3 years after harvesting (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 (*Quercus* spp.–*Carya* spp.) stand in a 0.67-ha watershed at Rose Lake Wildlife Experiment Station in southern Michigan, and ET was estimated to have returned to pretreatment 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 half 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—resulting from increased heat transfer to the snowpack (from solar radiation) and reradiation 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 to 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

Table 2. Water yield and water table responses to harvesting treatments in the North Central States

Location	Area, aspect, soils	Treatment description	Time period	Annual changes to water yields	Changes to water table: Annual	Changes to water table: Wet periods	Changes to water table: Dry periods	Reference
				mm	mm	mm	mm	
Marcell Experimental Forest, Minnesota Watershed 1	33.2 ha, no aspect given, mineral soil uplands, peat soils, central bog	Strip cut 43 percent of spruce in bog, strips run northwest to southeast	Years 1 to 5	NS	NS			Verry 1981
		Year 6 clearcut remaining spruce in bog (total harvested = 8 percent of watershed)	Years 6 to 10	NS		100[a]	–190[a]	
Marcell Experimental Forest, Minnesota 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[a] (42 percent)				Hornbeck and others 1993; Verry 1972, 1987
			Year 1	85[a] (39 percent)				
			Year 2	117[a] (58 percent)				
			Year 3	88[a] (70 percent)				
			Year 4	38[a] (20 percent)				
			Year 5	77[a] (34 percent)				
			Year 6	34[a] (45 percent)				
			Year 7	51[a] (34 percent)				
			Year 8	52[a] (21 percent)				
			Year 9	40[a] (15 percent)				
			Year 10	19 (18 percent)				
			Year 11	6 (3 percent)				
			Year 12	–22 (–8 percent)				
			Year 13	–9 (–9 percent)				
			Year 14	33[a] (16 percent)				
			Year 15	12 (4 percent)				
			Year 16	56[a] (26 percent)				
			Year 17	–1 (0 percent)				
			Year 18	–25[a] (–8 percent)				
			Year 19	1 (0 percent)				
			Year 20	–12 (–10 percent)				
			Year 21	–4 (–4 percent)				
Sand Plain, Northwestern lower Michigan	40-acre blocks, no aspect given, sands	Two replicate 16-ha blocks, strip cut 50 percent of pines, strips southeast to northwest orientation	Years 1 to 3		66[b] (20 to 30 percent under strips)			Urie 1971

NS = nonsignificant change indicated, but no value was given.

[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.

[b] Significance/nonsignificance information was not provided for this result.

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 preharvest levels. Increases in rainfall-associated peakflows were the result of reductions in soil moisture deficits after harvesting (Verry and others 1983). Peakflow rates from the annual series for 2-year events increased about 1.5 times preharvest levels, compared to 2.5 times for 10-year events (Verry 1986, Verry and others 1983). Similarly, flow duration curves showed that average daily flows increased across all ranges of flow rates with the exception of the very highest flows associated with maximum snowmelt peaks (Verry 1972).

Northeastern States

Most of the studies in the Northeastern States 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 or 20 to 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—such as 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 ≤6 years (table 3); and after 10 to 15 years, water yields commonly fell to levels lower than pretreatment (table 3). This 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 Northeastern States was almost entirely the result of increased discharge during the growing season, and that 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 higher 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 (such as the study sites at Caldwell Creek and Dickey Brook) compared to other New England study sites, such as Hubbard Brook in New Hampshire.

Increases in streamflow were expressed primarily during low flows. Shifts in flow frequency curves for Caldwell Creek and for 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 herbiciding followed clearcutting (Hornbeck and others 1997). For example, average daily growing-season flows equaling or exceeding 1 mm occurred an average of 26 days before clearcutting watershed 2 at Hubbard Brook. After clearcutting and herbiciding, growing-season flow equaled or exceeded 1 mm for 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 did 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 in one year clearcutting caused a shift forward of 17 days on one watershed (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).

Table 3. Water yield responses to harvesting treatments in the Northeastern States

Location	Area, aspect, soils	Treatment description	Time period	Changes to water yields: Annual	Growing	Dormant	Reference
				------------mm------------			
Hubbard Brook	15.8 ha, south,	Winter clearcut primarily	Year 1	347[a] (40 percent)	315[a] (344 percent)	25	Hornbeck and
Experimental	sands and	northern hardwoods,	Year 2	278[a] (29 percent)	231[a] (310 percent)	36	others 1970,
Forest, New	sandy loams	trees left in place,	Year 3	240[a] (26 percent)			1993, 1997;
Hampshire		herbicide stumps and	Year 4	200[a] (22 percent)			Pierce and
Watershed 2		ground cover	Year 5	146[a] (17 percent)			others 1970
			Year 6	44[a] (6 percent)			
			Year 7	12 (1 percent)			
			Year 8	52 (4 percent)			
			Year 9	67[a] (8 percent)			
			Year 10	3 (0 percent)			
			Year 11	4 (5 percent)			
			Year 12	64[a] (6 percent)			
			Year 13	–13 (–1 percent)			
			Year 14	–13 (–2 percent)			
			Year 15	–34 (–4 percent)			
			Year 16	–41[a] (–3 percent)			
			Year 17	–70[a] (–8 percent)			
			Year 18	–62[a] (–6 percent)			
			Year 19	–64[a] (–9 percent)			
			Year 20	–44[a] (–5 percent)			
			Year 21	–80[a] (–9 percent)			
			Year 22	–82[a] (–10 percent)			
			Year 23	–56[a] (–8 percent)			
			Year 24	–34 (–3 percent)			
			Year 25	–48[a] (–4 percent)			
Hubbard Brook	22 ha, aspect not	Whole tree clearcut of	Year 1	152[a] (23 percent)		–49[a b]	Hornbeck and
Experimental	given, sandy	northern hardwoods	Year 2	47 (5 percent)		–46[a b]	others 1997
Forest, New	loam	applied to 20 ha	Year 3	–15 (–2 percent)			
Hampshire			Year 4	–11 (–1 percent)			
Watershed 5			Year 5	4 (1 percent)			
			Year 6	46 (5 percent)			
			Year 7	51[a] (5 percent)			
			Year 8	66[a] (8 percent)			
			Year 9	47 (6 percent)			
			Year 10	20 (2 percent)			
			Year 11	21 (4 percent)			
			Year 12	46 (4 percent)			

continued

Table 3. Water yield responses to harvesting treatments in the Northeastern States (continued)

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

continued

Table 3. Water yield responses to harvesting treatments in the Northeastern States (continued)

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

NS = nonsignificant change indicated, but no value was given;.

[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.

[b] Based only snowmelt runoff only.

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

Reducing vegetation can result in other hydrograph responses, but the limited results reported in the literature from the Northeastern States 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 after 32 percent of the basal area was removed using a combination of clearcutting and thinning (Bent 1994). High flows (> 0.2 m^3/second/km^2) increased an average of 13 percent during the first 3 years after clearcutting and herbiciding 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 largest 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 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 only one short period or a few short periods. Individual stormflow totals during these spring melts can be much higher than during other times 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 average peak discharge at Caldwell Creek 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).

Ozark Mountains and Ouachita Plateau

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

In the Ozark Mountains, clearcutting a 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 more than what would have occurred with best management practices (Settergren and others 1980). The lack of change was attributed to the limited area that was harvested and the fact that disturbance was confined to the ephemeral headwaters. Had the harvesting been in lower portions of the watershed closer to the nonephemeral 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 Missouri soil series 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 exposed mineral soil and reduced soil infiltration 20 to 62 percent, with an average reduction of 38 percent (Arend 1941).

Even though Settergren and others (1980) observed no changes to stormflow after clearcutting a third of a watershed, some local soil moisture augmentation may have occurred because of reductions in transpiration. Substantial differences in soil moisture deficits were observed between clearcut and forested plots on the Koen Experimental Forest (Rogerson 1976). Average maximum soil water deficit in the clearcut plots was 78 mm, only 29 percent of the average maximum deficit of 267 mm in the forested plots. Soil moisture deficits in the clearcut plots were present only during summer and autumn; 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*) 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 the subsoil. The resulting soil disturbance increased roughness and detention storage in the furrows, and cut off soil

Table 4. Changes in stormflow volumes and peakflow magnitudes resulting from harvesting treatments in the Northeastern States

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

NS = nonsignificant change indicated, but no value was given.
[a] For storms with peaks >1.5 m^3/second/km^2 or storms with stormflows >1.5 m^3/second/km^2.
[b] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without a [b] are nonsignificant.
[c] For storms with 2-day precipitation totals >25.4 mm.
[d] Changes to mean peak discharge in this study were calculated from only statistically significant peaks that were >10 mm per day.

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 ET 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 with uncut controls (Miller and others 1988). The large average annual stormflow increases that were observed (table 5) indicated

Table 5. Water yield responses (as stormflow volumes) to harvesting treatments in the Ozark Mountains and Ouachita Plateau

Location	Acreage, aspect, soils	Treatment description	Time period	Stormflow changes	Reference
Ouachita Mountains, Oklahoma	1.6 to 4.2 ha, southwest, 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 49 [a] –11 –17	Beasley and others 2000, Miller 1984
Ouachita Mountains, Arkansas	4.08, 5.11, and 5.91 ha, north, southeast, and northwest, loam overlaying clay	Three replicate watersheds, clearcut and roller chop, burn, hand plant	Year 1 Year 2 Year 3	101 92 193	Beasley and others 2000, Miller and others 1988
	4.15, 4.35, and 5.74 ha, north, south, and west, loam overlaying clay	Three replicate watersheds, selection harvest	Year 1 Year 2 Year 3	101 74 149	Beasley and others 2000, Miller and others 1988
Ouachita Mountains, Arkansas	0.52 ha, northeast, stony silt loams	Overstory pine thinned, 57 percent basal area removed, mixed hardwood understory herbicided annually for 3 years	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6 Year 7	109 [a] [b] (79 percent) 57 82 66 0 49 41	Rogerson 1985
	0.59 ha, northeast, stony silt loams	Overstory pine clearcut, mixed hardwood understory herbicided annually for 3 years	Year 1 Year 2 Year 3 Year 4 Year 5 Year 6 Year 7	259 [a] [b] (193 percent) 141 113 135 143 160 102	Rogerson 1985
Athens Plateau, Arkansas	2 to 5 ha, aspect not given, fine sand or fine loam	Three replicate watersheds, clearcut, shear, windrow, plant	Year 1 Year 2 Year 3	166 [a] 388 237 [a]	Beasley and others 1986, 2000
	2 to 5 ha, aspect not given, fine sand or fine loam	Three replicate watersheds, clearcut, chemical site preparation, plant	Year 1 Year 2 Year 3	–3 176 –4	Beasley and others 1986, 2000

[a] indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.
[b] Significance/nonsignificance for this study was specified only for year 1.

that stormflow increased roughly proportionally to the amount of harvesting and site disturbance; however, the increases were not significant because of substantial variability in responses across the replicated sites. One of the three replicated sites in each harvesting treatment consistently yielded much higher annual stormflow volumes than the controls, presumably because they 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 stormflow increase for the clearcut/site-prepared watershed would have been 98 mm more than the average reported for year 1 and 100 mm more than year 2 (table 5). By contrast, selection-harvest values from the first 2 years essentially would have been unchanged (–5 and 0 mm different). These larger 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 also lengthen the time that stormflows, albeit in small volumes, were present. After harvesting, periods of stormflow extended farther into the summer and began earlier in the autumn. Peakflow increases also were related to the intensity of treatment, but peakflows did not differ significantly among the treatments and the controls.

In other nearby watersheds in the Ouachita Mountains, clearcutting and thinning pine followed by 3 years of herbiciding to control hardwood regrowth also decreased soil water deficits, which in turn increased discharge from ephemeral channels (table 5). The first growing season after treatment, soil water deficits were reduced by as much as 51 to 76 mm on the thinned watershed and 76 to 102 mm on the clearcut watershed (Rogerson 1985). 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 larger, both in volume and percentage (table 5). Water yields over the 7-year study increased an average of 23 percent from thinning and 67 percent from clearcutting; more than half of those volume increases occurred during the growing seasons (thinned 52 percent, clearcut 61 percent) (Rogerson 1985).

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 years (table 5) because vegetation deadening was incomplete, stump sprouting was common, and overall disturbance to watershed soils was less. 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 than pretreatment 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 located in the thinner rocky soils of the Ouachita Mountains. The result was almost no stormflow discharge in the Coastal Plain area except during the unusually wet second year; replicates in the Ouachita Mountain soils yielded much more stormflow.

Central and Southern Appalachian Mountains

The Appalachian Mountains 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 comprises only a small percentage of the hydrologic budget (Hewlett and Hibbert 1961). The vast majority of the available data for this area is from the Fernow Experimental Forest in north central West

Virginia and Coweeta Hydrologic Laboratory in western North Carolina. Limited amounts of data also are available from central Pennsylvania (including the Leading Ridge Watershed Research Unit) and the Cumberland Plateau. These studies 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 the Appalachian Mountains 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 after harvesting. Site preparation following clearcutting at Clover watershed in West Virginia (Kochenderfer and Helvey 1989) and Coweeta watershed 6 (Hibbert 1969) did not increase annual water yields (table 6) 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). 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*) and rhododendron (*Rhododendron maximum*) that accounted for 22 percent of the basal area of Coweeta watershed 19 resulted in significant, albeit short-term increases in annual yields (table 6).

In the Appalachian Mountains, yields typically decline quickly because of rapid regrowth and restoration of ET encouraged by high precipitation levels and relatively long growing seasons. For example, after clearcutting at Fernow, Leading Ridge, and Coweeta, discharges returned to pretreatment 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 because of changes in species composition and/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 higher annual increases than from clearcutting alone (table 6). This was likely because nearly all of 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 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 or a lack of best management practices or both factors 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 best management practices applied during or after harvesting (Reinhart and others 1963), and annual stream discharge was similar to other clearcut watersheds on the Fernow (table 6). Likewise the absence of best management practices in Kentucky (table 6) resulted in only slightly higher annual water yields (~30 mm) than a nearby watershed that had the same cutting treatment and application of best management practices (Arthur and others 1998). Coweeta watershed 28 had a high road density with 66 percent of basal area 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 after clearcutting and other intensive treatments. Aspect at Fernow did not affect annual discharge; at Coweeta annual increases from watersheds with a northerly aspect were almost always higher than those with a southerly aspect (Hewlett and Hibbert 1961). Discharges from most south-facing

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields: Annual	Growing	Dormant	Reference
					----------mm----------		
Robinson Forest, Kentucky Watershed B	Area not reported, east, loams and fine loams	Clearcut hardwoods and pines >35.5 cm d.b.h., cut and left stems <5 cm, BMPs employed	During clearcutting	NS			Arthur and others 1998
			First 17 months	178 mm[a] (123 percent)			
			Year 8	15 percent[b]			
			Years 1 to 8	37 percent[b]			
Robinson Forest, Kentucky Watershed C	Area not reported, east, loams and fine loams	Clearcut hardwoods and pines >35.5 cm d.b.h., cut and left stems <5 cm, no BMPs employed	During clearcutting	NS			Arthur and others 1998
			First 17 months	206 mm[a] (138 percent)			
			Year 8	12 percent[b]			
			Years 1 to 8	48 percent[b]			
Leading Ridge, Pennsylvania Watershed 2	42.9 ha, southeast, silt loams, stony loams, and cobbly loams	Riparian clearcut ~one-third of watershed (8.6 ha), herbicides to control stump sprouts during next 3 summers	Year 1	70 mm[a]	53[a]	–27	Hornbeck and others 1993, Lynch and others 1972
			Year 2	32 mm[a] (11 percent)	23[a]	–5	
			Year 3	63 mm[a] (16 percent)	25[a]	40[a]	
			Year 4	73 mm[a] (14 percent)	42[a]	26	
			Year 5	50 mm[a] (10 percent)			
			Year 6	94 mm[a] (10 percent)			
			Year 7	79 mm[a] (17 percent)			
			Year 8	132 mm[a] (25 percent)			
			Year 9	61 mm[a] (9 percent)			
			Year 10	193 mm[a] (32 percent)			
			Year 11	239 mm[a] (35 percent)			
			Year 12	138 mm[a] (21 percent)			
			Year 13	63 mm[a] (9 percent)			
			Year 14	73 mm[a] (28 percent)			
			Year 15	–25 mm (–4 percent)			
			Year 16	–37 mm (–7 percent)			
			Year 17	49 mm[a] (9 percent)			
			Year 18	22 mm (4 percent)			
			Year 19	56 mm[a] (11 percent)			
			Year 20	64 mm[a] (11 percent)			
			Year 21	–28 mm (–7 percent)			
			Year 22	26 mm (6 percent)			
			Year 23	36 mm[a] (6 percent)			
			Year 24	27 mm (3 percent)			

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields: Annual	Growing	Dormant	Reference
					----------mm----------		
Leading Ridge, Pennsylvania Watershed 3	104.0 ha, southeast, silt loams, stony loams, and cobbly loams	Commercial clearcut hardwoods on 44.5 ha with BMPs	Year 1	137 mm[a]	146[a]	–31	Lynch and Corbett 1990
			Year 2	39 mm	27[a]	10	
			Year 3	–61 mm[a]	25[a]	–89[a]	
			Year 4	51 mm[a]	1	60[a]	
			Year 5	–37 mm	–33	–11	
			Year 6	–20 mm	0.5	–20	
			Year 7	17 mm	8	1	
			Year 8	8 mm	2	6	
			Year 9	22 mm	3	7	
Fernow Experimental Forest, West Virginia Watershed 1[d]	29.9 ha, northeast, silt loams	Commercial clearcut hardwoods >13 cm d.b.h., no BMPs employed; 74 percent basal area removed	Year 1 [c]	56 mm[a]	30[a]	26	Kochenderfer and others 1990, Lull and Reinhart 1967
			Year 2	130 mm[a]	107[a]	16	
			Year 3	86 mm[a]	76[a]	19	
			Year 4	89 mm[a]	44[a]	44[a]	
			Year 5	61 mm	2	9	
			Year 6	46 mm[a]	30[a]	29	
			Year 7	36 mm	–25[a]	19	
			Year 8	28 mm	–10[a]	26	
			Year 9	20 mm	8	42	
			Year 10	15 mm	8[a]	8	
			Year 11	13 mm	2	14	
			Year 12		16[a]	7	
			Year 13		14[a]	4	
			Year 14		–4	–0.2	
			Year 15		5	19	
			Year 16		–27[a]	14	
			Year 17		–11[a]	28	
			Year 18		–5	27	
			Year 19		4	15	
			Year 20		3	10	
			Year 25		–10[a]	2	
			Year 30		26[a]	41[a]	

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

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

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

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

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

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

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

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

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields: Annual	Growing	Dormant	Reference
				---mm---			
Coweeta Hydrologic Laboratory, North Carolina Watershed 1[b]	16.2 ha, south, deep and permeable, (texture not reported)	Cove hardwoods deadened 25 percent basal area 1954; clearcut 100 percent basal area, no products removed, slash scattered, partial control burn 1956; planted to pine 1957	Year 1[f]	30 mm			Swank and Miner 1968
			Year 2	<25 mm			
			Year 3	<25 mm			
			Year 4[f]	145 mm			
			Year 5	18 mm			
			Year 6	58 mm			
			Year 7	41 mm			
			Year 8	71 mm			
			Year 9	69 mm			
Coweeta Hydrologic Laboratory, North Carolina Watershed 3[b]	9 ha, south, texture not reported	Clearcut	Year 1	127 mm			Hewlett and Hibbert 1961
Coweeta Hydrologic Laboratory, North Carolina Watershed 6[b]	8.9 ha, northwest, 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 herbiciding subsequent years to control hardwood regrowth; fertilized and limed	First 17 months	74 mm			Hibbert 1969
			Year 1[g]	–17 mm			
			Year 2	47 mm			
			Year 3	64 mm			
			Year 4	147 mm			
			Year 5	149 mm			
Coweeta Hydrologic Laboratory, North Carolina Watershed 7[b]	59.0 ha, south, texture not reported	Clearcut and yarded using mobile cable system; <10 percent of watershed area with soil disturbance	Year 1	260 mm (28 percent)			Swank and others 1982, 1988
			Year 2	200 mm			
			Year 3	170 mm			
			Year 4	120 mm			
			Year 5	40 mm			
			Year 6	40 mm			
Coweeta Hydrologic Laboratory, North Carolina Watershed 10[b]	86 ha, south, texture not reported	Commercial clearcut	Year 1	25 mm			Hewlett and Hibbert 1961

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields: Annual	Growing	Dormant	Reference
					---*mm*---		
Coweeta Hydrologic Laboratory, North Carolina Watershed 13[b]	16.2 ha, northeast, deep and permeable (texture not reported)	Clearcut trees and shrubs, 100 percent basal area cut, no products removed; allowed to regrow	Year 1	367 mm (57 percent)			Johnson and Kovner 1954, Kovner 1956, Meginnis 1959
			Year 2	277 mm (40 percent)			
			Year 3	278 mm (31 percent)			
			Year 4	248 mm (28 percent)			
			Year 5	200 mm (27 percent)			
			Year 6	252 mm (28 percent)			
			Year 7	201 mm (24 percent)			
			Year 8	185 mm (21 percent)			
			Year 9	132 mm (15 percent)			
			Year 10	131 mm (15 percent)			
			Year 11	145 mm (17 percent)			
			Year 12	147 mm (15 percent)			
			Year 13	127 mm			
Coweeta Hydrologic Laboratory, North Carolina Watershed 17[b]	13.4 ha, northwest, deep and permeable (texture not reported)	Clearcut all stems >1.2 cm d.b.h., 100 percent basal area cut; wood products left onsite; little soil disturbance; recut regrowth each growing season for most years during next 15 years	First 6 months	207 mm			Hoover 1944, Johnson and Kovner 1954
			Year 1	425 mm (65 percent)			
			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 Laboratory, North Carolina Watershed 19[b]	28.3 ha, northwest, loams, sandy loams, and sandy clay loams	All laurel and rhododendron on 28.3 ha cut close to ground, 22 percent basal area cut; slash left onsite, little soil disturbance	Year 1	71 mm	49	36	Johnson and Kovner 1956, Meginnis 1959
			Year 2	64 mm	39	15	
			Year 3	55 mm	30	45	
			Year 4	47 mm	20	22	
			Year 5	39 mm	11	26	
			Year 6	31 mm	1	9	
			Year 7		–8		
			Years 1 to 6	4 percent			

continued

Table 6. Water yield responses to harvesting treatments in the Appalachian Mountains (continued)

Location	Area, aspect, soils	Treatment description	Time after treatment	Changes to water yields: Annual	Growing	Dormant	Reference
					mm		
Coweeta Hydrologic Laboratory, North Carolina Watershed 22[b]	34.4 ha, north, texture not reported	All vegetation in alternate 10.1-m wide strip cuts herbicided, 50 percent basal area cut; no products removed	Year 1	198 mm			Hewlett and Hibbert 1961
Coweeta Hydrologic Laboratory, North Carolina Watershed 28[b]	144.0 ha, northeast, deep and permeable (texture not reported)	All trees and shrubs clearcut on 77 ha, cove vegetation thinned on 39 ha 66 percent basal area 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 Laboratory, North Carolina Watershed 37[b]	43.7 ha, northeast, texture not reported	Clearcut watershed, 100 percent basal area cut, no products removed, no roads constructed	Year 1 Year 2 Year 3	264 mm (18 percent) 91 mm (6 percent) 94 mm (6 percent)			Hewlett and Helvey 1970
Coweeta Hydrologic Laboratory, North Carolina Watershed 40	20.2 ha, southeast, texture not reported	Commercial logging, selection cut, 22 percent basal area removed	Year 1	0 mm			Hewlett and Hibbert 1961
Coweeta Hydrologic Laboratory, North Carolina Watershed 41[b]	28.7 ha, southeast, texture not reported	Commercial logging, selection cut, 35 percent basal area removed	Year 1	51 mm			Hewlett and Hibbert 1961

d.b.h. = diameter at breast height; BPMs = best management practices; NS = nonsignificant change indicated, but no value was given.

[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.

[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 U.S. Department of Agriculture Forest Service records.

[e] Significance/nonsignificance information for published growing and dormant season data for this watershed after year 5 was obtained from U.S. Forest Service records.

[f] Year 1 includes deadening, year 4 includes clearcutting.

[g] After grass establishment.

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 year or two 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 half 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 harvesting was not performed on multiple aspects in either location.

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 they might be due at least partially to soil depth, watershed configuration, and aquifer characteristics. 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 Appalachian Mountains are explained primarily by basal area removed—positively related—and incoming energy—negatively related (Douglass 1983, Douglass and Swank 1975). South-facing hillsides receive more radiation year round than north-facing ones, so that changes in ET, and subsequently discharge, after harvesting on the south-facing slopes may not be as dramatic as on north-facing slopes. Sites in the Central Appalachian Mountains may not experience aspect differences because the watersheds are not as steep and do not have as large elevational ranges (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—such as January to April (Hewlett and Hibbert 1961)—because of 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 the majority of their water-yield increases during the late growing season (Hewlett and Hibbert 1961) because reductions in ET 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); understory removal on watershed 19 produced small increases distributed throughout the year (Johnson and Kovner 1956).

At both Leading Ridge and Fernow (table 6), water-yield increases during the first 1 to 3 years after clearcutting predominantly occur during the growing season (Kochenderfer and others 1990, Lynch and others 1972, Reinhart and Trimble 1962, Reinhart and others 1963). 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 preclearcut 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 preharvest conditions in about 5 years, but dormant season yields remained elevated for all but 2 years during 18 years of postharvest 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 Appalachian Mountains (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 preharvest 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/second/km^2 (Johnson and Meginnis 1960). Curve positions for flows ≥55 L/second/km^2 were not shifted during either half or total watershed clearcutting and herbiciding 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/second/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 larger than the small increases to moderate or higher flows. In general, the higher intensity of vegetation removed, the larger the shift in the frequency curve (Reinhart and Trimble 1962) for a given site.

Excluding clearcut watershed 3, table 7 shows that all of the other harvested Fernow watersheds had much higher percentage increases of low flows than Coweeta—this is

Table 7. Flow frequency curve results for the Appalachian Mountains (refer to table 6 for watershed and treatment descriptions)

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

[a] A flow level of 50 percent represents median flow; 84 percent represents the median flow plus one standard deviation; 16 percent represents the median flow minus one standard deviation.
[b] Volume data were determined from contemporary reconstruction of flow frequency curves presented in Reinhart and others (1963).

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, as the Coweeta values represent average responses over 7 years and the Fernow data are average responses over only the first two 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 is expected because of the lower absolute increases observed across the Fernow compared to north-facing Coweeta watersheds.

Supplements to low flows can measurably decrease the number of low-flow or no-flow days in Appalachian headwater channels (table 8). Streams on clearcut and herbicided Fernow watersheds 6 and 7 always dried up for at least a month each year before deforestation; but when each was only half deforested, streamflow never dropped <0.55 L/second/km^2. When each was fully deforested, flows were always ≥3.3 L/second/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/second/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 the first growing season after treatment and 4 to 8 m^3 during the second growing season (Johnson and Kovner 1954). More intensive harvests tend to result in a larger 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 contributes to prolonging ground-water depletion rates during baseflow hydrographs, at least for watersheds subject to intensive harvests (table 9). For example, clearcutting Coweeta watershed 17 resulted in lengthening the time needed for flow to decrease from 20 to 4.7 L/second/km^2 by 25 days (Johnson and Meginnis 1960).

Fewer years of stormflow data and analyses are available for the Appalachian Mountains compared to annual and seasonal analyses. However, the available results

Table 8. Decreases in the number of days during which designated low-flow levels occurred following harvesting in the Appalachian Mountains (refer to table 6 for watershed and treatment descriptions)

Location	Flow level	Time period	Decrease in number of days during which low flow occurred	Reference
	L/second/km²			
Leading Ridge Watershed 2	<7.34	Year 1	40[a]	Lynch and others 1972
		Year 2	5	
		Year 3	61[a]	
		Year 4	46[a]	
Fernow Watershed 1	<3.67	Year 1	72[a]	Reinhart and others 1963, Trimble and others 1963
		Year 2	38[a]	
		Year 3	63[a]	
		Year 4	39[a]	
Fernow Watershed 2	<3.67	Year 1	22[a]	Reinhart and others 1963, Trimble and others 1963
		Year 2	47[a]	
		Year 3	27[a]	
Fernow Watershed 3	<3.67	Year 1	21[a]	Reinhart and others 1963, Trimble and others 1963
		Year 2	14[a]	
Fernow Watershed 5	<3.67	Year 1	5	Reinhart and others 1963, Reinhart and Trimble 1962, Trimble and others 1963
		Year 2	13[a]	
		Year 3	5	

[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.

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 to peakflow rates or stormflow 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 stormflow for the 30 largest storms during the first 4 years after clearcutting (Hewlett and Helvey 1970), so even more extreme 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 stormflows at Coweeta only occur for larger storms, as the moisture storage associated with the deep soils prohibits changes to stormflow 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 preplanning (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 the runoff events that were in the top 23 percent of events were examined. For these high-flow events, growing season peakflows increased 21 percent, and stormflows increased 24 percent; change was minimal annually and almost nonexistent 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, as roads can direct concentrated flow directly to stream channels. The higher the road density and closer the 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 caused by 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 on Fernow watersheds 3 (clearcut) and 6 (clearcut+herbicide). On each of these catchments, average peak discharge during the growing season increased by >300 percent (table 10). Although the 300-percent

Table 9. Changes in depletion times during low flows following basal area reductions in the western North Carolina highlands of the Appalachian Mountains (refer to table 6 for watershed and treatment descriptions)

Location	Flow depletion	Before clearcut	After clearcut	Resulting streamflow increase
		Requirement for depletion to occur		
	L/second/km²	*number of days*		*mm*
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

Source: Johnson and Meginnis (1960).

Table 10. Changes in stormflow volumes and peakflow magnitudes following harvesting for the Appalachian Mountains (refer to table 6 for watershed and treatment descriptions)

		Hydrologic changes						
		Mean peak discharge change			Mean stormflow change			
Location	Time period	Annual	Growing	Dormant	Annual	Growing	Dormant	Reference
Leading Ridge Watershed 2	Years 1 to 3.5[b]	115 L/second/km^2[a] (118 percent)	280 L/second/km^2[a] (351 percent)		0.5 mm[a] (32 percent)	1.7 mm[a] (171 percent)		Lynch and others 1972
Fernow Watershed 1[c]	Year 1[d] Years 1 to 4[d]	4 percent	21 percent	 –4 percent	7 percent	24 percent	 2.5 percent	Lull and Reinhart 1966, Reinhart 1964, Reinhart and Trimble 1962
Fernow Watershed 3	Year 1[e]		300 percent[a]	NS	NS			Patric 1980
Fernow Watershed 6	Year 1[f]		400 percent[a]	NS				Patric and Reinhart 1971
Fernow Watershed 7	Year 1[f]		NS	NS				Patric and Reinhart 1971
Coweeta Watershed 7	Years 1 to 3[g] Years 1 to 4[g]	19 L/second/km^2[a] (15 percent) 17 L/second/km^2[a] (15 percent)			0.3 mm[a] (10 percent) 0.3 mm[a] (10 percent)			Swank and others 1982, 1988, 2001
Coweeta Watershed 13	Year 1	NS			NS			Meginnis 1959
Coweeta Watershed 17	Years 1 to 2	NS			NS			Hoover 1944, Meginnis 1959
Coweeta Watershed 19	Year 1				NS			Johnson and Kovner 1956, Meginnis 1959
Coweeta Watershed 28	Years 1 to 9 Years 1 to 2	 30 percent[a]			17 percent[a]			Swank and others 1988, 2001
Coweeta Watershed 37	Years 1 to 4[h]	65.6 L/second/km^2[a] (7 percent)			5.8 mm[a] (11 percent)			Hewlett and Helvey 1970, Swank and others 2001

NS = nonsignificant change.
[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.
[b] For events with stormflow >0.025 cm. Annual extends from April through November each year. Growing season includes May through October each year.
[c] Significance/nonsignificance information was not provided for this watershed.
[d] For storms >109 L/second/km^2.
[e] After clearcutting.
[f] After full deforestation.
[g] For precipitation ≥2 cm.
[h] For 30 largest events.

Table 11. Changes in hydrograph parameters following harvesting in the Appalachian Mountains (refer to table 10 for information about changes to peakflow magnitudes and total stormflow volumes; refer to 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
		percent		*percent*				
Coweeta Watershed 7[a]	Years 1 to 4	0	10 percent[b]	5[b]	6[b]	11	14 percent[b]	Swank and others 2001
Coweeta Watershed 37	Years 1 to 4	NS	NS	NS				Hewlett and Helvey 1970, Swank and others 1988
Leading Ridge Watershed 2	Years 1 to 3.5[c]	–3 during both growing and dormant seasons	4.2 hr (33 percent)[b] growing season; no change dormant season				2.54 mm[d] (12 percent) annually; 5.08 mm[d] (123 percent) growing season; 1 percent[d] dormant season	Lynch and others 1972

NS = nonsignificant change indicated, but no value was given.
[a] For precipitation ≥2 cm.
[b] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without a [b] are nonsignificant.
[c] April through November 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.

increase on Fernow watershed 3 was significant, it represented only moderate peakflow increases (Patric 1980). Growing season stormflow on Leading Ridge watershed 2 also increased by 171 percent but the increases were associated with storms that produced relatively low initial flow rates (Lynch and others 1972).

Activities applicable to fuels reduction in the Appalachian Mountains 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 Appalachian Mountains are fairly moist (Swift and others 1993), supporting ground conditions that make the severity of fires relatively light even when the burn is high intensity (Van Lear and Kapeluck 1989). After commercial clearcutting—followed by application of high-intensity burning of standing residuals on one plot and felled residuals on another—in South Carolina, soil infiltration rate was not different from the unburned clearcut plots (179 cm/hour): 183 cm/hour for the standing-residual plot and 157 cm/hour for the felled-residual plot (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 soils hydrophobicity did not develop (Van Lear and Kapeluck 1989).

Swift and others (1993) also found that soils did not become hydrophobic after a low-intensity fire that followed felling (both overstory and understory) and burning on a poor-quality site in western North Carolina. Humus as well as some charred litter was 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 as overland flow showed no evidence of increasing. The lack of change to soil infiltration allowed soil moisture levels to increase in late summer immediately after harvesting in the top 60 cm of soil and even somewhat farther in autumn 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 what they had been the previous summer and autumn. 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 that streamflow in Piedmont watersheds can be highly responsive to even moderate changes in the other variables of the water balance equation (equation 1).

Hewlett (1979) found that clearcutting 32 ha of loblolly pine (*Pinus taeda*) in the Georgia Piedmont followed by double roller chopping increased water yields by 254 mm the first year after harvest and site preparation, and 126 mm the second year (table 12). Similarly, after harvesting and site preparation using a KG blade and discing in North Carolina, average runoff increased 345 mm the first year and >200 mm in both the second and third years (table 12). Replanting with grass following those same treatments apparently influenced infiltration and ET substantially, because runoff was 6 to 7.5 times less during those same 3 years on planted plots (Douglass and Goodwin 1980). Employing shearing without discing resulted in runoff values that were between the other two treatments, but generally closer to the lower end values for planted grass.

For considerably 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 harvesting (Van Lear and others 1985). However, harvesting coupled with a high-severity burn in Georgia is believed to have increased runoff, even though it was not measured directly (Van Lear and Kapeluck 1989). After treatment the 0.35-ha watershed developed a network of gullies, which acted as channels. These apparently were intercepting and conveying significant amounts of soil water or local ground water or both, because the gully sides were eroding—in part, because of flowing water. The gullies were expected to continue to grow in length and width for several years. Although infiltration also was not measured, the authors discounted the probability that a hydrophobic layer had formed based on other fire/soil research results.

By contrast, very temporary hydrophobic conditions—only a few minutes in duration—were observed during simulated rain applications to plots that were cut and burned (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/hour). Plots with 10- and 20-percent slopes also displayed hydrophobicity, but the runoff from the same rain intensity during the initial period of water repellency was much less. Average 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/hour), 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.

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
				mm	
North Carolina [a]	0.25 to 0.75 ha, aspect not given, sandy clay loams, sandy clays, clay loams	Site preparation using KG blade shearing, windrowing, burning, and disking; 4 replicated watersheds	Year 1 Year 2 Year 3	345 242 223	Douglass and Goodwin 1980
	0.43 to 0.62 ha, aspect not given, sandy clays, sandy clay loams, clay loams, sandy loams	Site preparation using KG blade shearing, windrowing, burning; 4 replicated watersheds	Year 1 Year 2 Year 3	70 142 71	
	0.33 to 0.53 ha, aspect not given, clay, sandy clay loams	Site preparation using KG blade shearing, windrowing, burning, discing, planting to grass; 4 replicated watersheds	Year 1 Year 2 Year 3	46 40 35	
Georgia [a]	32.4 ha, southwest, loam overlaying sandy loam	Harvest, roller chop twice	Year 1 Year 2	254 126	Hewlett 1979, Hewlett and others 1984

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

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 increased average peak discharge by 150 percent and doubled average stormflow (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/second/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 in wet antecedent conditions were most susceptible to change, increasing as much as 35 to 50 percent during large events (Hewlett 1979), whereas stormflows in moderate-to-dry antecedent conditions were

Table 13. Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the South Carolina Piedmont (Douglass and others 1983)

			Hydrologic change		
Area, aspect, soils	Treatment description	Time period	Mean peak discharge	Mean stormflow	Other parameters
		months	--------------------*percent*-------------------		
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	55 to 60 [a]	Increased significantly	Nonsignificant change in time to peakflow and event length
1.1 ha, aspect not given, sandy loam overlaying clay	One watershed with 3 consecutive years of control burns, then clearcut pine, slash bladed off with bulldozer	First 21	150 [a]	100 [a]	

[a] Indicates a statistically significant change at the alpha level used by the original authors.

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 pretreatment (Hewlett and Doss 1984). On four 1-ha watersheds in the upper Piedmont of northern Georgia, clearcutting overstory vegetation after ground herbiciding 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 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, and the Midsouth States (Arkansas, Texas, Mississippi, and Louisiana) generally are wetter in the dormant season and drier in the growing season (Langdon and Trousdell 1978). Hydrology is expressed in terms of water-table levels or surface flows or both. Water-table measurements are most common in the flatter terrain of the lowlands (Grace and others 2003), although surface flows also can be present—particularly in artificial 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 1983a). In these situations, outflows are very strongly dependent 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 more topographic relief exists.

Increases in water-table levels are the most common hydrologic responses reported following harvesting of the 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 the first 2 to 3 years after harvesting or longer (table 14). They are short lived (table 14) because revegetation is very rapid in these warm, long growing seasons (Beasely and others 1986) and reductions in ET control water-table fluctuations (Amatya and others 2006b, Aust and Lea 1992, Riekerk 1989, Xu and others 1999). ET 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 ET would be most marked (Grace and others 2006; Lockaby and others 1997c; Xu and others 1999, 2000).

Even though ET reductions are responsible for creating postharvest 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 highest and most easily detectable during dry years or periods when they 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 (*Pinus palustris*) or loblolly pine and mixed hardwoods were harvested, Williams and Lipscomb (1981) reported that the longleaf and loblolly dominated plots had similar average first-year water-table rises (table 14) after the lightest cuts (18 percent of basal area) and the heaviest cuts (67 percent of basal area). Not much 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 1983a, Williams and Lipscomb 1981). The presence of more wet days in winter and early spring of one year resulted in only half the water-table increase (61 mm),

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

[a] Significance/nonsignificance information was not provided for these sites.
[b] Plus one standard deviation.

compared to drier conditions of the same time period 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 and/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). The average water-table increase (table 14) during the year after harvesting in wet conditions was 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). 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 to 32 cm/hour 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 larger on damaged, better drained soils than on damaged, poorly drained soils. However, better drained soils typically have longer periods of drier conditions and shallower damage, making any needed mitigation easier to accomplish (Aust and others 1995).

Some forest management practices have resulted in lowering water-table levels. Both conventional bedding and mole-plow bedding site preparation in poorly drained soils in South Carolina reduced water-table depths by nearly equal amounts (~150 to 180 mm) for about 2 years following site preparation, compared to nonbedded harvested sites (Xu and others 2000). 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 (for example, ~0.2 m) beneath harvest blocks than outside the harvest boundaries in July; 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 or higher temperatures (or both) in cut areas, even though only modest soil temperature increases of 2 °C to 4 °C have been reported in clearcuts elsewhere in the Coastal Plain (Aust and Lea 1991, Messina and others 1997).

Outflow and streamflow increases after 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 ET (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 conducted. Summer and others (2006) noted that streamflow increased significantly after clearcutting and thinning of the streamside zone in two watersheds in southwestern Georgia, but the amount 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 because harvest-only studies are lacking for 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 1983b).

Clearcutting followed by intensive mechanical site preparation that included shearing on three watersheds in southeastern Arkansas increased first-year water yields by

122 mm (table 15)—a thirteenfold 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 average annual water yields fivefold, but the absolute 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 eastern Texas; harvesting with roller chopping at the same Texas site resulted in outflows, 57 mm, that were only slightly larger than outflows from harvesting and deadening in Arkansas (41 mm) (table 15). In an analysis of harvesting followed by two levels of site preparation—minimum disturbance (clearcutting pine, roller chopping, bedding, and planting) and maximum disturbance (clearcutting pine, stump removal, burning, windrowing, harrowing, bedding, and planting)—in Florida, the maximum intensity treatment resulted in significant

Table 15. Changes to annual outflow or stream discharge following harvesting and site preparation in the Coastal Plain

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

[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.
[b] Significance/nonsignificance information was not provided for this site.

first-year outflow increases of 150 mm (150 percent) compared to a nonsignificant 30-mm increase (23 percent) from the minimum intensity treatment (table 15). The maximum treatment left almost no residual vegetation, but the minimum left some intact vegetation and allowed sprouting (Riekerk 1983b). Overall, increases to first-year outflows for the maximum-disturbance watershed 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, 1983b). By contrast, most of the first-year increase in outflows from the minimum-disturbance watershed was primarily from precipitation during one wet month; other increases that contributed to the first-year augmentation were small, intermittent, and strongly dependent on 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 a year after site preparation—shearing, burning, and bedding—applied 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 (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 reestablished ET rates, which reduced soil moisture storage.

Prescribed burning, regardless of whether it is 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 South Carolina did not increase streamflow (Amatya and others 2006a). Burning an additional 60 percent of the watershed over the next 3 years also did not increase streamflow. A later prescribed fire covering 84 percent of the watershed was followed by an increase in outflow of 64 percent in the first year and 70 percent in the second year after burning, 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 caused by the combination of reduced ET 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 biennial burning on sandy loam plots, or by biennial burning for 10 years, or annual burning for 10 years in silt loams plots supporting longleaf pine (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 hardwood-dominated 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 after 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 South because surface flows tend to be ephemeral or intermittent at best, and typically storm driven. However, examination of flow frequencies from a study of harvesting plus maximum site preparation (Riekerk 1983b) showed that the resulting water-yield increases, which were only 2.54 mm of daily flow, came primarily from intermediate-sized 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 larger increases in stormflow and peakflow compared to other clearcutting and site-preparation techniques (table 16). In eastern Texas, the first-year increase was 49 L/second for peakflow and 146 mm for stormflow (Blackburn and others 1986), compared to

Table 16. Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the Coastal Plain

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

continued

Table 16. Changes in stormflow volumes and peakflow magnitudes to harvesting treatments in the Coastal Plain (continued)

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

BMPs = best management practices; d.b.h. = diameter at breast height.
[a] Indicates a statistically significant change at the alpha level used by the original authors. Unless otherwise indicated, values without an [a] are nonsignificant.
[b] Significance/nonsignificance information was not provided for these sites.

14 L/second for peakflow and 125 mm for stormflow in southeastern Arkansas (Beasley and Granillo 1983, 1988). Peakflows and stormflow volumes remained somewhat elevated for several more years, but these later year increases typically were much less than the first-year increases (table 16). Although 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) various site-preparation techniques produced minimal differences in stormflow (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).

Herbiciding to kill the overstory in the Upper Coastal Plain in Mississippi (Ursic 1970, 1982) had larger effects on peakflow the first 3 years than did harvests with intensive site preparation (Beasley and Granillo 1983, 1988, Blackburn and others 1986; table 16). However, the watersheds on which the herbicides were applied were very small (each ~0.86 ha), and small watersheds have less moisture storage capacity, particularly if the soils are shallow; this can result in large responses to a given disturbance (Douglass and others 1983, Van Lear and others 1985). Where clearcutting was followed by herbiciding on 7.9- and 8.5-ha watersheds, the peakflow and stormflow responses were small or were (most often) less than predicted (Wynn and others 2000), particularly from the combination of herbiciding 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 herbiciding (Beasley and Granillo 1983, Blackburn and others 1986). In steeper Coastal Plain terrain, 33 to 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 of these Coastal Plain watersheds, only 1 to 3 percent of precipitation became stormflow (Beasley 1979, Beasley and Granillo 1983, Blackburn and others 1986).

Comparisons among Physiographic Areas

Forest hydrology research related to stream responses from harvesting has been ongoing for at least a half century in parts of the Eastern United States (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 (Shepard and others 1993). One of the oldest wetland studies focusing on harvesting effects on water-table levels in the Eastern United States is from the Marcell Experimental Forest in northern Minnesota (Verry 1981). Studies of wet, flatlands in the South are much more recent—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 because ET losses from the watershed have decreased. Because forest ET 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 aquifers or streamwater. Conversely, if soil moisture is very high in the growing season and precipitation remains above normal, water yields or water-table levels on harvested and unharvested sites may not differ much, 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 larger hydrologic changes than understory removals, probably because the higher leaf area indexes of overstory trees promote faster transpiration and more interception of water. But when understory vegetation comprises a substantial percentage of the basal area removed (Johnson and Kovner 1956, Meginnis 1959), hydrologic changes are observable, although they tend to be much smaller and shorter lived than those occurring with heavy or complete reductions in overstory vegetation. Overall, literature on eastern landscapes 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 larger number of hydrologic studies involving clearcutting or clearcutting+site preparation makes these the most useful for comparing responses across landscapes.

Although data from the North Central States are limited (table 2), they suggest that water-table elevations increase much less in response to harvesting than in the Coastal Plain (table 14); although in the Coastal Plain, additional disturbances associated with site preparation often accompany harvesting. The difference is attributable to the higher ET rates in the Coastal Plain. Net radiation is low in northern latitudes because cold soils act as sinks for heat. Because ET is dependent on net radiation, transpiration rates are lower in the North (Verry 1997), which contributes to smaller water-table changes from harvesting. ET from peatlands in the Marcell Experimental Forest averaged 63 percent (50.5 cm) of precipitation (Verry and Timmons 1982), compared to as much as 60 to 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, harvesting almost always led to an increase in water-table elevations. Lockaby and others (1994, 1997b) and Xu and others (2000) were the exceptions to this finding. They reported decreases in water-table elevations in the Coastal Plain, which they attributed to increasing wind exposure and ground temperatures after harvesting. In wetlands of the North Central States, Verry (1981) reported similar decreases in water tables during dry years following harvesting, which was attributed to higher 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 the Coweeta studies in the Southern Appalachian Mountains. In general, discharges from northern aspects following clearcutting exceeded those found elsewhere in the Eastern United States. However, despite the colder climate and lower ET rates (450 mm) in the Northeastern States (Likens and Bormann 1995) compared to 704 mm in the Southern Appalachian Mountains (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 mountains were similar to those from clearcutting watersheds in the central mountains and clearcutting uplands in the North Central States (tables 6 and 2). Northeastern responses were similar to these levels (tables 2 and 6) only when partial cutting was employed (table 3).

Annual discharges from clearcutting and site preparation in the Ozark Mountains and Ouachita Plateau(which used stormflow totals because the monitored streams are ephemeral) are comparable to those from the Central Appalachian Mountains, south-facing slopes in the Southern Appalachian Mountains, and the North Central States (tables 2, 5, and 6). However, because streamflow comes as stormflow in this area, the increases are expressed during much shorter periods than in the Appalachian Mountains 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 (table 5) compared to those for the Appalachian Mountains (table 10). Note that the watersheds treated in Ozark and Ouachita studies tend to be much smaller than those elsewhere in mountainous areas; thus, although depth (mm) is comparable across sites, the total annual runoff volumes (L) from the Ozark Mountains and Ouachita Plateau are much smaller.

In the few available Piedmont studies that involved site preparation following clearcutting, annual discharge varied tremendously (table 12). Runoff ranged from values similar to high-end values in the Southern Appalachian Mountains to low-end values reported elsewhere in the Central Appalachian Mountains (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 (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 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, ET, land cover, and topography) in the Eastern United States to influence outflow and streamflow responses (Amatya and others 2006a, Douglass and others 1983, Grace 2005, Miwa and others 2003, Riekerk 1983b, Young and Klawitter 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 result of on-the-ground activities, not the purpose of the activities. As noted previously, the majority of available studies have involved harvesting intensities that far exceed what would be done during typical fuel management in forests, with the exception of 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 what would be expected 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 (Douglass and Van Lear 1983, Van Lear and others 1985). Overstory removal will reduce only the interception component of ET, which has been reported to range between 10 and 26 percent of annual precipitation in eastern landscapes, depending on species and stand age (Helvey 1967, Lull and Reinhart 1966, Swank and others 1972). But because these data are for trees with leaves, the crown condition of the overstory prior to removal (such as salvage logging) will determine the importance of interception. Interception will not go to zero after harvesting, however, 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 removals produce measurable changes in annual water yields (Hornbeck and Kochenderfer 2001, Hornbeck and others 1997). Fuel reductions for the sole purpose of fire suppression (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 situations, and changes that did occur should be short lived, particularly in forests of the South, as changes there usually last only a year or two. This is fortuitous, because the Coastal Plain and lower Piedmont are the areas 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 eastern landscapes (Van Lear and Harlow 2002).

Overall, where hydrologic responses of prescribed fires have been studied in the Eastern United States, they have resulted in 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 layer are completely combusted and soil becomes exposed (Wells and others 1979). Reductions in infiltration rates in the Eastern United States appear to be caused primarily by pore clogging from fine soil particles once soil is exposed (Arend 1941, Wells and others 1979) rather than by physicochemical changes to soil that result in water repellency (DeBano 1966); this is because hydrophobicity is rarely reported and very short lived in the Eastern United States.

Particular care should be taken when burning in the Piedmont, as this area is perhaps the most susceptible to major hydrologic changes from soil disturbance. Relatively dry soils from warm temperatures, coupled with thin organic layers overlaying thin soils, can make this area more susceptible to gullying and erosion than the steeper areas that are typically thought to be 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 undertaken when applying 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 burning them produces much higher soil temperatures than burning dispersed materials (Cromer and Vines 1966, Robert 1965, Well and others 1979). These activities increase the probability that soil will be negatively affected 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 acceptable levels.

Soil disturbance by new fire line construction may be one of the biggest long-term impacts of fuel-reduction activities. Hand-constructed firebreaks will have little if any effect because litter can quickly be restored to the surface from wind action or annual leaf fall or both. Soil infiltration rates also should not be substantially affected by hand-constructed fire lines. By contrast, mechanically constructed fire lines such as bulldozed lines are more like roads, or at least skidroads, 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. Although fire lines lack the repeated trafficking that roads have and tracked equipment that often is used to construct fire lines exerts lower pressure compared to 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. Fire lines often are subjected to all-terrain and other vehicle use during prescribed fires, which can result in further compaction. Therefore, the same care needed for planning and constructing and closing roads 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 if the landscape is reforested and not converted to another use. The primary hydrologic cumulative effect from harvesting that has been raised as a possible concern is downstream flooding, which results from simultaneous accumulation of large volumes of water from upstream sources (Hewlett 1982). But even in watersheds where vegetation removal has been substantial, 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 Eastern United States occurs during growing seasons or low flows (or both), 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 fuels reduction practices in the Eastern United States. This approach was needed because information specifically pertaining to fuels reduction is largely missing from the literature. Most of the available investigations have involved much larger reductions of ET than would occur for controlling fuels, so we predominantly have information about upper end or "worst case" effects. However, from the standpoint of being able to accurately describe and disclose expected effects in environmental documents required by the National Environmental Policy Act and other legislation, studies are needed that specifically focus on fuel-reduction activities and their effects on soil and water resources. The public would be better served if the data used in these environmental documents directly applied to the proposed activities, so that direct and cumulative effects could be more accurately evaluated.

Furthermore, our knowledge about the effects of controlled burns is extremely limited, despite the fact that burning is becoming an increasingly used management tool. Controlled burns in forests usually are applied to reduce dead, downed fuels and possibly to 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 postharvesting site preparation; if so, the effects would likely 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 replicated studies. It is now particularly important to perform these types of studies for several reasons: there is new interest in employing 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; repeated burning is being used or considered for a variety of uses (Bowles and others 2007); and burning is being considered for application where it has long been excluded, which can result in severe initial burns (Knapp and others 2007). These new applications may have effects that are measurably different from what one might expect based only on currently available, sparse datasets.

Conclusions

The initial foundation of what we know about forest management effects on water balance and overall hydrologic expression in the Eastern United States comes primarily from studies at Coweeta Hydrologic Laboratory and Fernow Experimental Forest. These sites have the most comprehensive sets of long-term hydrologic 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.

Although biological, physical, and climate conditions are quite varied throughout the Eastern United States, the similarity of results among study sites is striking. In general, water-yield increases from reducing vegetation do occur when the level is >20 to 25 (approximately) percent of the watershed basal area. Larger percentages of basal area removal result in proportional increases in annual water yield, 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-sized 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 mountains that are less steep or forests with lower topographic relief. The timing of the spring snowmelt hydrograph can be changed by varying the size of harvested sites and the character of the opening and associated regeneration. Wetland soil characteristics in both the most northern or southern landscapes play a large role in controlling how hydrologic responses will be expressed in flatlands: whether hydraulic conductivities are rapid or slow largely determines the degree of influence of ET on water-table levels. On steep hillsides, the extent of water delivery to channels is at least partially dependent on the characteristics of the channel network, such as density, length, and degree of incision. These and other commonalities among vastly different physiographic areas illustrate the broad transferability and application of findings, particularly once one adjusts for differences in precipitation, climate, topography/relief, soils, and species composition.

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