Cumulative Watershed Effects of Fuel Management in the Western United States

Chapter 7.

Fuel Management and Water Yield

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Introduction

There have been numerous studies worldwide demonstrating that changes in forest density can cause a change in water yield. Bosch and Hewlett (1982), Hibbert (1967), Stednick (1996) and Troendle and Leaf (1980) have summarized the findings from most of these studies. In general, as Hibbert (1967) observed, reducing forest cover increases water yield; establishing forest cover on sparsely vegetated land decreases water yield; and response to treatment is highly variable and, for the most part, unpredictable.

Although the first two of these conclusions are still accepted, the hydrologic response to changes in forest cover, although variable, is more predictable than Hibbert (1967) concluded (Bosch and Hewlett 1982; Stednick 1996; Troendle and Leaf 1980). This change in thinking results from the increased number of observations available with each successive review and an improved understanding of the factors influencing streamflow response. Streamflow response to a change in forest cover is strongly related to climate, species composition, and the percentage change in vegetation density (fig. 1). The data from 95 watershed experiments conducted in the United States show that, on average, annual runoff increases by nearly 2.5 mm for each 1 percent of watershed area harvested (Stednick 1996). Because runoff is quite variable from year

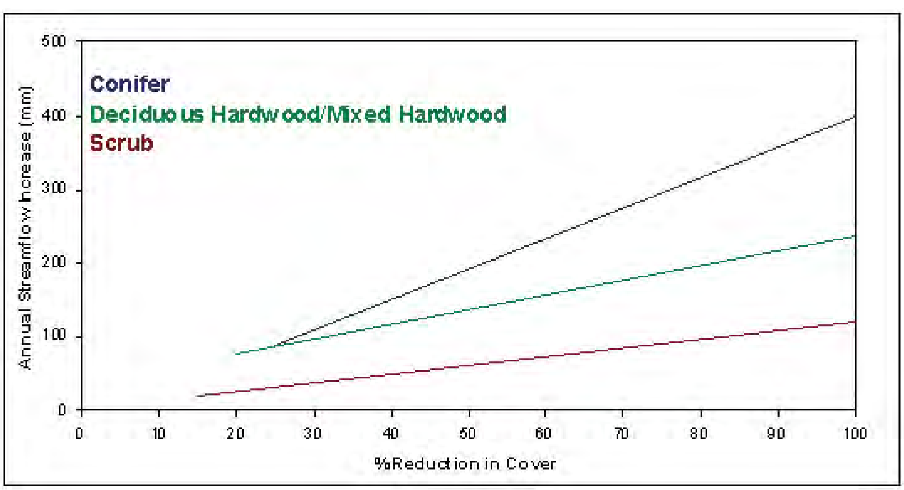

Figure 1. The relationship between reduction in vegetation cover and increases in stream flow for three vegetation types (redrawn from Bosch and Hewlett 1982).

to year, the general conclusion is that approximately 20 percent of the basal area of the vegetation must be removed before a statistically significant change in annual runoff can be detected (Bosch and Hewlett 1982; Hibbert 1967; Stednick 1996). However, as Bosch and Hewlett (1982) suggest, reductions in forest cover of less than 20 percent (fig. 1), particularly in more humid areas, may well produce statistically non-significant increases in streamflow that would presumably decrease to zero increase in streamflow at zero reduction in forest cover.

Much of our understanding about the effects of forest disturbance on water yield has come from paired watershed experiments. Unfortunately, very few of these catchment-scale experiments provide data on the hydrologic response to fuel reduction since the vast majority of the treatments imposed a partial or complete clearcutting of the mature trees rather than a partial cut or thinning (Stednick 1996). Hence, much of our understanding of the hydrologic impacts of thinning and prescribed fire comes from inference supported by various plot and process studies.

Objectives

This chapter has three objectives pertaining to the effects of fuel management on water yield:

1. Determine whether regionalization can help reduce the variability in treatment response that made streamflow change unpredictable according to Hibbert (1967).
2. Assess the effect of forest disturbance on each component of the water balance—interception and evaporation, transpiration, infiltration, and storage—and use this to help infer how fuel reduction treatments may impact annual water yields as well as peak and low flows.
3. Identify tools that can help hydrologists and land managers predict both the on-site and cumulative changes in water yield that may result from vegetative treatments.

Hydrologic Impact of Forest Disturbance on Streamflow Characteristics

Regionalization of Hydrologic Response

The hydrologic cycle represents the processes and pathways involved in the circulation of water from land and water bodies to the atmosphere and back again. An understanding of the hydrologic cycle is fundamental to understanding the effects of different forest practices on key components of the water balance, including soil moisture and streamflow. The hydrologic cycle is often expressed in the form of a water balance or continuity equation:

$$\text{Runoff} = \text{Precipitation} - (\text{Evaporation} + \text{Transpiration Loss} \pm \text{Change in Storage}) \quad (1)$$

Precipitation can be in the form of rainfall, snowmelt, or fog drip; evaporation includes evaporation from both the soil and the surface of plant canopy and litter (interception loss); and change in storage includes soil moisture and groundwater. Evaporation and transpiration are usually regarded as losses and reduce the amount of precipitation that is transformed into runoff. Changes in storage can be very important over short time periods (in other words, seasonal or less than 1 year), but are generally assumed to be zero over long periods unless there is continuing groundwater extraction.

Although the components of the hydrologic cycle are always the same, the relative importance of each component can vary considerably with geographical location and from season to season. The complex interactions between climate and vegetation

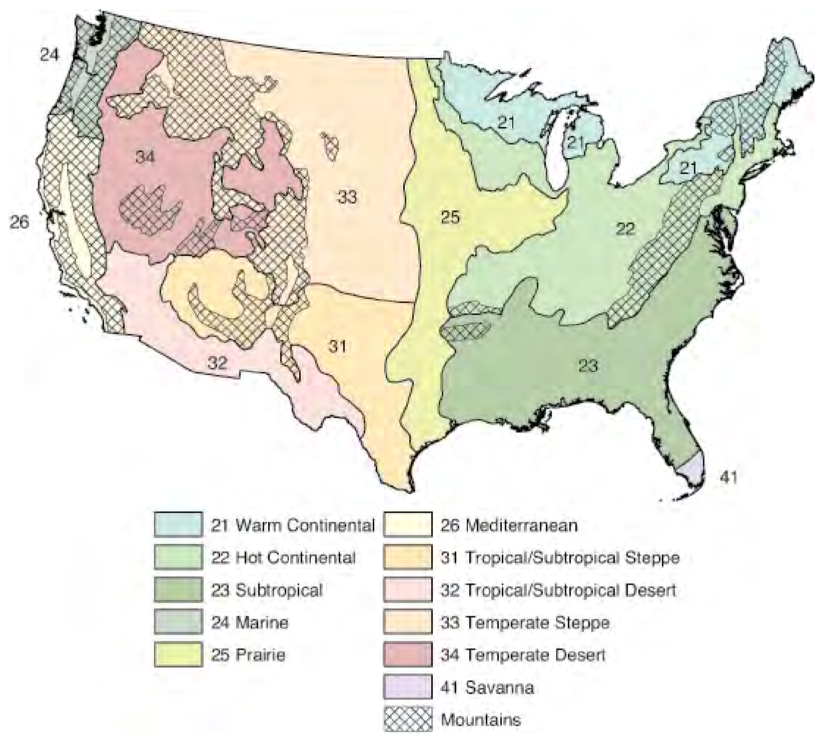

Figure 2. Ecoregion classification based on Bailey (1994).

control the role that the individual components play in the water balance and the influence that forest disturbance has on the water balance.

In the mid-1970s, Bailey (1976, revised 1994) developed an ecoregion map of the United States that depicted the relationship between vegetation patterns, climate, and landscape or topography (fig. 2). Vegetation types with similar moisture and energy requirements were found to be present in reoccurring patterns within and between ecoregions for given site conditions. Differences in vegetation patterns between ecoregions were primarily influenced by differences in the amount and seasonal distribution of water and energy. Precipitation and energy are largely controlled by elevation, latitude, aspect, topography, prevailing wind direction, and proximity to oceans, and the balance between precipitation and energy are the primary controls on streamflow. The concepts used in developing the ecoregion classification for the United States (Bailey 1976) have been successfully applied to North America (Bailey and Cushwa 1981) and the rest of the world (Bailey 1998). Ecoregion classification provides a useful framework for stratifying hydrologic response and predicting the effects of vegetation manipulation on water yield.

In the late 1970s, the ecoregion concept (Bailey 1976) was used to stratify the United States into seven hydrologic regions (fig. 3) in order to better predict the effects of silvicultural activities on non-point source pollution (EPA 1980). The resulting handbook, *An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources*, is commonly referred to as WRENSS. This contained graphical procedures, stratified by region, to predict the effects of forest disturbance on streamflow, erosion, temperature, and nutrients. The same hydrologic regionalization is being used here to help understand and predict the effects of forest disturbance, including fuel reduction treatments, on annual water yield, peak flows, and low flows.

This chapter will emphasize the hydrologic effects of fuel reduction treatments in the Rocky Mountain region (WRENSS Hydrologic Region 4 in fig. 3) for the following reasons. First, this synthesis focuses on the western United States. Second, more than 50 percent of all National Forest System lands are contained within the Rocky Mountain region, and excessive fuel loadings and departures from historical ecological conditions are particularly severe (Romme and others 2003). These factors mean that fuel reduction programs are most likely to be concentrated in this region.

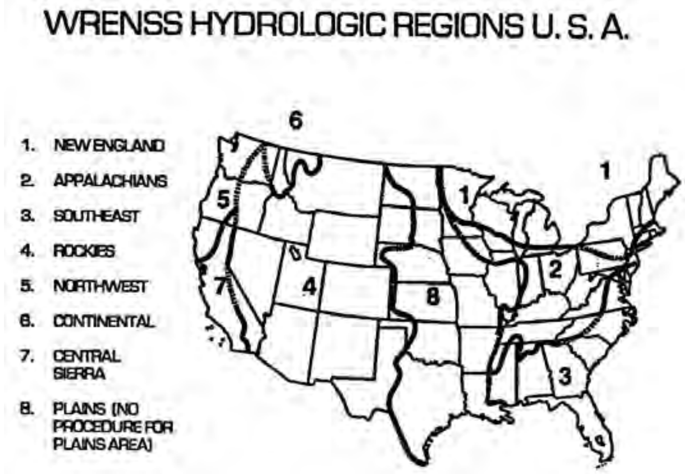

Figure 3.The United States divided into seven hydrologic regions (see Troendle and Leaf 1980).

In addition, the hydrologic effects of fuel treatments are potentially more important in this region because possible changes in water yield may be more important and longer-lived than in other regions. From a process standpoint, the Rocky Mountain region provides examples of how vegetation management strongly influences snowpack accumulation and melt as well as summer evaporation and transpiration. This means that the processes being discussed here will cover the key processes for nearly all forested areas in the United States, even though the relative magnitude will vary by region. This chapter first discusses and explains the observed variations in the hydrologic responses to forest disturbance in the Rocky Mountain region, uses these observations to predict the likely effects on fuel reduction treatments, and then compares these responses to the potential hydrologic responses that may occur in other ecoregions in the western United States.

Water Yield

Numerous publications have quantified the effects of forest disturbance on streamflow in different regions of the United States (for example, Brown and others 1974; Debano and others 2004; Douglas 1983; Gary 1975; Harr 1983; Hornbeck and others 1997; Kattleman and Ice 2004; Keppeler and Zeimer 1990; NRC 2008; Reinhart and others 1964; Troendle and Leaf 1980; Troendle 1983). These studies have shown that the magnitude of change in water yield is most strongly related to the amount of precipitation and the proportion of forest cover that is removed. The increases in flow following forest disturbance can be quite large in the humid southeast, northeast, north central, and northwest regions of the United States. In contrast, increases in water yield due to removing woody vegetation are an order of magnitude smaller in drier areas such as the Southwest. The effect of a decrease in forest density on water yield can occur regardless of whether this is due to disturbance from fire, insects, disease, or timber harvest. Afforestation or an increase in forest density generally has the opposite effect on water yield than does forest removal.

The magnitude of the hydrologic response to disturbance between years will depend on the summed effect of the changes in processes as indicated by equation 1. These include the degree to which the management activity alters net precipitation to the soil by altering interception losses and infiltration characteristics and the soil moisture evaporation and transpiration. The timing of a change in streamflow within a year depends on when precipitation or snowmelt exceeds both evapotranspiration demand and soil moisture recharge requirements. Hence, any effort to predict the effect of forest disturbance on water yield requires an understanding of how the disturbance affects the water balance with respect to the amount and timing of precipitation inputs (whether there are changes in flow pathways) and the degree to which soil moisture storage and recharge requirements have been altered as a result of changes in evaporation and transpiration.

Rocky Mountain Region

The Rocky Mountain region is fortunate to have a long series of carefully controlled paired watershed experiments to evaluate the effects of forest harvest on water yield. Worldwide, the first such experiment was conducted at Wagon Wheel Gap in south-central Colorado on the headwaters of the Colorado River (Bates and Henry 1928; Troendle and King 1987; Van Haveren 1988). This study was followed by a series of watershed studies in the region (Hoover and Leaf 1967; Stednick and Troendle 2004; Troendle and King 1985, 1987; Troendle and Leaf 1981), but the longest running and most detailed study has been conducted on the Fool Creek watershed on the Fraser Experimental Forest in central Colorado (Hoover and Leaf 1967; Troendle and King 1985).

The results of the Fool Creek study are presented in more detail because this is the longest and most comprehensive study in the Rocky Mountain region, and the process-based understanding developed at Fool Creek applies throughout the snowmelt dominated Rocky Mountain region. Mean annual precipitation at Fool Creek is about 760 mm per year while annual evapotranspiration ranges from 450 to 570 mm per year (Troendle and King 1985). At a nearby study site, the average annual evapotranspiration (ET) is directly proportional to precipitation once precipitation exceeds 462 mm (18.2 inches) (Troendle and Reuss 1997).This relationship can be expressed by:

$$ET_{mm} = 462mm + 0.284\ (Precipitation_{mm} - 462mm) \qquad (2)$$

Annual water yields from the Fool Creek watershed were calibrated against East St. Louis Creek for a 15-year period. From 1954 to 1956, approximately 40 percent of the Fool Creek watershed, or 50 percent on the commercially forested area, was clearcut in alternating cut and leave strips. Comparison of the mean annual hydrographs for the 15-year calibration period and the first 15 years after harvest clearly shows that, on average, forest harvest increased both annual and peak flows (fig. 4). Numerous other studies have shown that the changes in runoff shown in figure 4 are typical of the effect of forest disturbance in the cold snowmelt region typical of the Rocky Mountains (Bates

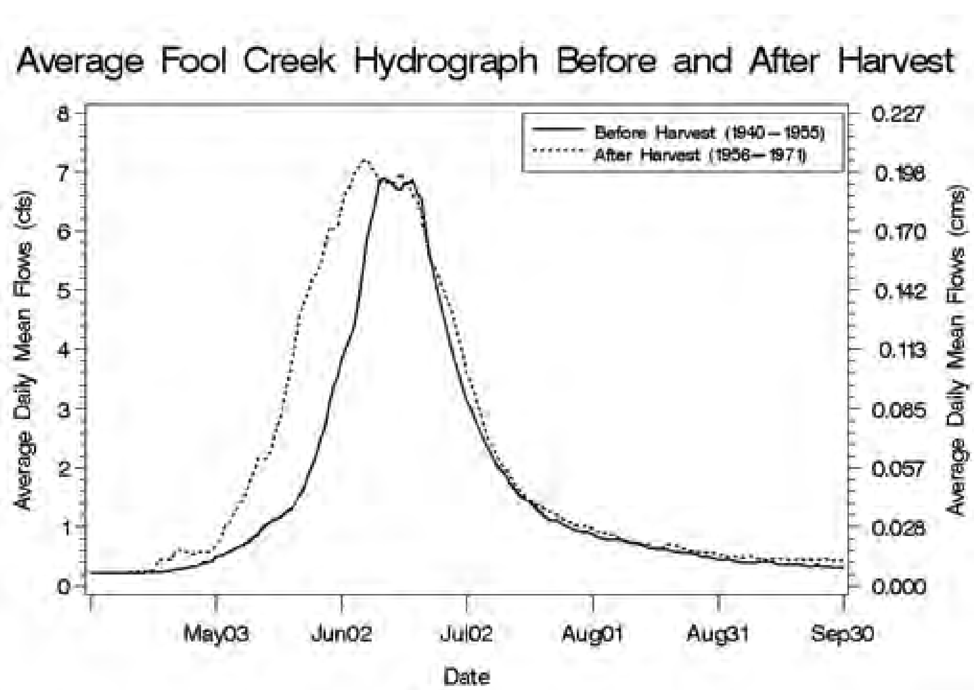

Figure 4.The average hydrograph from the Fool Creek Watershed for the 15-year period both before and after treatment.

and Henry 1928; Swanson and Hillman 1977; Swanson and others 1986; Troendle and Bevenger 1996; Troendle and King 1987; Troendle and Reuss 1997).

Within the first 15 post-treatment years, the observed increases in annual water yield have ranged from a high of 16.2 cm in the wettest year to a low of 3.6 cm in the driest year. The "average" first-year response to the treatment on Fool Creek was equivalent to a 10.0 cm increase in seasonal water yield (Troendle and King 1985). During the 1956 to 1983 post treatment period, on average, these increases are due to the 50 percent reduction in the annual ET that would have occurred on the clearcut portion of the watershed (Troendle and King 1985; Troendle and Reuss 1997). By 1983, 28 years after harvest, regrowth in the clearcuts was causing a significant decline in the average annual water yields.

A month-by-month analysis showed that significant increases in flow occurred primarily in May with only an occasionally significant increase in June. No detectable impact has been documented on flows from July to October (Troendle and King 1985). There is little opportunity for measurable increases in water yield to occur during most of the growing season because summer evapotranspiration is limited by the amount of available water. The high summer water deficit explains why, on average, less than 5 percent of summer rainfall is transformed into streamflow (Bevenger and Troendle 1987; Garstka and others 1958; Troendle and King 1985) and the reduction in summer evapotranspiration does not detectably increase summer or fall streamflow.

The observed changes in the cold snow zone's water yield after forest removal are due to both a decrease in winter interception and a reduction in growing season soil moisture depletion (Dietrich and Meiman 1974; Goodell and Wilm 1955; Potts 1984b; Troendle 1987, 1988; Troendle and Meiman 1986; Troendle and Reuss 1997; Wilm and Dunford 1948). In the cold snow zone, such as at Fool Creek, precipitation accumulates over the winter as snow pack, with minimal melt over this accumulation period. When the snowpack begins to melt in spring, the melt water first recharges the soil by replacing the water that was depleted during the previous growing season. Once soil moisture storage is filled, the excess meltwater is available to become streamflow. At Fool Creek, which is comprised mostly of east- and west-facing slopes, approximately 30 percent of the increase in water yield can be attributed to the decrease in interception and resultant increase in the amount of water contained in the snowpack. The reduced evapotranspiration during the previous summer also reduces the amount of meltwater needed for soil moisture recharge in the clearcut. This process accounts for approximately 50 percent of the increase in water yield. The remaining 20 percent of the observed increase in water yield results from the reduction in evapotranspiration losses during April and May (Troendle and King 1985).

On north-facing slopes, the reduction in winter interception losses can account for more than 50 percent of the increase in annual water yield after forest harvest (Troendle and King 1987; Troendle and Meiman 1986). In contrast, on south-facing slopes, the reduction in winter interception may account for only 20 percent of the observed change in annual water yield. This difference in the role of winter interception is because the snow remains in the canopy almost continuously from November to May on north-facing slopes. The tremendous surface area of exposed snow allows a great deal of evaporative loss to occur despite the lower incoming solar radiation compared to south-facing slopes, and this can be attributed to the low relative humidity and relatively strong vapor pressure deficit. On south-facing slopes, the forest canopy is less dense and intercepts less snow, and the intercepted snow is more likely to melt and fall out of the canopy, thus allowing less time for interception losses to occur. Surprisingly, the 13- to 19-cm change in summer evapotranspiration appears to be independent of aspect and varies primarily with the amount of annual precipitation (Troendle 1987, 1988).

A similar hydrologic response to Fool Creek has been documented following forest harvest for other watershed studies in the Rocky Mountain region, and these include Wagon Wheel Gap in south-central Colorado (Bates and Henry 1928), Dead Horse Creek in central Colorado (Troendle and King 1987), Coon Creek in southern Wyoming (Troendle and others 2001), thinning in South Dakota (Anderson 1980), tree mortality due to insect attacks in northwestern Colorado (Love 1955), beetle kill in southwestern

Montana (Potts, 1984a), and wildfire in northern Wyoming (Troendle and Bevenger 1996). It should be noted that the forest cover at Wagon Wheel Gap was predominantly aspen as compared to mostly conifers in all of the other watersheds.

At lower elevations in the Rockies, there is less snow, summers are hotter and drier, and the dominant tree species are ponderosa pine and Douglas-fir. The fire regimes in the ponderosa pine and mixed Douglas-fir/ponderosa pine forests have been severely affected by fire suppression. It is within these forest types that most of the thinning and prescribed fire treatments are being proposed or taking place. A comparison of the potential water yield changes from these sites to the more extensively studied changes in the cold snow zone helps illustrate the magnitude and causes of the variations that confounded Hibbert in 1967.

Studies in southwestern Idaho indicate that forest harvest causes smaller and less persistent increases in annual water yields than at Fool Creek. The observed changes in water yield are strongly influenced by aspect. At Boise Basin, 42 percent of the area was logged or burned in 1929 and 1930. Ten years later the increase in annual water yield was only 7.6 mm (Rosa 1961). At Silver Creek, 23 percent of the basin was clearcut, primarily on south-facing slopes, and there was no detectable increase in water yield. In contrast, a clearcut and prescribed fire on a nearby 1-ha catchment with a northerly aspect doubled the subsurface flow during spring runoff. This doubling in runoff was due to a 5- to 8-cm decrease in on-site evapotranspiration. As in the cold snow zone, these increases in water yield were smaller when there was less precipitation and greater energy input. These results indicate that the general lessons learned from the cold snow zone apply to lower elevation sites in the Rocky Mountain region, but the predicted increases in water yield from lower elevations must take into account the lower precipitation and greater differences by aspect.

Equation 1 and the results from the Rocky Mountain region show that the increased runoff after forest disturbance is the integrated response to the amount and timing of precipitation and snowmelt inputs, soil moisture recharge requirements, and the evapotranspirational demands at the time of soil moisture recharge. In the humid, rain-dominated regions in the eastern United States, the maximum increases in flow can be as much as 300 or 400 mm per year following clearcutting (Hornbeck and others 1997; Stednick 1996). Unlike the cold snow zone, these increases in streamflow often occur in the late summer and early fall because that is when precipitation begins to exceed the reduced amount of soil moisture recharge in the harvested areas. Once soil moisture recharge is satisfied in the harvested and unharvested areas, the only difference in winter water yield and peak discharges will be due to the difference in rainfall interception losses between the harvested and unharvested areas. In the snow-dominated areas, the timing of the water yield increase would include a spring component similar to the Rocky Mountain region, although there would also be an increase in growing season flows if there is sufficient precipitation. Overall, the magnitude of the changes in annual water yield do not differ greatly between the Northeast (Hydrologic Region 1, fig. 3) and the Rocky Mountain region (Hydrologic Region 4, fig. 3) for a similar reduction in basal area. However, the increases in water yield tend to be less persistent because of the relatively rapid vegetative regrowth after forest harvest, and some long-term studies indicate a decrease in summer and annual streamflow 25 to 35 years after harvest. A plot of the data from the Northeast also suggests that a detectable change in water yield can occur after removing only 10 to 12 percent of the basal area (Hornbeck and others 1997), and this can be attributed to the wetter conditions during the summer growing season.

The effect of timber harvest on water yield from the "warm" snow and rain-on-snow zones of the Cascades of Oregon and Washington (Hydrologic Region 5, fig. 3) and the Sierra Nevada of California (Hydrologic Region 7, fig. 3) have both similarities and differences in response compared to that of the cold snow zone of the Rocky Mountain region (Kattleman and Ice 2004; Rice and others 2004). Snowpacks are generally at or near 0 °C, so snowmelt can occur during the winter and precipitation can occur as snow, rain, or a mixture of snow and rain at any time throughout the winter. Nearly all forests are coniferous, so winter interception losses are higher than in the deciduous forests of the east, but less than the interception losses in the cold snow zone in the Rocky Mountain region because the snow rapidly melts out of the canopy in all but the highest elevation zones. Forest harvest in areas with high annual precipitation and high soil moisture storage capacity can cause a greater reduction in summer evapotranspiration than in the cold snow zone forests like Fool Creek, and this can lead to more soil moisture carryover relative to uncut sites. This difference in soil moisture carryover can lead to larger increases in annual water yields, such as in the first-year values of 300 to 400 mm that have been observed from paired watershed studies in Oregon (Jones and Post 2004; Stednick 1996). As in the eastern United States, the relatively rapid regrowth means that the water yield increases due to forest harvest are typically eliminated in a much shorter time than at Fool Creek, and the rapid regrowth can lead to a decrease in summer and annual water yields within 1 to 3 decades after harvest.

Precipitation and Interception

Throughout much of the Rocky Mountain hydrologic region, the annual hydrograph is dominated by the melting of the winter snowpack. In snow dominated areas of the western United States, the amount of water present in the snowpack on 1 April can explain from 60 to 90 percent of the variation in annual runoff (Bevenger and Troendle 1987; Garstka and others 1958; Troendle and King 1985). Overall, as much as 95 percent of the total annual streamflow in the cold snow zone originates as melting snow, while only 3 to 5 percent of the rainfall becomes stormflow. In contrast, up to 24 percent of the rainfall can be returned as stormflow in some of the more humid areas in the eastern United States, and this can approach 70 percent for some rainstorms under exceptionally wet antecedent conditions (Hewlett and others 1977; Woodruff and Hewlett 1970).

In the cold snow zone of the Rocky Mountains, virtually any reduction in stand density will increase snowpack accumulation (for example, Gary and Troendle 1982; Haupt 1979; Meiman 1970, 1987; Packer1962; Troendle and Kaufmann 1987; Wilm and Dunford 1948). In the higher elevation lodgepole pine and spruce-fir forests, the increase in the snowpack on partially cut stands is directly proportional to the percent of basal area removed and the increases observed in clearcuts (Goodell 1952; Love 1953; Troendle and Meiman 1984; Wilm and Dunford 1948). As noted previously, the increases in peak snow water equivalent in the cold snow zone after forest disturbance

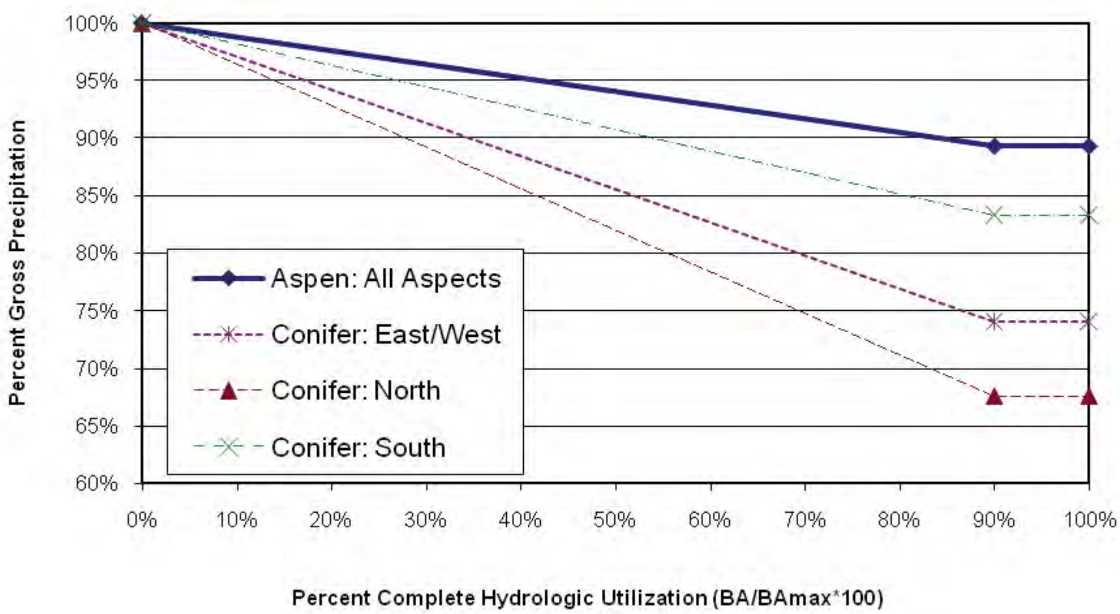

Figure 5. Percent of gross precipitation reaching the forest floor in the Central and Northern Rocky Mountains as stand density increases from 0 (opening) to 100-percent of the maximum basal area for the site (from Troendle and others 2003).

are greatest on north-facing slopes and smallest on south-facing slopes. Increases on east- and west-facing slopes are intermediate (Troendle and others 2003, 2005; fig. 5). In drier ponderosa pine forests, a reduction in basal area did not detectably increase the snow water equivalent on south, east, and west aspects, but did substantially increase the snow water equivalent on north-facing slopes (Haupt 1979).

The amount of interception loss during and after individual snowfall events varies significantly with storm size, storm intensity, wind speed, and location (in the case of small clearings). In coniferous forests in the cold snow zone, one generally can expect that 25 to 35 percent of the winter snowpack will be intercepted and lost to the atmosphere by some combination of sublimation and evaporation. Timber harvest in a deciduous forest, such as an aspen forest, will also increase peak snow water equivalent, but the much smaller amount of canopy reduces winter interception losses to about 10 to 12 percent. Process-based studies have shown that the observed increases in the winter snowpack after forest harvest result from the reduction in interception losses rather than a redistribution of snow during or after a storm event (Schmidt and Troendle 1989, 1992; Troendle and King 1987).

The magnitude and significance of interception losses by forest vegetation to the overall water balance have been documented by Kittredge (1948), Coleman (1953), and others. Interception losses may account for 25 to 35 percent of the annual precipitation, depending on the amount, type, and intensity of precipitation and the type and density of forest vegetation. In the cold snow zone, the effect of a reduction in winter interception on water yield is particularly important because the storm-based changes in interception accumulate over the course of the winter and can represent a significant increase in water inputs during spring melt. The snow interception losses measured in the cold snow zone of the Rocky Mountain region are surprisingly consistent with values from other cold snow regions in the United States (Troendle and Leaf 1980). The increase in net precipitation resulting from forest removal is proportional to the reduction in stand density and can range up to 15 to 30 percent for individual storm events (Kittredge 1948).

Soil Moisture and Summer Evapotranspiration

The effects of a change in stand density or leaf area index on summer evaporation, and especially transpiration, are not as linear as the changes in snowpack accumulation. Clearcutting in the Central Rocky Mountains reduces on-site soil moisture depletion by 13 to 19 cm during the growing season, regardless of aspect (Dietrich and Meiman 1974; Troendle 1987, 1988; Troendle and Kaufman 1987; Troendle and Meiman 1984;

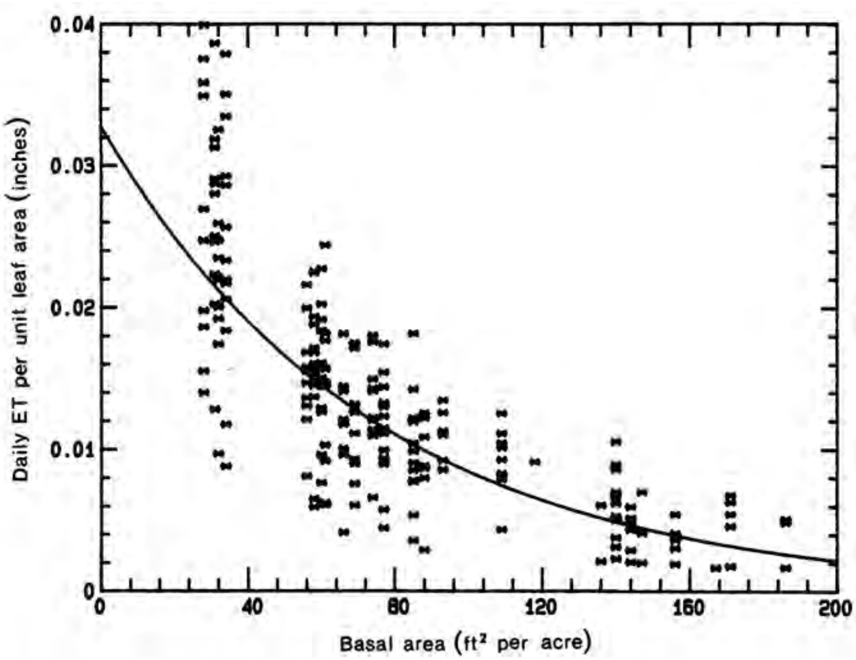

Figure 6. Daily ET (soil water depletion) per unit of leaf area as a function of basal area (from Troendle 1987).

Wilm and Dunford 1948). However, thinning can have very little effect on summer evapotranspiration rates as the residual trees can capture some or all of the savings in soil water by increasing water use (MacDonald 1986; Troendle 1987). The variations in the relationship between leaf area index and daily evapotranspiration (fig. 6) illustrates the ability of trees to adjust their water use in accordance with soil moisture availability as well as other factors. This means that the relationship between stand density and soil water depletion is statistically significant in wet years when there is less competition for soil water, while in dry years, there may be no correlation between basal area and soil water depletion because evapotranspiration from the residual stand may use all of the available water, regardless of the reduction in stand density (Troendle 1987). Hence, the potential for thinning to reduce summer transpiration and increase water yields depends on the amount of precipitation. If the sum of the water stored in the soil and summer precipitation exceeds potential evapotranspiration, thinning may increase the amount of water available for streamflow because of the reduction in summer evapotranspiration. If the sum of the stored water and summer precipitation are less than the potential evapotranspiration, any reduction in evapotranspiration due to thinning or forest harvest will be lost to evaporation from the soil and transpiration by the residual vegetation. If there is not a reduction in summer evapotranspiration there will not be any reduction in the amount of water needed for soil moisture recharge. In water limited systems, such as most of the Rocky Mountain hydrologic region, summer precipitation is low and soil water reserves are often depleted on all aspects and across a wide range of stand densities and forest types. Therefore, it is unlikely that most fuel reduction treatments will sufficiently decrease soil water depletion to cause an increase in annual water yields unless precipitation amounts exceed evaporative demand. In most areas, the only mechanism for fuel treatments to increase water yields is to (1) reduce interception losses and thereby increase rainfall runoff during the winter when soils are relatively wet or (2) increase the snow water equivalent and increase runoff during the spring melt period.

Peak Flows

The effect of forest disturbance on the size of peak flows can be predicted by the changes in the dominant controlling factors, which include:

1. the change in peak snowmelt rates;
2. the change in rainfall interception, particularly when the soils are relatively wet;
3. the degree to which roads and other disturbances intercept water and alter the pathway that water takes to the stream channel,
4. alteration of the infiltration rate to the extent that runoff pathways are changed, and
5. changes in soil moisture content and storage capacity (Anderson and others 1976).

With respect to the change in peak snowmelt rates, the magnitude of the effect of forest disturbance (other than fire) on peak discharges in the cold snow zone is similar to the observed changes in annual water yields. In the case of Fool Creek, peak flow increased by an average of about 20 percent (fig. 4); however, the three largest peaks of the post treatment period, from 1967 to 1998, were not significantly increased (Laurie Porth, personal communication). During those years when snow packs are greater and more long lasting, melt rates in the clearings appear similar to those in the forest and differences in soil moisture resulting from timber harvest are eliminated before the peak, thus diminishing the effects of forest removal on peak discharge for those largest events. Other studies in the cold snow zone have shown a 20 to 50 percent increase in the average peak flows due to clearcutting, but these have also shown no significant increase in the largest peaks of record (Troendle and Bevenger 1996; Troendle and King 1985; Troendle and others 2001).

A comparison of pre- and post-harvest flow duration curves indicates that the flows most affected by forest harvest are those that exceed the lowest 40 percent of the discharges but do not exceed the 90th percentile. However, the duration of bankfull discharge at Fool Creek, which is assumed to equal the 1.5-year instantaneous discharge, increased from 3.5 days to 7 days per year after the timber harvest (Troendle and Olsen 1994). The longer duration of bankfull flows was presumed to increase channel scour as indicated by the observed increases in annual sediment yields after patch clearcutting on the North Fork of Deadhorse Creek (Troendle and King 1987).

There has been considerably more debate over the effect of forest harvest on peak flows in the maritime snow climates of the Pacific Northwest and Continental/Maritime hydrologic regions (Grant and others 2008; Jones and Grant 1996; Thomas and Megahan 1998). This debate is due in part to the fact that the largest peak flows are typically due to mid-winter rain-on-snow events, and forest harvest can affect a series of processes that control the amount of snow in the canopy and on the ground, as well as the amount of heat that is available to melt the snowpack. These additional processes, when combined with the variability in climatic conditions during a storm and within a watershed, can make it very difficult to determine exactly how forest harvest affects peak flows from a given event.

Plot-scale studies have shown that rain-on-snow events accompanied by high winds can dramatically increase snowmelt rates in forest openings (Beaudry and Golding 1983; Berris and Harr 1987; Christner and Harr 1982; Harr 1986; Marks and others 1998; Storck and others 1998, 1999). This increase in melt rates is due to the increased condensation of moist air on the snowpack driven by the high winds and the resulting transfer of heat to the snowpack (Berris and Harr 1987; Harr 1986; Marks and others 1998; Storck and others 1999). Much less research has been done on how thinning affects this process, but basic research on turbulence theory suggests that even widely spaced cylinders (for example, trees) can be effective in reducing turbulence at the bottom surface (Poggi and others 2004a, b). This would suggest that thinning may have little effect on peak snowmelt rates during rain-on-snow events in the transient snow zone.

Forest roads, whether paved or unpaved, typically have very low infiltration rates and, therefore, convert nearly all of the rainfall or snowmelt into overland flow. When they are cut into the hillslopes, they also can intercept the slower moving subsurface flow. Depending on their connectivity with the stream network, roads may deliver this water directly to the channel. The increase in runoff and faster flow velocities act together to increase the size of peak flows (LaMarche and Lettenmaier 2001; Luce 2002; Megahan 1972; Wemple and Jones 2003; Wemple and others 1996) as well as total runoff. Skid trails can also generate surface runoff because of their lower infiltration rates, but generally these are not deeply incised to the hillslopes and, therefore, do not intercept subsurface stormflow. A compilation of published data indicates that the proportion of roads that are connected to the stream network is proportional to mean annual precipitation, as this tends to increase the number of streams and road crossings, which are a primary source of road-stream connectivity. The effect of roads on the size of peak flows can be minimized by outsloping and reducing their density and proximity to stream channels.

As a result of tracked or wheeled vehicles, soil compaction can reduce infiltration rates to the point that overland flow is generated during storm or snowmelt events. Again, this will increase the amount and velocity of runoff and thereby increase the size of peak flows. As with roads, best management practices are usually implemented during mechanical operations to reduce or eliminate this problem, including avoiding operations, such as minimizing high traffic areas during wet weather when the soils are more susceptible to compaction.

Other mechanisms that increase the size of peak flows in rain-dominated areas include the post-harvest increases in soil moisture and rainfall interception. Wetter soils allow a greater percentage of the precipitation to become streamflow, and the reduction in summer evapotranspiration generally results in wetter soils through the growing season. This would cause an increase in the runoff response in the first fall rainstorms. However, once the soil moisture in uncut areas has been fully recharged, there would be minimal differences in soil moisture between the cut (or thinned) and uncut areas and the initial soil moisture effect would be largely eliminated. Since the largest runoff events occur under wet conditions, the change in soil moisture due to timber harvest is unlikely to affect the size of the largest peak flows (Troendle 1987).

Forest harvest or forest thinning will also reduce the amount of rainfall interception by reducing the total leaf area. Any reduction in interception will effectively increase the amount of precipitation reaching the mineral soil, and this change should increase the size of peak flows. Again, this change will be most important in the smaller storms and less in the larger, more intense storms as the forest canopy can generally capture only a few millimeters of water and evaporation rates during large storms are relatively small due to the small amounts of incoming solar radiation and high relative humidity.

A recent review on the effects of forest harvest on peak flows in western Oregon supports these basic principles (Grant and others 2008). First, data from a variety of paired watershed experiments shows that forest harvest has a progressively smaller effect on peak flows as recurrence interval increases, and this is consistent with our general understanding of runoff processes and results from the Rocky Mountain region. The observed changes in the size of peak flows varied by watershed, but the peak flow increases ranged from 0 to 40 percent in the rain and transient snow zones and from 0 to 50 percent in the snow zone. The observed increases in peak flows generally approach the limit of detectability (about a 10 percent change) at a recurrence interval of approximately 6 years (Grant and others 2008). The largest increases in the size of peak flows occur in the fall because of the higher soil moisture carryover in harvested areas. The timing of the largest increases is consistent with equation 1 and the observed changes in the cold snow zone where the runoff increase occurs almost entirely on the rising limb of the snowmelt hydrograph because of the soil moisture carryover from the previous summer and corresponding reduction in the amount of water needed for soil moisture recharge in the following spring.

As in the cold snow zone, the magnitude of the observed changes in the size of peak flows in western Oregon is generally linear with respect to the proportion of the watershed that has been harvested (Grant and others 2008). The effect of roads cannot be clearly disentangled or quantified relative to the effect of timber harvest, although the data and modeling studies suggest that roads can increase the size of peak flows (for example, Bowling and others 2000; Grant and others 2008; Jones 2000). Using the mean response lines from different watershed studies, thinning less than 40 percent of a watershed is unlikely to cause a detectable change in the size of peak flows in rain-dominated areas and would result in only a 14 percent increase in the size of peak flows in the transient snow zone (Grant and others 2008).

In conclusion, both the available data and our understanding of hydrologic processes indicate that thinning should generally have little or no effect on the size of peak flows. In general, the changes in the size of peak flows due to forest management are small relative to the interannual variability in the size of the largest runoff events, and this again makes it difficult to link thinning with statistically significant hydrologic, geomorphic, or ecological changes.

Hydrologic Recovery

The longevity of hydrologic response following timber harvest appears to be unique in the cold snow zone of the Rocky Mountain region relative to other hydrologic regions, and this includes both the changes in water yield and snowpack accumulation. At Fool Creek the "average" 10-cm first-year increase in flow had declined by only 28 percent over the first 28 years following timber harvest (Troendle and King 1985). Recent streamflow data suggest that full hydrologic recovery will require 60 or more years (Laurie Porth, personal communication).

The duration of hydrologic recovery is more speculative when the silvicultural practice is a thinning or individual tree removal as compared to clearcutting strips, patches, or entire watersheds. It is generally assumed that the residual trees will very quickly occupy the site and use the soil moisture savings. However, the significant increases in snow pack accumulation persisted for at least 20 years after a partial cut that removed 40 percent of the basal area at Deadhorse Creek (Laurie Porth, personal communication; Troendle and King 1987). The persistent increase in the snowpack after partial cutting implies that at least a portion of the associated increase in annual water yields and peak flows would also be long lasting in the cold snow zone.

In contrast to the cold snow zone, the hydrologic response to clearcutting and thinning is relatively short-lived throughout the balance of the United States (Beasley and others 2004; Brown and others 1974; Douglass 1983; Harr 1983; Hornbeck and Kockenderfer 2004; Hornbeck and others 1997; Jackson and others 2004; Jones and Post 2004; Kattleman and Ice 2004; Keppeler and Zeimer 1990; Troendle and Leaf 1980). The shorter duration is due to the much more rapid rate of vegetative regrowth, which is due largely to the warmer temperatures and greater availability of water. Paired watershed studies suggest that the increase in annual water yields resulting from clearcutting will drop to zero within 30 years, and there may then be a period of a net decrease in water yields as a result of the active regrowth and changes in species composition (Jones and Post 2004). The persistence of any increase in annual water yields due to thinning or partial cuts will be much shorter due to the tendency for the residual vegetation to uptake any savings, and these are likely to disappear within 5 or possibly 10 years. When this occurs, any increase in low flows is also likely to be very short-lived.

Hydrologic Effects of Prescribed Fire

Prescribed burning is the controlled use of fire to achieve specific management objectives (Walstad and others 1990), and it is commonly used to reduce fuel buildup and the associated risk of severe wildfire (Norris 1990). Between 1998 and 2007, 6.7 million hectares managed by federal agencies in the United States were treated with prescribed fire (NIFC 2008). Relative to wildfires and forest harvest, the effects of prescribed burning have received little study until recently.

The hydrologic effects of prescribed burning are largely a function of fire severity and area burned. High severity burns that consume protective litter and expose mineral soil generally increase runoff and sediment yields, whereas low severity burns that only consume the upper litter layers have much less hydrologic impact (Benavides-Solorio and MacDonald 2001, 2005; Tiedemann and others 1979). Because prescribed fires are typically intentionally set during times when flame lengths are expected to be low, fire residence times are expected to be short, soil heating is expected to be low, and the effects of prescribed fires on soil properties are limited in severity and extent. The percent exposed mineral soil following low severity prescribed burns is generally between 5 and 30 percent, whereas values ranging from 35 to 95 percent have been reported following high severity prescribed burns or wildfires (Benavides-Solorio and MacDonald 2001, 2005; Cooper 1961; Robichaud and others 1993; Swift and others 1993; Robichaud and Waldrop 1994; Van Lear and Kapeluck 1989). The occurrence of surface runoff and erosion after fires is highly dependent on the amount of ground cover. Most studies indicate that little overland flow or surface erosion occurs when there is less than 35 to 40 percent bare mineral soil (Benavides-Solorio and MacDonald 2005; Robichaud and Brown 1999). This may be a useful first-order threshold for predicting whether there is likely to be a significant increase in surface runoff, but the hydrologic effects of fire depend on many other factors beyond burn severity and percent bare soil. These include the amount of vegetation that is killed by the fire, proportion of a watershed that is burned, location of the areas burned within a watershed, soil type, rate of vegetation recovery, and precipitation regime after burning (Luce 2005).

On-Site Effects

The surface condition after a prescribed fire is typically a mosaic-like pattern of low severity, high severity, and unburned patches (Robichaud 2000). The connectivity of runoff producing patches imparts a strong control on water and sediment yields to the stream channel (Doerr and Moody 2004; Luce 2005; Shakesby and others 2000). The patchiness of burn severity allows unburned and low severity patches to infiltrate runoff and trap sediment that is generated on adjacent high severity patches (Biswell and Schultz 1957; Cooper 1961; Swift and others 1993). The patterns of burn severity help control the spatial scale at which the effects of prescribed burning can be detected. For example, strong soil water repellency in high severity patches may have little effect at the watershed scale if only a small percentage of the watershed burns at high severity, or if there are intervening low severity or unburned patches (Huffman and others 2001).

Effects on Streamflow

Since low severity prescribed fires do not cause a high degree of tree mortality or litter combustion, the effects on evapotranspiration and forest floor water storage are generally too small to change watershed-scale water yields. For example, the 1 to 10 percent basal area mortality reported following low severity prescribed burns in ponderosa pine is below the 20 percent threshold at which changes in streamflow are usually detectable (Gottfried and DeBano 1990). The reduction in forest floor water storage due to prescribed burning varies, but the lower-most litter layer must be modified or removed before the water holding capacity of the forest floor is significantly reduced (Agee 1973; Brender and Cooper 1968; Clary and Ffolliot 1969; Cooper 1961). Therefore, prescribed fire is unlikely to increase watershed-scale runoff unless a large proportion of the watershed burns at high severity.

As evidence, water yields did not increase following a prescribed fire that burned 43 percent of an Arizona ponderosa pine watershed (Gottfried and DeBano 1990). The lack of a significant increase in flow was likely due to the fact that the fire killed only 1 percent of the pre-burn basal area and left most of the litter intact (Gottfried and DeBano 1990). Two successive prescribed fires that completely burned four loblolly pine watersheds in South Carolina had no detectable effect on streamflow (Douglass and Van Lear 1983). Similarly, prescribed fires in giant sequoia-incense cedar forests in Sequoia National Park in California had no effect on streamflow in a 100-ha watershed where 60 percent of the area was burned, and in a 20,000-ha watershed where eight fires burned 11 percent of the watershed over a 7-year period (Heard 2005). The absence of any change in water yield was attributed to the low severity burn in the 100-ha watershed and the small proportion that was burned in the 20,000-ha watershed. In contrast, a different prescribed fire in Sequoia National Park did cause streamflow to increase (Williams and Melack 1997). The fire was more severe than the low severity burn described by Heard (2005) and killed most of the younger trees and understory vegetation and consumed the majority of the forest litter (Williams and Melack 1997).

The effects of prescribed fire can vary by cover type. When the cover type is chaparral, the relative intensity of the burn may be greater, a greater percentage of the vegetation is consumed, and a greater percentage of the soils become water repellent. In two chaparral watersheds, burning 80 to 90 percent of the area by moderate and high severity fires increased water yields by 4 and 14 times, respectively, relative to unburned areas (Riggan and others 1994).

These results confirm that light to moderate prescribed fire has little effect on streamflow. This is largely because only a small percentage of the vegetation is affected and net changes in infiltration characteristics are minimal. Since the major components of the water balance are not substantially altered, there is little or no effect on streamflow.

In some vegetation types, particularly chaparral, there is a much greater propensity for prescribed fires to burn at higher severity. In these areas, the use of prescribed fire as a fuel reduction treatment may have a greater hydrologic effect. In each case, the integrated hydrologic response to successive prescribed fires must be compared to the hydrologic response resulting from the likely frequency and severity of a wildfire.

Predicting Changes in Water Yield

The 1980 WRENSS Handbook includes a set of graphical procedures that have proven useful for estimating the hydrologic impacts of various silvicultural activities on water yield and water quality (EPA 1980). The hydrology chapter has regional evapotranspiration estimates based on the hydrologic regions in figure 3. Regionalized curves and modifier functions are then provided to estimate the changes in actual evapotranspiration in response to changes in stand density and stand condition (Troendle and Leaf 1980). The predicted changes in evapotranspiration were assumed to affect the amount of water available for stream flow. For snowmelt-dominated areas, the changes in forest cover alter net precipitation and the amount of evapotranspiration. In rain-dominated areas, the precipitation is not adjusted to reflect stand conditions and the change in evapotranspiration is estimated directly.

The understanding of hydrologic processes in the cold snow zone has evolved significantly since WRENSS was developed, and a new version of the model, WinWrnsHyd, has been produced (Swanson 2004). One of the most significant changes is how this program simulates the effects of forest harvest on snow accumulation. The revised snowpack sublimation and scour routines are more sensitive to wind speed, surface roughness, and opening size. These changes allow one to better link the changes in wind speeds due to removing some or the entire forest canopy to changes in snow accumulation, and to more accurately predict the effects of leaving or removing slash or other forms of roughness on snowpack accumulation. The net effect is to make the model more sensitive and more accurate with respect to the effects of partial cuts and thinning on water yields (Shepperd and others 1992).

WinWrnsHyd is programmed in Microsoft Access and uses database tables as input so that different harvesting scenarios can be created using GIS or other forest planning tools. Data reflecting stand conditions can be input as a series of "snapshots." Alternatively, if growth curves are available, the data for one or more silvicultural prescriptions, occurring simultaneously or at different time intervals, can be input to the model and the effects of regrowth on hydrologic response can be simulated as a time series. The WinWrnsHyd program can also estimate the likely changes in peak flows following forest disturbance. These procedures and updates are particularly relevant because, as noted earlier, the cold snow zone is of tremendous importance for water supply purposes, and fuel reduction treatments in this zone are more likely to affect runoff for a longer period than similar treatments in other ecoregions.

Cumulative Watershed Effects

The concern over cumulative effects arises because the effect of a single activity may not be significant, but the effect may be significant when combined with the effect of other management activities. A cumulative effect can occur spatially, such as the effect of multiple management activities within a basin, or over time, such as the hydrologic effect of one activity persists and the residual effect is superimposed on the effect of a second activity on the same site (MacDonald 2000).

The potential for generating a cumulative effect in space depends on the magnitude of each effect, their persistence over time, and the extent that the effect is delivered to the downstream location. In the case of fuel management activities, the hydrologic effect of a given activity is likely to be relatively small because only some of the forest canopy is being removed. As noted earlier, it has been generally accepted that at least 20 percent of the basal area in a forested watershed must be removed to obtain a detectable change in stream flow. As watershed size increases, it is increasingly unlikely that forest management will affect more than 20 percent of the basal area in a watershed before hydrologic recovery eliminates the hydrologic change due to some of the management actions. The implication is that the hydrologic effect of a fuel management activity is most likely to be detectable immediately below the activity, and the rate of hydrologic recovery will make it difficult to detect the effect of multiple activities over time and space, especially in larger watersheds (MacDonald 2000). As an example, clearcutting 36 percent of the North Fork of Deadhorse Creek sub-basin in the Fraser Experimental Forest in central Colorado caused a significant increase in streamflow. However, this change was not detectable a few hundred meters downstream at the main stream gauge on Deadhorse Creek, as the harvest in the North Fork watershed affected less than 6 percent of the area in the Deadhorse Creek watershed (Troendle and King 1987).

The potential for cumulative watershed effects due to fuel management will also be limited because most of the fuel management activities in the western United States will be concentrated in the drier forest types that have the greatest risk of high severity wildfires. As noted earlier, most studies have shown that forest harvest will not result in a detectable change in streamflow when mean annual precipitation is less than 18 to 20 inches. In contrast, thinning has been demonstrated to cause moderate increases in streamflow in the central Appalachians where precipitation greatly exceeds 18 to 20 inches (Reinhart and others 1964). But in humid areas, the hydrologic recovery is quite rapid (Hornbeck and others 1997). In general, the absolute changes in runoff due to fuel reduction activities in the drier forest types will be small or undetectable relative to the potential changes in more humid areas. The potential for cumulative hydrologic effects is further limited because the persistence of a hydrologic change due to thinning or a partial cut will generally be relatively short everywhere except in the cold snow zone, but these forest types are less likely to be the focus of fuel reduction treatments (Romme and others 2003).

Another issue in assessing the potential cumulative hydrologic effect is whether a given change in flow will be transmitted downstream to the location of interest. In most mountainous areas, any change in flow generated by forest harvest or fuel management activities should not be substantially altered by downstream transmission losses. However, seepage losses may become significant when streams and rivers flow onto broad, semi-arid alluvial plains. In such areas, the streams are likely to be losing water to the underlying alluvial aquifer during at least the drier portions of the year. In other words, the increase in streamflow may be “lost” to groundwater storage. The potential for transmission losses will be a function of the scale of the analysis, relative and absolute magnitude of the changes in flow, and specific watershed characteristics.

In most cases, the measurement and detection issues mean that the magnitude of a potential cumulative hydrologic effect will have to be assessed by modeling. As an example, Troendle and Nankervis (2000) and Troendle and others (2003) estimated the changes in average annual water yield resulting from long-term vegetation changes in the North Platte River Basin (table 1). Current vegetative conditions in the river basin were extrapolated backwards in time from United States Forest Service stand condition records, and water yields under the different forest conditions from 1860 to 2000 were simulated using the WRENSS model. The results suggested that streamflow from National Forest System lands has decreased 3 inches (76 mm) from 1860 to 2000 as the result of an increase in forest density (table 1). Although these decreases are difficult to detect using the existing streamflow records on the North Platte River, they are considered real and significant by water users and planners in the Platte River Basin. A separate study using a combination of precipitation, snowpack, and streamflow records reached similar conclusions (Leaf 1999).

Table 1. Water yield from National Forest land in the North Platte River basin from 1860 to 2000.

Year	Area (ha)	Predicted water yield (mm)
1860	448,418	376
1880	448,418	343
1900	448,418	366
1920	448,418	340
1940	448,418	307
1960	448,418	302
1980	448,418	307
2000	448,418	300

In a more recent assessment, Troendle and others (2007) used the WRENSS Hydrologic Model to predict the changes in water yield resulting from proposed fuel management treatments in the Upper Feather River watershed in the Sierra Nevada of California. Because proposed treatments influenced only a small percentage of the total vegetation on the entire study area, the cumulative impact on water yield was minimal. However, the GIS-based modeling was useful for demonstrating that the treatments could have an on-site or local affect on annual water yields.

Conclusions

One can conclude that fuel reduction treatments in forested watersheds will probably have little detectable impact on water yields either on-site or downstream. Most prescriptions are not likely to remove the 20 percent of basal area that is needed in most areas to generate a detectable change in flow. As Bosch and Hewlet (1982) concluded and subsequent data (Hornbeck and others 1997) and modeling (Troendle and others 2003, 2007) support, removing less than 20 percent of the basal area may also result in a change in flow, but this change will not be detectable. In cases where there is a detectable hydrologic response to fuel management treatments, the observed response will be greatest in wet years and smallest or non-detectable in dry years. Fuel reduction treatments that are carefully implemented and do not induce overland flow as a result of skid trails or compaction should generally have little or no detectable effect on peak discharges. With the exception of the cold snow zone in the Rocky Mountain region, any change in flow due to fuel reduction treatments will be short-lived.

Prescribed fires, when designed and used as a fuel reduction tool, are probably less likely to influence water yield than mechanical treatments because of the smaller reduction in basal area and lack of ground disturbance by heavy machinery. Prescribed fires that kill a significant proportion of the mature canopy or expose more than 35 to 50 percent of the mineral soil may have a significant, detectable effect on annual water yields or storm runoff.

Simple models are available to simulate the on-site and cumulative hydrologic impacts of virtually any individual or combination of forest disturbance scenarios. The use of these models should be a required component of the planning process in order to assess both on-site and cumulative impacts over time.

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Cumulative Watershed Effects of Fuel Management in the Western United States

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Abstract

Fire suppression in the last century has resulted in forests with excessive amounts of biomass, leading to more severe wildfires, covering greater areas, requiring more resources for suppression and mitigation, and causing increased onsite and offsite damage to forests and watersheds. Forest managers are now attempting to reduce this accumulated biomass by thinning, prescribed fire, and other management activities. These activities will impact watershed health, particularly as larger areas are treated and treatment activities become more widespread in space and in time. Management needs, laws, social pressures, and legal findings have underscored a need to synthesize what we know about the cumulative watershed effects of fuel management activities. To meet this need, a workshop was held in Provo, Utah, on April, 2005, with 45 scientists and watershed managers from throughout the United States. At that meeting, it was decided that two syntheses on the cumulative watershed effects of fuel management would be developed, one for the eastern United States, and one for the western United States. For the western synthesis, 14 chapters were defined covering fire and forests, machinery, erosion processes, water yield and quality, soil and riparian impacts, aquatic and landscape effects, and predictive tools and procedures. We believe these chapters provide an overview of our current understanding of the cumulative watershed effects of fuel management in the western United States.

Keywords: cumulative effects, watershed, wildfire, fuel management, water quality, soil erosion

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Foreword

This document is the result of a major interdisciplinary effort to synthesize our understanding of the cumulative watershed effects of fuel management. This document is the product of more than 20 authors and 40 reviewers including scientists from four Forest Service Research Stations and numerous universities. Chapter outlines and contents were first reviewed at a workshop in April 2005. Authors then drafted chapters that were peer-reviewed over the next two years. We edited all chapters twice before submitting them for a third round of editing by RMRS publication specialists. Chapter topics include overviews of the effects of fuel management on both terrestrial and aquatic watershed processes. The other editors and I are grateful to all authors and reviewers for their considerable efforts in the development of this document over the past four years. We wish to acknowledge the Stream Team and the National Fire Plan for financial assistance. As with all syntheses, science will continue to generate new knowledge, which will in time supersede the contents of this document. Readers are encouraged to seek updated and locally derived information to supplement the contents of this document. My personal thanks go to all the authors, reviewers, my coeditors and RMRS publishing staff for the considerable effort necessary to develop and publish this synthesis.

William J. Elliot, PE, PhD
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