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Fuels Management and Water Yield

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1. Introduction

There have been numerous studies worldwide demonstrating that changes in forest density can cause a change in water yield. Hibbert (1967), Troendle and Leaf (1980), Bosch and Hewlett (1982), and Stednick (1996) 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 (Troendle and Leaf 1980, Bosch and Hewlett 1982, and Stednick 1996). This change in thinking results from the increased number of observations available with each successive review as well as a much 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. The data from 95 watershed experiments conducted in the United States shows that, on average, streamflow increases by nearly 2.5 mm for each 1 percent of watershed area harvested (Stednick 1996). Because streamflow is quite variable from year to year, the general conclusion is that approximately 20 percent of the basal area of the vegetation must be removed, above the point of measurement before a statistically significant change in flow can be detected (Hibbert 1967, Bosch and Hewlett 1982, and Stednick 1996). However, as Bosch and Hewlett (1982) suggest, reductions in forest cover below 20% may well produce statistically non-significant responses that presumably approach zero increase at zero change 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 needed data on hydrologic response to fuels reduction since the vast majority of the treatments imposed a partial or complete clearcutting rather than a partial cut or thinning (Stednick 1996). Hence, much of our understanding of the hydrologic impacts of thinning or partial vegetation removal, and prescribed fire, comes from inference supported by various plot and process studies.

2. Objectives

This manuscript has three objectives pertaining to the effects of fuels management on water yield:

1) Revisit the basis for using regionalization to aid in stratifying the variability in treatment response that Hibbert (1967) felt made streamflow change prediction difficult.
2) Review the impact that forest disturbance has on each of the components of the water balance: stream flow, precipitation, and evapotranspiration and then draw inference on how fuels reduction treatments may impact water yield.
3) Identify tools that can help hydrologists and land managers predict both the on-site and the cumulative changes in water yield that may result from vegetative treatments.

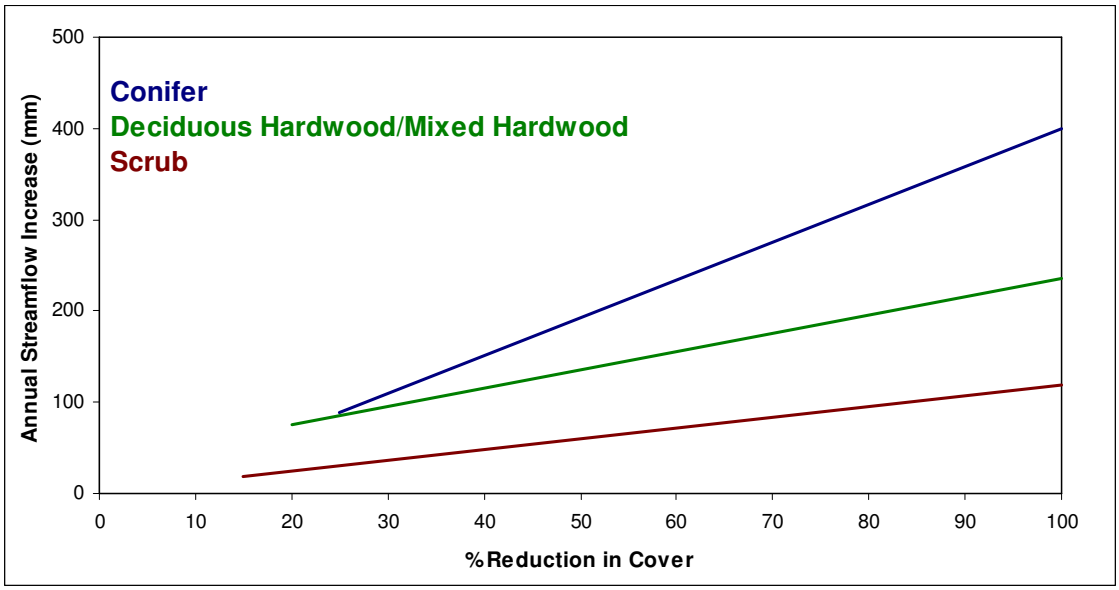

Figure 1: The relationship between reduction in vegetation cover and increases in stream flow for three vegetation types (redrawn from Bosch and Hewlett 1982).

3. Hydrologic Impact of Forest Disturbance on Streamflow Characteristics

3.1 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:

$$\text{Streamflow (runoff)} = \text{Precipitation} - (\text{Evaporation} + \text{Transpiration Loss} \pm \text{Change in Storage} \qquad (1)$$

where 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"); and change in storage includes both soil moisture and groundwater. Evaporation and transpiration are usually regarded as losses and reduce the amount of precipitation transformed into streamflow. Change in storage can be very important over short time periods (i.e. seasonal or less than one year) but over long periods is generally assumed to be zero, unless significant groundwater depletion is occurring.

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 interaction of climate and vegetation control the role the individual components of the water balance as well as the influence that forest disturbance has on the water balance.

In the mid 1970's, Bailey (1976, revised 1994) developed an ecoregion map of the United States that depicted the relationship between vegetation patterns, climate, and landscape or topography (Figure 2). He found that vegetation, with similar requirements for moisture and energy, were present in reoccurring patterns within each ecoregion in a predictable fashion on similar sites. Differences in vegetation patterns between ecoregions were primarily influenced by differences in the amount and seasonal distribution of water and energy available to meet plant requirements. Precipitation and energy, as well as streamflow, are influenced by topography as well as proximity to oceans. 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 framework useful in stratifying hydrologic response and predicting the effects of vegetation manipulation on water yield.

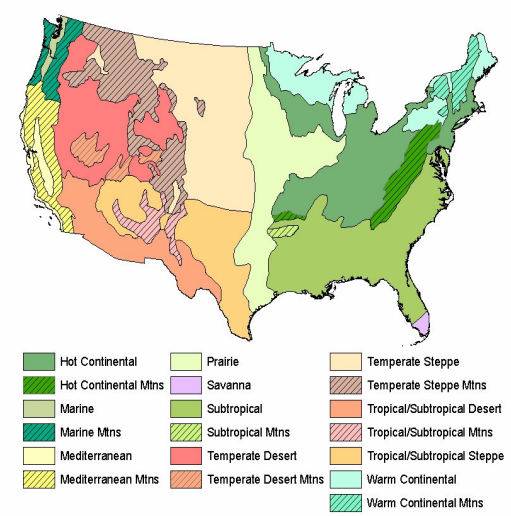

Figure 2: Ecoregion classification based on Bailey (1994).

In the late 1970's, the ecoregion concept (Bailey 1976) was used to stratify the United States into 7 hydrologic regions (Figure 3) in order to better predict the effects of silvicultural activities on non-point source pollution (US-EPA 1980). The handbook, An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources, commonly referred to as WRENSS, was developed for this purpose and contained graphical procedures, stratified by region, to predict the effects of forest disturbance on streamflow, erosion, temperature, and nutrients. The same hydrologic regionalization is used here for reviewing the effects of forest disturbance, including fuels reduction treatments, on annual water yield, peak flows, and low flows.

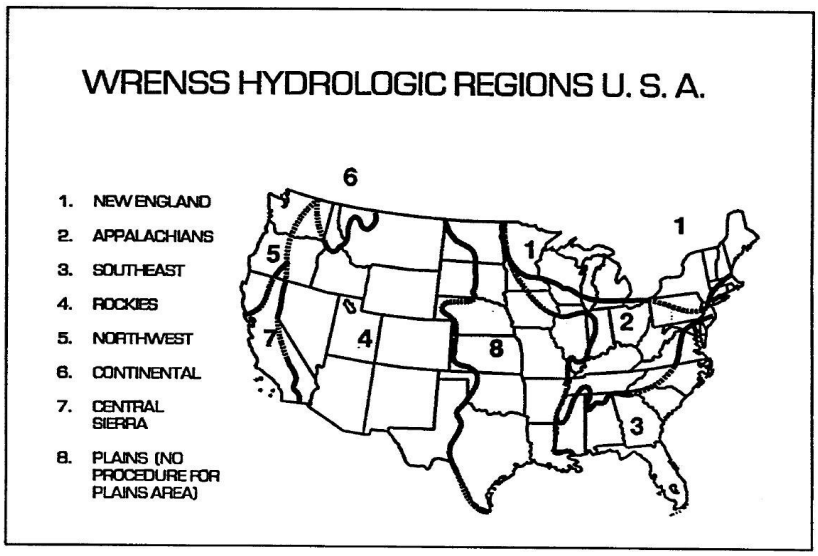

Figure 3: The United States divided into 7 hydrologic regions (see Troendle and Leaf 1980).

3.2 Water Yield

A large number of reports have quantified the effects of forest disturbance on streamflow in different regions of the United States (e.g., Hornbeck et al 1997, Douglas 1983, Reinhart et al 1964, Keppeler and Zeimer 1990, Harr 1983, Brown et al 1974, Kattleman and Ice 2004, Troendle and Leaf 1980, Troendle 1983, Gary 1975, and Ice and Stednick 2004). These studies have shown that the magnitude of change in water yield is most strongly related to the amount of precipitation and severity of treatment. 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 the arid southwest than in the humid Pacific Northwest. The impact that forest disturbance has on water yield can occur regardless of whether the disturbance is from fire, insects and disease, or timber harvest. The impact aforestation has on water yield is generally opposite that of deforestation. The hydrologic response to disturbance in a particular year

will depend on the summed effect of the changes in processes as indicated by equation 1, and these include the degree to which the management activity influences net precipitation to the soil by reducing interception, changes the amount of soil moisture evaporation, and changes the amount of transpiration and soil water depletion. The timing of any change in streamflow depends on when precipitation or snowmelt exceeds both evapotranspiration demand and soil moisture recharge requirements. Prediction of the effect of forest disturbance on water yield requires an understanding how the disturbance impacts 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 the evapotranspirational loss.

This paper will emphasize the hydrologic effects of fuels reduction treatments in the Rocky Mountain region (WRENSS Hydrologic Region 4) for several reasons. First, this volume is focusing on the western United States. Second, more than 50 percent of all National Forest System lands are contained within the Rocky Mountain region and issues of excessive fuel loading and departure from historical ecological conditions are particularly severe. This implies that a significant fuels reduction program will be concentrated in this region. In addition, the hydrologic effects of fuels treatments are potentially more important in this region due to the fact that the hydrologic response to vegetation disturbance is longer-lived than in other regions and the relatively arid climate means the potential changes in water yield may be more important than in other regions. From a process standpoint, the Rocky Mountain region provides examples of how vegetation management strongly influences winter snowpack accumulation and melt processes as well as summer evaporative and transpirative processes, or all components of the water balance. The potential range in variation of hydrologic response in the Rocky mountain region will presented and then compared with the potential hydrologic response that may occur in other ecoregions in the western United States where fuels reduction treatments may be implemented.

3.2.1Rocky Mountain Region

The Rocky Mountain region is fortunate in having a 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, Van Haveren 1981, Troendle and King 1987). This study was followed by a series of watershed studies in the region (Hoover and Leaf 1967, Troendle and Leaf 1981, Troendle and King 1985, Troendle and King 1987, Troendle et al 2001, Stednick and Troendle 2004), 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 because they illustrate the key principles that apply to the snowmelt dominated Rocky Mountain region. At Fool Creek, mean annual precipitation is estimated to average about 760 mm per year while the annual evapotranspiration ranges from 450 to 570 mm per year (Troendle and King 1985). At a nearby study site, Troendle and Reuss

(1997) estimated that average annual Evapotranspiration (ET) is directly proportional to precipitation once precipitation exceeds 462 mm (18.2 inches) and this relationship can be expressed by:

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

After a 15 year calibration period, approximately 40 percent of the Fool Creek watershed, or 50-percent on the commercially forested area, was clearcut from 1954 to 1956 in a pattern of alternating cut and leave strips. Comparison of the "average" 15-year pre- and 15-year post-treatment hydrograph for Fool Creek (Figure 4) clearly shows that, on-average, forest harvest increased both annual flow and peak flow. The difference between the pre- and post-treatment hydrographs is typical of the effect of forest disturbance on runoff in the cold snowmelt region typical of the Rocky Mountains (Bates and Henry 1928, Swanson and Hillman 1977, Swanson et al. 1986, Troendle and King 1987, Troendle and Bevenger 1994, Troendle and Reuss 1997, Troendle et al. 2001).

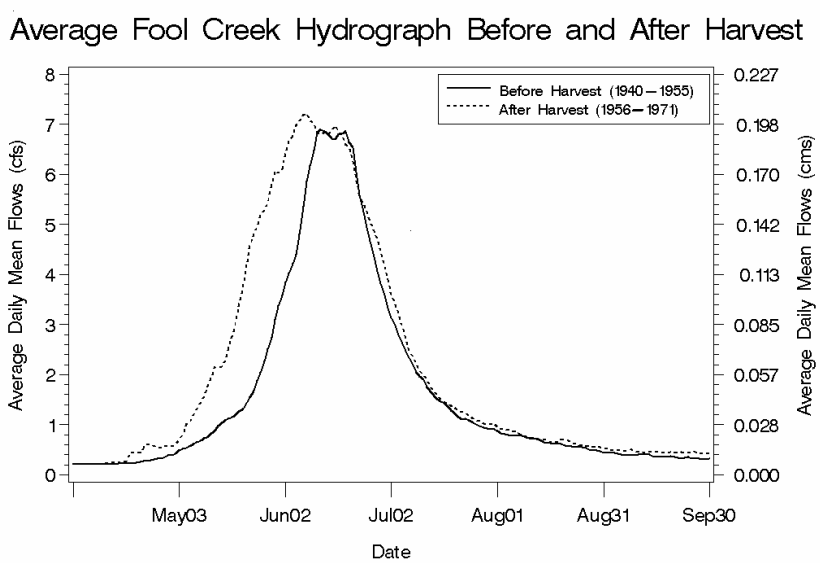

Figure 4: The average hydrograph from the Fool Creek Watershed for the 15 year period both before and after treatment.

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, observed increases in streamflow have ranged from a high of 16.2 cm in the wettest year to a low of 3.6 cm in the driest year. On average, streamflow increases reflect a 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 clear cuts appeared to initiate a significant decline in streamflow. At Fool Creek, significant increases in flow occur primarily in May with only an occasionally significant increase in June. No detectable impact has been documented on recession flows from July to October (Troendle and

King 1985). There is little opportunity for measurable increases in water yield to occur during 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% of summer rainfall is transformed into streamflow (Garstka et al 1958, Troendle and King 1985, Bevenger and Troendle 1987), and why a reduction in summer interception does not affect streamflow.

Changes in evapotranspiration in the cold snow zone, following forest removal, are due to both a reduction in growing season soil moisture depletion and a decrease in winter interception (Wilm and Dunford 1948, Dietrich and Meiman 1974, Potts 1984b, Troendle and Meiman 1986, Troendle 1987, Troendle and Reuss 1997). 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, any excess melt water is available to become streamflow. At Fool Creek, which is comprised mostly of east and west facing slopes, approximately 30% 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, while approximately 50% of the increase in water yield can be attributed to the reduction in evapotranspiration during the previous summer and the corresponding reduction in meltwater used for soil moisture recharge during the following spring. The remaining 20% of the observed increase in water yield is attributed to the reduction in evapotranspiration losses during April and May (Troendle and King 1985). In contrast, reduced winter interception losses can represent more than 50-percent of the potential flow change following clear and partial cutting on north slopes (Troendle and Meiman 1986, Troendle and King 1987) while representing only 20-percent of the flow change on south slopes. On North facing slopes, snow remains in the canopy almost continuously from November to May and although the evaporation rate is low, the tremendous surface area of exposed snow surface allows a great deal of evaporative loss to occur. In contrast, on South facing slopes, intercepted snow quickly leaves the less dense forest canopy thus allowing less interception loss. Surprisingly, the 13- to 19-cm change in summer evapotranspiration that occurs on all sites appears to be independent of aspect and dependent only on precipitation amount (Troendle 1987).

Within the Rocky Mountain region, a hydrologic response similar to Fool Creek has been documented following forest harvest at 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 et al 2001), thinning in South Dakota (Anderson 1980, Troendle 1987b), tree kill due to insect attacks in northwestern Colorado (Love 1955), wildfire in northern Wyoming (Troendle and Bevenger 1996), and beetle kill in southwestern Montana (Potts, 1984a).

At lower elevations in the Rockies, where there is less snow and summers are hotter and drier, ponderosa pine and Douglas-fir provide the dominant forest cover. The ponderosa pine and mixed Douglas-fir/ponderosa pine timber type has been recognized as one of the areas where fire regimes have been most affected by fire suppression and the area that ecologists have suggested is in the most need of restoration. It is important to discuss water yield change from these sites as compared to the more extensively researched cold snow zone that lies above.

Observations on the effects of forest removal at Silver Creek and the Boise Basin Experimental Forest, in southwestern Idaho show smaller increases in water yield that are also strongly influenced by aspect. Forty-two percent of the Boise basin was logged or burned in 1929 and 1930. Ten years later, the increase in water yield was 7.6 mm (Rosa, 1961). At Silver Creek, 23% of the basin was clearcut, primarily on south facing slopes, and no increase in water yield was recorded. In contrast, a doubling of subsurface flow during spring runoff was observed following a clearcut and prescribed fire on a nearby small (1-ha.) catchment with a northerly aspect. This doubling in runoff represents a 5 to 8 cm decrease in evapotranspiration on-site. As is the case for observations in the cold snow zone, the increases occurred during spring snowmelt and hydrologic response at these sites follows the general pattern seen in the cold snow zone: that when there are less precipitation and greater energy inputs, increases in annual runoff are not as great. In summary the general lessons learned from the cold zone apply to lower elevation sites in the arid Rocky Mountain region; however any estimates of increased yield from lower elevations must account for the lower precipitation.

Obviously, streamflow generation processes are more complex than implied in the above description. However, both streamflow and the increases in flow that occur following forest disturbance generally occur in response to precipitation input as well as the recharge requirements in the soil, and evapotranspirational demands that exist at the time of recharge. For example, in the humid, rain dominated regions in the eastern United States; maximum increases in flow vary from 100 to 250 mm per year following clearcutting (Hornbeck et al 1993). Lesser increases occur following partial cutting as a plotting of data from all studies in the Northeast indicate some change occurs once 10- to 12-percent of the basal area is removed (Hornbeck et al 1993). However, unlike the cold snow zone, increases in streamflow often occur in the late summer and early fall because that is when precipitation occurs in amounts adequate to exceed the reduced storage requirement of the soil in the harvested areas. By winter, soil moisture differences that may have existed between disturbed and undisturbed sites are often eliminated because the soils are fully recharged so there are is often little detectable difference in either total water yield or peak discharges during this period. Interestingly enough, however, the magnitude of the changes in flow that occur as the result of similar reductions in basal area do not differ greatly between the Northeast (Hydrologic Region 1, Figure 2) and the Rocky Mountain region (Hydrologic Region 4, Figure 2).

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, Figure 2) and the Sierra Nevada of California (Hydrologic Region 7, Figure 2) have both similarities

and differences in response compared to that of the cold snow zone of the Rocky Mountain region. Snowpacks are generally warmer, at or near 0° C, at the surface and precipitation can occur as snow, rain and snow, or rain at any time throughout the winter. Winter Interception losses are less although flow changes are somewhat similar. In general, aspect differences are similar.

3.3 Precipitation and Interception

Throughout much of the Rocky Mountain hydrologic region the annual hydrograph is dominated by the melt of the winter snowpack. In snow dominated areas of the western United States, from 60 to 90 percent of the variation in annual runoff can be explained by the amount of water present in the snowpack on 1 April (Garstka et al. 1958, Troendle and King 1985, Bevenger and Troendle 1987). Overall, as much as 95 percent of the total annual streamflow in the cold snow zone originates as melting snow, while only 3-5% of the rainfall becomes stormflow. In contrast, as much as 24% of the rainfall in some areas of the eastern United States is returned as stormflow, and this can approach 70% for some rainstorms when there are exceptionally wet antecedent conditions (Woodruff and Hewlett 1970, Hewlett et al 1976).

In the cold snow zone of the Rocky Mountains, virtually any reduction in stand density will increase snowpack accumulation (e.g. Wilm and Dunford 1948, Gary and Troendle 1982, Gary and Watkins 1985, Troendle 1987, Troendle and Kaufmann 1987, Meiman 1987). In the higher elevation lodgepole pine and spruce-fir forests, the increase in snowpack under partially-cut stands is proportional to the increases observed in clearcuts (Wilm and Dunford 1948, Love 1953), and the magnitude of the increase in snowpack is directly related to the percent of the basal area that is removed (Love 1953, Goodell 1952, Troendle and Meiman 1984). In the drier ponderosa pine forests, a reduction in basal area did not result in a detectable increase in snow water equivalent on south, east, and west aspects, but did substantially increase the snow water equivalent on north slopes (Haupt, 1951).

In the cold snow zone the greatest increases in peak snow water equivalent after forest disturbance occur on north-facing slopes, while the smallest increases occur on south-facing slopes. Increases on east- and west-facing slopes are intermediate (Troendle et al. 2003, Figure 5). 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 25-35% 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 aspen, also will increase peak snow water equivalent, but the much smaller amount of canopy means that interception losses during the winter are typically only 10-12% of the total snowfall. These estimates are fairly consistent across all hydrologic regions in the United States (Troendle and Leaf 1980). In contrast, studies in the Rocky Mountain region and the Continental/Maritime region have indicated a less dramatic increase in snowpack with aspect (Packer 1963, Meiman 1970, Haupt 1979,

Toews and Gluns 1986, Troendle et al 1994, Schmidt et al 1998, Troendle and Reuse 1997). The general conclusion is that an increase in the winter snowpack after forest harvest results from a reduction in interception losses rather than a redistribution of snow. Any reduction in the forest canopy generally will increase the amount of water in the snowpack, and some or much of this increase in snowpack can be transformed to an increase in streamflow.

Summaries on the interception of precipitation, both rain and snow, by forest vegetation such as by Kittredge (1948), Coleman (1953), FAO (1962) and others have documented the magnitude and significance of interception losses in the overall water balance. It is a dominant component and may represent 25 to 35 percent of the annual precipitation in some regions, depending on precipitation distribution and specie composition. In the cold snow zone, the role of any reduction in interception on water yield is magnified because the incremental changes in interception that occur on an event basis are aggregated over the course of the winter and accumulated into what can become a significant increase in precipitation input at the time of melt. Net precipitation during individual rainfall events can be increased 15- to 30-percent as stand density is decreased (Kittredge 1948).

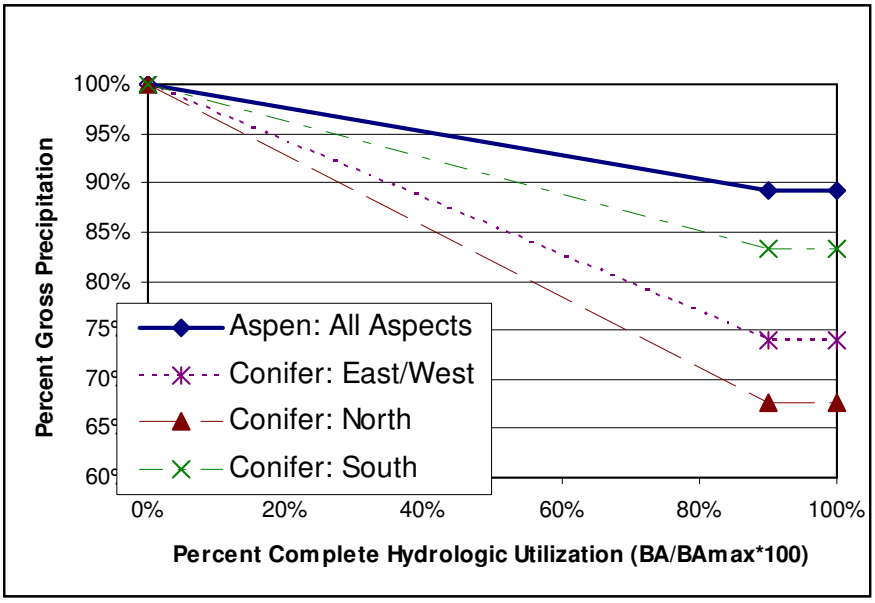

Figure 5: Percent of gross precipitation reaching the forest floor in the Central and Northern Rocky mountains as stand density increases from 0 (opening) to 100-percent of the maximum basal area for the site (from Troendle et al 2003).

3.4 Soil Moisture and Summer Evapotranspiration

The effects of forest disturbance on summer evapotranspiration, particularly transpiration, are not as linearly related to changes in stand density (or leaf area index) as the changes in snowpack accumulation. Clearcutting in the Central Rocky Mountains reduces on-site soil moisture depletion by 13-19 during the growing season regardless of aspect (Wilm and Dunford 1948, Dietrich and Meiman 1974, Troendle and Meiman

1984, Troendle 1987, Troendle and Kaufman 1987, Troendle 1988). When a stand is thinned rather than clear-cut, the residual trees can capture some or all of the savings in soil water, as water use per unit of leaf area can increase dramatically as stand density is reduced (Troendle 1987, MacDonald 1986). The relationship between leaf area index is quite variable (Figure 6) and dependent on many factors mostly related to soil water availability. The relationship implied in figure 6 is relatively universal; as the relative amount of available water increases, water use per unit of leaf area also increases. The relationship between stand density and soil water depletion, following thinning, is statistically significant in wet years when there is less competition for soil water, while in dry years soil water depletion during the growing season may not be correlated with basal area as the residual stand may use all of the available water, regardless of reductions in stand density (Troendle 1987). Hence the potential for thinning to reduce summer transpiration and increase streamflow depends strongly on the amount of precipitation. If the sum of the water stored in the soil and summer precipitation exceeds potential evapotranspiration, such as does occur in average or wet years in the Rocky Mountain region, thinning may increase the amount of water available for streamflow as a result of the reduction in summer evapotranspiration. If stored water and summer precipitation are less than the potential evapotranspiration rate, any reduction in evapotranspiration due to removing the forest canopy will be lost to soil evaporation and transpiration by the residual vegetation, and there will not be any soil water savings available to reduce recharge requirements the next spring. In water limited systems such as 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 specie compositions during most growing seasons. This means that following forest thinning there is no reduction in summer evapotranspiration that can be carried forward to reduce the amount of water needed for soil moisture recharge when snowmelt begins in the spring.

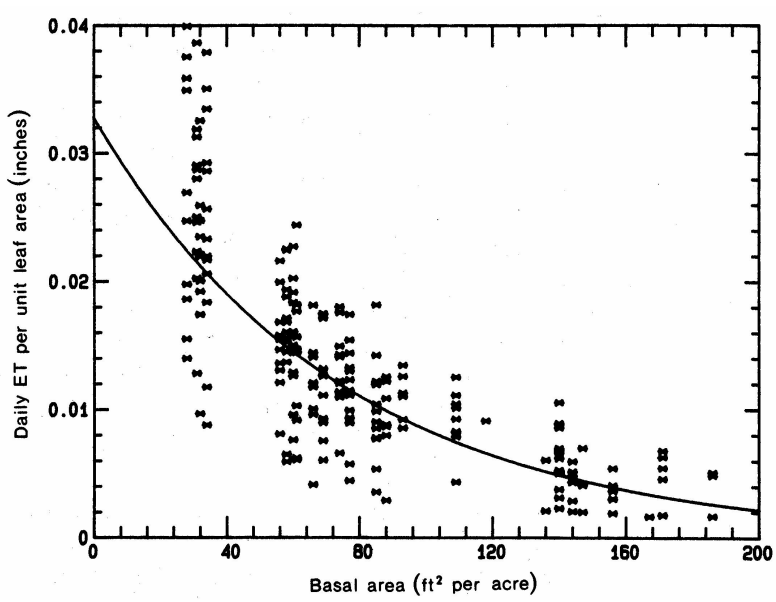

Figure 6: Daily ET (soil water depletion) per unit of leaf area as a function of basal area. From Troendle 1987

As a consequence, It is unlikely that fuels reduction treatments, particularly thinning, will result in major changes in soil water depletion and any savings are likely to be used by either the residual stand or in the production of under story vegetation which can respond quickly to increased moisture availability. Streamflow may still be increased because of interception savings in the snowpack but not because of reduced soil moisture recharge requirements.

3.5 Peak Flows

The affect of forest disturbance on peak discharge is largely dependant on five factors; 1) the amount of snow, 2) the degree to which snowmelt rates are altered, 3) the degree to which roads and other disturbances intercept water and alter the pathway that water takes to the stream channel, 4) the degree to which the infiltration rate or capacity of the soil to absorb water is altered and therefore pathway is changed, and 5) the degree to which soil moisture content, and therefore storage requirement, is altered.

In general, the magnitude of the impact of forest disturbance (other than fire) on peak discharges in the cold snow zone does not differ significantly from the annual yield responses observed. In the case of Fool Creek, peak flow increased an average of 20-percent (see Figure 4). However, the 3 largest peaks of the post treatment period from 1967-1998 were not significantly increased (Laurie Porth, personal communication, Rocky Mountain Research Station). The largest peaks were not effected because there was a large amount of snowpack covering the entire watershed, interception savings contributed to increased snowpack in the clear cuts but they were probably inconsequential at the time of peak, melt rates in the clearings were similar at that time of year to those in the forest, and by the time the peak occurred the soil moisture differences resulting from timber harvest had been eliminate; all of which negated the effect of timber harvest by the time that peak discharge occurred. In similar studies in other cold snow zone watersheds, average peak flows increased from 20 to 50-percent but again the largest peaks of record were not significantly increased (Troendle and King 1985, Troendle and Bevenger 1996, Troendle et al 2001). The peak flows most affected are those that exceed the lowest 40 percent of the discharges but do not exceed the 90 percentile. In the case of Fool Creek, the duration of bankful discharge, or the 1.5-year maximum instantaneous discharge, was extended from 3.5 to 7 days per year following treatment (Troendle and Olsen 1994).

There is 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. 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. As in the cold snow zone, studies suggest that extensive forest harvest can significantly increase the low to moderate peak flows (i.e., flows with a recurrence

interval of less than 5- to 10-years) following major forest disturbance but the lack of observations of less frequently occurring peaks (those occurring at return intervals greater than 10-years) yields a statistical lack of significance for estimated increases.

In moist snow climates, rain-on-snow events accompanied by high winds can dramatically increase snowmelt rates in forest openings (Christner and Harr, 1982; Beaudry and Golding, 1983; Harr, 1986; Berris and Harr, 1987; MacDonald and Hoffman, 1995; Jones and Grant, 1996; Marks et al., 1998; Storck et al., 1998; Storck et al., 1999). The effect is primarily from increased condensation of moist air on the snowpack driven by the high winds (Harr, 1986, Berris and Harr, 1987, Marks et al., 1998, Storck et al. 1999). The key management control on the effect is in controlling wind speed at the snow surface. While the research has made clear the contrast between mature old-growth forest and clearcut openings, less has been done to explore effects of thinning or post-fire salvage. Basic research on turbulence theory suggests however that even widely spaced cylinders (e.g. trees) can be effective in reducing turbulence at the bottom surface (Poggi et al., 2004a, 2004b), so thinning may have little effect on peak snowmelt rates during rain-on-snow events in maritime regions.

Roads, depending on their connectivity with the stream network, can intercept rainfall and slower moving subsurface flow and deliver that water directly to the channel, reducing the time of concentration, and increasing peak flows (Megahan, 1972; Wemple et al., 1996; LaMarche and Lettenmaier, 2001; Luce, 2002; Wemple and Jones, 2003) as well as total flow. This effect is influenced by both road density and the connection of the road system to the stream system. Some control can be achieved with best management practices by reducing both density and proximity to stream channels; however the potential impact from roads designed for fuel management operations must carefully balance access needs with the short reaches typically used for yarding thinned materials. The interception of water by roads may be greater in snow dominated environments than in rain-dominated climates (Luce, 2002).

Changes to the soil that reduce infiltration capacities (i.e. hydrophobic /plugged soils following fire or disturbed soil surfaces resulting from compaction) can also alter the pathway that precipitation takes to the stream channel, quickening storm response time and increasing flood magnitude. A key change in the process is that much more water may be made available to surface runoff. Effects are often in the summer when precipitation intensity is high and water repellency is greatest, and the resultant erosion can be dramatic (Luce, 2005). As with roads, best management practices are usually implemented during mechanical operations to reduce or eliminate this problem. Generally, the intent of prescribed burning is to reduce fuel loading without severe effects to the soil, so impermeable soils are rarer than with wildfire.

In the absence of altered pathway, increases in peak flow response following forest removal is largely a reflection of the higher soil moisture content on the harvested portion of the watershed. Wetter soils allow a greater percentage of the precipitation to become available streamflow. Once the soil moisture under the uncut area is recharged any

potential effect that harvesting would have on peak discharge is either eliminated or severely diminished. Full soil moisture recharge can occur during snowmelt, during the dormant season in humid areas, or during the larger rainfall events so it is unlikely that timber harvesting, even clear cutting, could significantly affect the largest storms. One can expect that the effect of partial tree removal, as would be the case in a fuels reduction treatment, will have minimal affect on peak discharge because the effect of treatment on soil moisture can be expected to be minimal (Troendle 1987a). Mid-range peaks may still be increased because of interception savings in the snowpack but not because of reduced soil moisture recharge requirements.

3.6 Hydrologic Recovery:

The longevity of hydrologic response following timber harvest appears to be unique in the Rocky Mountain region relative to other hydrologic regions. Treatment effects are quite long lasting both in terms of water yield and snowpack accumulation. During the first 28 years following timber harvest, the "average" 10 cm first-year increase in flow at Fool Creek had declined by only 28-percent to 7.2 cm (Troendle and King 1985) and full hydrologic recovery is currently projected to require 60 or more years (Laurie Porth, personal communication, Rocky Mountain Research Station). The time required for hydrologic recovery when the silvicultural practice is a thinning, or individual tree removal, rather than clear cutting, is more speculative. 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 documented to have occurred under the 40-percent basal area removal partial cut at Deadhorse Creek (Troendle and King 1987) still persisted 20 years after harvest (Laurie Porth, personal communication, Rocky Mountain Research Station). This implies that at least a portion of the increase in flow following partial cutting, or thinning, in the cold snow zone would be long lasting. This is not the case in humid regions where regrowth occurs much more rapidly and the accumulation of a winter snow pack is not the primary source of streamflow generation.

Unlike the cold snow zone, the longevity of treatment effects, either clear cutting or thinning, is relatively short lived through out the balance of the United States (Hornbeck et al 1997, Hornbeck and Kockenderfer 2004, Douglas 1983, Jackson et al 2004, Beasly et al 2004, Keppeler and Zeimer 1990, Harr 1983, Brown et al 1974, Kattleman and Ice 2004, Troendle and Leaf 1980). Vegetation response following harvest is quite rapid and the effects of treatment can be expected to diminish in a little as 10- to 20-years or less.

4. Hydrologic effects of prescribed fire on runoff characteristics

Prescribed burning is the controlled use of fire to achieve specific management objectives (Walstad et al., 1990) and is commonly used to reduce fuels buildup and the associated risk of severe wildfire (Norris, 1990). Between 1995 and 2000, 7.5 million hectares managed by federal agencies in the U.S. were treated with prescribed fire (NIFC, 2006). Relative to wildfires and forest harvest, the effects of prescribed burning have received

little study, and questions concerning the impact to watershed resources remain unanswered (Anderson et al., 1976; Tiedemann et al., 1979; Gottfried and DeBano, 1990).

The hydrologic effects of prescribed burning are less severe than those of wildfire. In managed forests, the effects of roads and forest harvest may also exceed those of prescribed burning (McNabb and Swanson, 1990). 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 (Wells et al., 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, and soil heating is expected to be low, the effects on soil are limited in severity and extent. The percent exposed mineral soil following low severity prescribed burns is generally between 5 and 30%, whereas values ranging from 35 to 95% have been reported following high severity prescribed burns or wildfires (Cooper, 1961; Van Lear and Danielovich, 1988; Van Lear and Kapeluck, 1989; Robichaud et al. 1993; Swift et al., 1993; Robichaud and Waldrop, 1994; Benavides and MacDonald, 2001; 2005). The hydrologic effects of fire depend on many factors, including: the severity of the burn, the proportion of the watershed burned, watershed physiography, soil type, the rate of vegetation recovery, and the precipitation regime during the recovery period (Luce, 2005).

4.1 Impacts on-site

After prescribed fire, the resulting surface condition is a mosaic-like pattern composed 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 (Shakesby et al., 2000; Doerr and Moody, 2004; Luce, 2005). Where the burn severity is patchy, unburned and low severity patches infiltrate runoff and trap sediment generated on adjacent high severity patches (Biswell and Schultz, 1957; Cooper, 1961, Swift et al., 1993). The burn severity pattern controls 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 (Huffman et al., 2001).

4.2 Impacts 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 1-10% basal area mortality reported following low severity prescribed burns in ponderosa pine is below the 20-percent threshold at which changes in streamflow might be detectable (Gottfried and DeBano, 1990; Gundale, 2005). The reduction in forest floor water storage due to prescribed burning of ponderosa pine varies, but even the lower-most litter layer must be modified or removed before the water holding capacity of the forest floor is significantly

reduced (Cooper, 1961; Clary and Ffolliot, 1969; Agee, 1973). Therefore prescribed fire does not pose a threat to increasing watershed-scale runoff unless a large proportion of the watershed burns at high severity.

Water yields did not increase following a prescribed fire that burned 43% 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% of the pre-burn basal area and left most of the litter intact (Gottfried and DeBano, 1990). Similar results were found after repeated prescribed burning of South Carolina loblolly pine watersheds (Douglass and Van Lear, 1983). Four watersheds were burned in entirety by each of two successive prescribed fires, but burning had no detectable effect on streamflow (Douglass and Van Lear, 1983). Changes in streamflow were not detected following prescribed fires in giant sequoia-incense cedar forests of Sequoia National Park (Heard, 2005). The effects of burning were examined at two spatial scales; in a 100 ha watershed where 60% of the area was burned, and in a 20,000 ha watershed where eight fires burned 11% of the watershed over a seven year period. Prescribed burning did not alter water yield in either watershed, which was attributed to the low-severity burn in the 100 ha watershed and the small burned proportion of the 20,000 ha watershed. In contrast, a prescribed fire in Sequoia National Park caused 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 most of the forest litter (Williams and Melack, 1997).

The impacts of prescribed fire on streamflow are somewhat variable depending on cover type. In forested watersheds, light to moderate prescribed fire has little effect on streamflow. This is largely because only a small percentage of the vegetation is impacted and net changes in infiltration characteristics are minimal. The major components of the water balance are not impacted and therefore watershed function is not altered. When the cover type is chaparral, the relative intensity of the burn appears to be greater, a greater percentage of the vegetation is consumed, and a greater percentage of the soils become water repellant. Increased water yield was observed following prescribed burning of chaparral watersheds, although the increases were associated with either severe burns or above normal rainfall (Riggan et al., 1994). The fires burned 80-90% of the watershed area. Exaggerating the response is the fact that in the more arid ecoregions, where brush species tend to be dominant, the precipitation regime consists of less precipitation dominated more by extreme events; so the opportunity for hydrologic response to prescribed burning is greater.

Overall, the use of prescribed fire as a fuels reduction treatment on forest land will probably not result in a significant alteration of streamflow; unless the prescribed fire becomes a wildfire.

5. Predicting Changes in Water Yield

In 1980 the US-EPA published a set of graphical procedures useful in estimating the hydrologic impacts of various silvicultural activities on water yield and water quality.

The document, Water Resources Evaluation of Non-Point Sources in Siviculture, is referred to as the WRENSS Handbook (US-EPA 1980). Chapter III, Hydrology, presented a set of regionalized curves that could be used to adjust estimates of evapotranspiration to account for changes in stand density or condition (Troendle and Leaf 1980). Predicted change in evapotranspiration was considered to represent a change in water available for stream flow. WRENSS provides regional estimates of evapotranspiration as well as the modifier functions necessary to adjust for a range of silvicultural prescriptions. In the snow dominated procedure, precipitation was modified by the configuration of the forest which, in turn, modified the amount of evapotranspiration. In the rain dominated procedures, precipitation is less relevant in that it is not adjusted to reflect stand condition and change in evapotranspiration is estimated directly.

The understanding of hydrologic processes in the cold snow zone has evolved significantly since WRENSS was originally developed and a new version of the model, WinWrnsHyd, has been produced (Swanson 2005). One of the most significant changes is that this program incorporates the latest research on how forest harvest affects snow accumulation. These make the model more sensitive to the impacts of partial cuts or thinning on water yield in the cold snow zone (Shepperd et al. 1992). The revised snowpack sublimation and scour routines are more sensitive to wind speed and surface roughness as well as opening size. This allows one to assess the effects of leaving or removing slash or other forms of roughness on snowpack accumulation, and integrate the changes in snow accumulation with the changes in wind speeds due to removing some or the entire forest canopy.

WinWrnsHyd is programmed in Microsoft Access and uses data base 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.

6. 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 over space, such as the effect of multiple management activities within a basin, or over time, such as when 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 fuels 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% of the basal area in a forested watershed must be removed to order to obtain a detectable change in stream flow. As watershed size increases, it is increasingly unlikely that forest management will rapidly affect more than 20% of the basal area in a watershed, and this means that a given change is progressively less likely to be detected in the downstream direction (Harr 1989).

Furthermore, most fuels management activities in the west are likely to be concentrated in drier areas that have a higher risk of high-severity wildfires, and the resultant hydrologic effects will be less than in wetter areas or more humid areas. 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 18-20 inches. Thinning has been demonstrated to cause moderate increases in streamflow in the central Appalachians where precipitation greatly exceeds 18-20 inches (Reinhart et al 1964) but the hydrologic recovery was quite rapid (Hornbeck et al 1993). Finally, the persistence of a hydrologic change due to a reduction in the forest canopy generally will be relatively short everywhere except in the cold snow zone. The implication is that the hydrologic effect of a fuels management activity is most likely to be detectable immediately below the activity, and the effect of multiple activities is likely to be diluted in the downstream direction (MacDonald, 2000). For example, clearcutting 36% of the North Fork of Deadhorse Creek sub-basin in the Fraser Experimental Forest in central Colorado, caused a significant increase in stream flow. However this change in flow was not detectable a few hundred meters downstream at the main stream gauge on Deadhorse Creek, as the harvest on the North Fork represented only 5.6-percent of the total Deadhorse Creek watershed (Troendle and King 1987).

A concern in assessing the potential cumulative hydrologic effect is whether a given increase will be transmitted downstream to the location of interest without incurring significant transmission losses. In most mountainous areas one can assume that total transmission losses will not be substantially altered by the change in flow that might be generated by forest harvest or fuel management activities. However, seepage losses may be significant as 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, and this means that an increase in streamflow may be "lost" to groundwater storage. The potential for transmission losses will be both a function of the scale of the analysis, the flow regime, and the 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 et al. (2003) estimated the changes in average annual water yield resulting from long-term vegetation changes in the North Platte River Basin. Current vegetative conditions in the river basin were extrapolated backwards in time from U.S. 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)	PredictedWater 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

7. Summary

One can conclude that forest fuels reduction treatments, will probably have little detectable impact on water yield either on-site or downstream. Most prescriptions are not likely to exceed the 20-percent basal area removal threshold necessary to result in a detectable change in flow. However, in some regions and in some forest types, such as Ponderosa Pine along the Front Range of Colorado, fuel reduction treatments that reduce basal area to 50 $ft^2 \cdot A^{-1}$ or less may be severe enough to cause a significant reduction in soil water depletion that could result in a low level flow change (MacDonald, unpublished data). As Bosch and Hewlet (1982) concluded and subsequent data (Hornbeck et al 993) and modeling (Troendle et al 2003) support, lesser changes forest density may result in measurable but non-significant increases in streamflow. Both data and models also suggest there is little measurable response in either precipitation input or streamflow if less than 10-percent of the basal area is impacted above the point of interest. The magnitude of any hydrologic response to low level treatments is greatest in

wetter years and probably non existent in dry years and it can be further assumed that properly implemented fuel reduction treatments would have virtually no detectable effect on peak discharges. With the exception of the Rocky Mountain region, it can be expected that any flow change would be short lived.

It can be expected in the Rocky Mountain, and similar, region that any prescription severe enough to cause a change in snowpack accumulation may result in a water yield change.

Properly implemented prescribed fires, used as a fuel reduction tool, are probably less likely to influence water yield than are mechanical treatments because the level of disturbance is less. However, the same cannot be said for a prescribed burn that becomes a wildfire.

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 come a critical component in the planning process as a means of assessing long term impacts.

8. Literature Cited

Agee, J.K., 1973. Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil. University of California Water Resources Center Contribution Report No. 143. 57 p.

Anderson, Mark Theodore. 1980. Water quantity and quality of three adjacent Black Hills watersheds. Rapid City, SD: South Dakota School of Mines and Technology. Unpublished M.S. Thesis 158 p.

Anderson, Henry W., Marvin D. Hoover, and Kenneth G. Reinhart. 1976. Forests and Water: Effects of forest management on floods, sedimentation, and water supply. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA. USDA Forest Service GTR PSW 18/1976, 115 p.

Bailey, R. G. 1976. Map: Ecoregions of the United States. USDA Forest Service, Intermountain Region, Ogden Utah. Scale 1:7,500,000.

Bailey, R. G. 1994. Map: Ecoregions of the United States (rev.) USDA Forest Service, Washington, DC. Scale 1:7,500,000.

Bailey, R. G. 1995. Description of the Ecoregions of the United States. 2nd ed. Rev. and expanded. Misc. Pub. No. 1391(rev.) USDA Forest Service, Washington, DC with separate map at scale 1:7,500,000.

Bailey, R. G. 1998. Ecoregions: The ecosystem geography of the oceans and continents. Springer-Verlag, New York. With Separate maps of the Oceans and Continents at 1:80,000,000.

Bailey, R. G. and C. T. Cushwa. 1981. Ecoregions of North America. FWS/OBS-81/29. U. S. Fish and Wildlife Service, Washington , DC. Scale 1:7,500,000.

Bates, C. G. and A. J. Henry. 1928. Forest and stream flow experiment at Wagon Wheel Gap, Colorado. U.S. Monthly Weather Review, Supplement 30. Washington D.C. 79 p.

Beasley, R. Scott, Edwin L. Miller, Wilbert H. Blackburn, and Edwin R. Lawson. 2004. Assessing the Effects of Intensive Forest Management: Watershed Studies in the Mid-South. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 113-128.

Beaudry, P. G., and D. L. Golding. 1983. Snowmelt during rain-on-snow in coastal British Columbia, in Proceedings of the 51st Western Snow Conference, pp. 55–66, Colorado State Univ., Fort Collins, Colorado.

Benavides-Solorio, J., and L. H. MacDonald. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes 15:2931-2952.

Benavides-Solorio, J., and L. H. MacDonald. 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. International Journal of Wildland Fire 14:457-474.

Berris, S. N. and R. D. Harr. 1987, Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon, Water Resources Research, 23, 135-142.

Bevers, M., J. Hof, and C. Troendle. 1996. Spatially optimizing forest management schedules to meet stormflow constraints. Journal of the American Water Resources Association. 32(5), 1007-1015.

Bevinger, G.S. and C.A. Troendle. 1987. The Coon Creek water yield augmentation pilot project. p. 145-149. In: Troendle, Charles A.; Kaufmann, Merrill R.; Hamre, R. H.; Winokur, Robert, P., Tech. coord. Management of subalpine forests: Building on 50 years of research. Proceedings of a technical conference; July 6-7, 1987; Silver Creek, CO. Gen. Tech. Rep. RM-149. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Biswell, H.M. and A. M. Schultz. 1957. Surface runoff and erosion as related to prescribed burning. Journal of Forestry 55:372-374.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. of Hydrology. 55: 2-23.

Bowling, L. C., P. Storck, D. P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States, Water Resources Research, 36, 3223-3240.

Brender, E.V. and R. W. Cooper. 1968. Prescribed burning in Georgia's piedmont loblolly pine stands. Journal of Forestry, 66:31-36.

Brown, H. E., M. B. Baker, Jr., J. J. Rogers, W. P. Cleary, J. L. Kovner, F. R. Larsen, C. C. Avery, and R. E. Campbell. 1974. Opportunities for increasing water yields and other multiple use values on Ponderosa Pine forest lands. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO>USDA Forest Service Res. Paper RM-129, 36 p.

Christner, J., and R. D. Harr. 1982. Peak streamflows from the transient snow zone, western Cascades, Oregon, in Proceedings of the 50th Western Snow Conference, pp. 27–38, Colorado State Univ., Fort Collins, Colorado.

Clary, W.P. and P. F. Ffolliot. 1969. Water holding capacity of ponderosa pine forest floor layers. Journal of Soil and Water Conservation 24:22-23.

Cooper, C.F., 1961. Controlled burning and watershed condition in the White Mountains of Arizona. Journal of Forestry 59:438-442.

DeBano, Leonard F., Peter F. Ffolliott, and Malcus B. Baker Jr. 2004. Fifty Years of Watershed Management in the Southwest: Some Lessons Learned. Chapter 6. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 155-168.

Dietrich, T. L. and J. R. Meiman. 1974. Hydrologic Effects of Patch Cutting of Lodgepole Pine. Hydrology Paper 26. Colorado State University, Fort Collins, CO. 31 p.

Doerr S.H. and Moody J.A. 2004. Hydrological effects of soil water repellency: on spatial and temporal uncertainties. Hydrological Processes, 18, 829–832.

Dobrowolski, J.P., J. P. Blackburn, and H. A. Pearson. 1992. Changes to infiltration and interrill erosion from long-term prescribed burning in Louisiana. Water Resources Bulletin 28:287-298.

Douglas, J.E. and D. E. Van Lear. 1983. Prescribed burning and water quality of ephereral streams in the piedmont of South Carolina. Forest Science 29:181-189.

Douglass, J. E. 1983. The potential for water yield augmentation from forest management in the eastern United States. Water Resource Bulletin. 19(3): 351-358.

Eagleson, P. S. 1978. Climate, soil, and vegetation. 7. A derived distribution of annual water yield, Water Resour. Res., 14, 765-776.

Field, J.P., K. W. Farrish, and E. A. Carter. 2003. Soil and nutrient losses following site preparation burning in a harvested loblolly pine site. Transactions of the American Society of Agricultural Engineers. 46:1697-1703.

Field, J.P., K. W. Farrish, B. P. Oswald, M. T. Romig, and E. A. Carter. 2005. Forest site preparation effect on soil and nutrient losses in east Texas. Transactions of the American Society of Agricultural Engineers 48:861-869.

Garstka, W.U.; L.D. Love; B.C. Goodell; F.A. Bertle 1958. Factors affecting snowmelt and stream flow. Washington DC: U.S. Department of Interior, Bureau of Reclamation; U.S. Department of Agriculture, Forest Service; 189 p.

Gary, Howard L. 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine type. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. Research Paper RM- 139. 32 p.

Gary, Howard L. and Charles A. Troendle. 1982. Snow accumulation and melt under various stand densities in Lodgepole pine in Wyoming and Colorado. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Note RM-417. Fort Collins, CO. 7 p.

Gary, H. L. and R. K. Watkins 1985. Snow pack accumulation before and after thinning a dog-hair stand of lodgepole pine. Res. Note RM-450. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 4 p.

Goodell, B. C. 1952. Watershed management aspects of thinned young Lodgepole pine stands. J. of For. 50: 374-378.

Goodell, B. C., and H. G. Wilm. 1955. How to get more snow water from forest lands. USDA Agricultural Yearbook, 1955. pp 228-234.

Gottfried, G.J. and L. F. DeBano. 1990. Streamflow and water quality responses to preharvest prescribed burning in an undisturbed Arizona ponderosa pine watershed: *in*, Gundale, M.J., T. H. DeLuca, C. E. Fiedler, P. W. Ramsey, M. G. Harrington, and J.E. Gannon. 2005. Restoration treatments in a Montana ponderosa pine forest: Effects on soil physical, chemical, and biological properties. Forest Ecology and Management 213:25-38.

Heard, A.M., 2005. Effects of landscape scale prescribed fire on hydrology and stream chemistry. M.S. Thesis. Colorado State University, Fort Collins, CO. 146 p.

Harr, R. D. 1983. Potential for augmenting water yield through forest practices in western Washington and western Oregon. Water Resources Bulletin. 19(3): 383-393.

Harr, R. D. 1986. Effect of clearcutting on rain-on-snow runoff in western Oregon: A new look at old studies., Water Resources Research, 22, 1095-1100.

Haupt, H. F. 1951. Snow Accumulation and Retention on Ponderosa Pine Lands in Idaho, Journal of Forestry, 49, 869-871.

Haupt, H. F. 1979. Effects of timber cutting and revegetation on snow accumulation and melt in Northern Idaho.USDAForest Service, Intermountain Forest and Range Experiment Station, Research PaperINT-114

Hewlett, J.D., G.B. Cunningham, and C. A. Troendle. 1977. Predicting stormflow and peakflow from small basins in humid areas by the R-index method. Water Resource Bull. 13(2):23 p.

Hibbert, A. R. 1967. Forest treatment effects on water yield. In: W. E. Sopper and H. W. Lull (Editors) Forest Hydrology. Pergamon, New York, N.Y. PP. 527-543.

Hoover, M. D. and C.F. Leaf 1967. Process and significance of interception in Colorado sub alpine forest. In: W. E. Sopper and H. W. Lull (Editors) Forest Hydrology. Pergamon, New York, N.Y. PP. 213-224.

Hornbeck, J. W., C. W. Martin, and C. Eagar. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. Canadian Journal of Forest Research. 27: 2043-2052.

Hornbeck, James W. and James N. Keckenderfer. 2004. A Century of Lessons About Water Resources in the Northeastern Forests. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 19-32.

Huffman, E.L., L. H. MacDonald, and J. D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes 15:2877-2892.

Ice, George G. and John D. Stednick, eds. 2004. A Century of Forest and Wildland Watershed Lessons. Society of American Foresters, Bethesda, MD. 287 p.

Jackson, Rhett C., Ge Sun, Devandra Amatya, Wayne T. Swank, Mark Reidel, jim Patric, Tom Williams, Jim N. Vose, Carl Trettin, W. Michael Aust, R.Scott Beasley, Hanlin Williston, and George G. Ice. 2004. Fifty Years of Forest Hydrology in the Southeast. In:

A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 33-112.

Jones, J. A. 2000. hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. Water Resources Research 36(9): 2621-2642.

Jones, J. A. and G. E. Grant. 1996. peak flow response to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32(4): 959-974.

Kattleman, R. C., N. H. Berg, and J. Rector. 1983. The potential for increasing stream flow from Sierra Nevada watersheds. Water Resource Bulletin. 19(3): 395-401.

Kattleman, Rick and George G. Ice. 2004. Dry/Cold, Wet/Warm, and Transient Snow: Regional Differences in Forest Snow Hydrology. Chapter 8. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 187-200.

Kaufmann, Merrill R. and Charles A. Troendle. 1981. Leaf area, foliage biomass, and sapwood conducting area in four subalpine forest tree species. Forest Science 27:477-482.

Kaufmann, Merrill R., Carleton B. Edminster, and Charles A. Troendle. 1982. Leaf area determinations for subalpine tree species in the central Rocky Mountains. U.S. Department of Agriculture, Forest Service, Research Paper: RM-238, 7 p.

Kaufmann, Merrill R., Charles A. Troendle, Michael G. Ryan, and H. Todd Mowrer. 1987. Trees...The link between silviculture and hydrology p. 54-60. In: Troendle, Charles A.; Kaufmann, Merrill R.; Hamre, R. H.; Winokur, Robert P. Tech. Coord. Management of subalpine forests: Building on 50 years of research. Proceedings of a technical conference; July 6-9,1987; Silver Creek, CO. Gen. Tech. Rep. RM-149. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 253 p.

Keppeler, Elizabeth T. and Robert R. Zeimer. 1990. Water yield and summer low flows at Casper Creek in Northwestern California. Water Resources Research: 26(3) 1669-1679.

La Marche JL, Lettenmaier DP. 2001. Effects of forest roads on flood flows in the Deschutes River, Washington. Earth Surface Processes and Landforms 26: 115–134.

Leaf, Charles F. 1975. Watershed management in the Rocky Mountain sub alpine zone: the status of our knowledge. Res. Pap. RM-137. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 31 p.

Leaf, Charles F. 1999. Cumulative Hydrologic Impacts of U.S. Forest Service Management Practices on the Routt, Arapaho-Roosevelt, Pike, and Medicine Bow National Forests: Potential for Water Yield Improvement. Platte River Hydrologic Research Center. Research Paper PRHRC-3. 15 p.

Leaf, C. F. and G. E. Brink. 1973. Hydrologic simulation model of Colorado sub alpine forest. U.S. Dep. Agric. For. Serv. Res. Pap. RM-107, Rocky Mount. For. And Range Exp. Stn., Fort Collins, CO. 23 p.

Love, L. D. 1953. Watershed Management in the Colorado Rockies. J. Soil and Water Cons. 8: 107-112.

Love, L. D. 1955. The effect on stream flow of the killing of spruce and pine by the Englemann spruce beetle. Trans of the Am Geo Union. 36(1): 113-118.

Luce, C. H. 2002. Hydrological Processes and Pathways Affected by Forest Roads: What Do We Still Need to Learn? Hydrological Processes, 16, 2901-2904.

Luce, C. H., 2005, Fire Effects on Runoff Generation Processes, in Anderson M.G. and J.J. McDonnell eds., Encyclopedia of Hydrological Sciences, Vol 3, John Wiley and Sons, Chichester. pp. 1831-1838.

MacDonald, L. H., and J. A. Hoffman. 1995. Causes of peak flows in northwestern Montana and northeastern Idaho, Water Resources Bulletin, 31, 79-95.

McNabb, D.H. and F. J. Swanson. 1990. Effects of fire on soil erosion: *in*, Walstad, J.D., Radosevich, S.R., and Sandberg, D.V., eds. Natural and prescribed fire in Pacific Northwest forests. Corvallis, OR. p. 159-176.

Marks, D., J. Kimball, D. Tingey, and T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest Flood, Hydrol. Process., 12, 1569-1587.

Megahan WF. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. In Proceedings, National Symposium on Watersheds in Transition. American Water Resources Association: Fort Collins, CO; 350–356.

Meiman, James R. 1987. Influence of forests on snow pack accumulation. In: Management of Sub alpine Forests: Building on Fifty Years of Research. Proceeding of a Technical Conference, Silver Creek, Colorado, July 6-9, 1987. US For Serv Gen Tech Rep RM-149. 61-67.

Meiman, J. R. 1970. Snow accumulation related to elevation, aspect, and forest canopy. In: Snow Hydrology, proceedings of a Workshop Seminr, 1968. Queens Printer for Canada, Ottawa. Pp 35-47.

National Interagency Fire Center, 2005. Prescribed fire statistics. http://www.nifc.gov/stats/prescribedfirestats.html (Accessed 5 January 2006).

Norris, L.A., 1990. An overview and synthesis of knowledge concerning natural and prescribed fire in Pacific Northwest forests. *in*, Walstad, J.D., Radosevich, S.R., and Sandberg, D.V., eds. Natural and prescribed fire in Pacific Northwest forests. Corvallis, OR. p. 7-22.

Packer, P. E. 1962. Elevation, aspect, and cover effects on maximum snowpack water equivalent in a western white pine forest . Forest Science. 8: 225-235.

Pase, C.P. and A. W. Lindenmuth. 1971. Effects of prescribed fire on vegetation and sediment in oak-mountain mahogany chaparral. Journal of Forestry 69:800-804.

Poggi, D., A. Porporato, L. Ridolfi, J. D. Albertson, and G.G. Katul. 2004. The effect of vegetation density on canopy sub-layer turbulence, Boundary-Layer Meteorology, 111, 565-587

Poggi, D., A. Porporato, L. Ridolfi, J. D. Albertson, and G.G. Katul. 2004. Interaction between large and small scales in the canopy sublayer, Geophys. Res. Lett., Vol. 31, No. 5, L05102

Potts, D. F. 1984a. Hydrologic impacts of a large-scale mountain pine beetle (Dendroctonus ponderosae) epidemic, Water Resources Bulletin, 20, 373-377.

Potts, D. F. 1984b. Snow accumulation, melt and soil water recharge under various lodgepole pine stand densities in western Montana. In: Proceedings, 52nd Western Snow Conference; 1984 April 17-19; Sun Valley, ID. Fort Collins, CO: Colorado State University.

Rosa, J. M. 1961. Some forest, climatic and topographic factors which determine the characteristics and hydrographs from melting snow, In Proceedings Watershed Conference, September 12, 1961, McCall, ID, Northwest Branch, Soil and Water Conservation Division, Agricultural Research Service, pp. 31.

Rice, Raymond M, Robert R. Zeimer, and Jack Lewis. 2004. Evaluating Forest Management Effects on Erosion, Sediment, and Runoff: Casper Creek and Northwestern California. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 223-238.

Riggan, P.J., R. N. Lockwood, P. M. Jacks, C. G. Colver, F. Weirlich, L. F. DeBano, and J. A. Brass. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. Environmental Science and Technology 28:369-375.

Reinhart, K. G., A. R. Eschner, and G. R. Trimble. 1964. Effect on streamflow of four forest practices. USDA Forest Service, Northeastern Forest Experiment Station. Research Paper NE-1. 79 p.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology 231-232:220-229.

Robichaud, P.R. and T. A. Waldrop. 1994. A comparison of surface runoff and sediment yields from low-and high-severity site preparation burns. Water Resources Bulletin 30:27-34.

Robichaud, P.R., C. H. Luce, and R. E. Brown. 1993. Variation among different surface conditions in timber harvest sites in the southern Appalachians, *in*, International workshop on soil erosion, Proceedings. Moscow, Russia. September 1993. The center for technology transfer and pollution prevention. Purdue University, West Lafayette, IN. p. 231-241.

Schmidt, R.A. and C.A. Troendle. 1989. Snowfall into a forest and clearing. Journal of Hydrology 110:335-348.

Schmidt, R.A. and C.A. Troendle. 1992. Sublimation of intercepted snow as a global source of water vapor. In: Proceedings 60th Western Snow Conference; 1992 April 14-16; Jackson Hole, WY. Fort Collins, CO: Colorado State University; 60: 1-9.
Schmidt, R. A., C. A. Troendle, and J. R. Meiman. 1998. Sublimation of snowpacks in subalpine conifer forests. Canadian Journal of Forest Research. 28: 501-513.

Shakesby R.A., Doerr S.H. andWalsh R.P.D. 2000. The erosional impact of soil hydrophobicity: current problems and future research directions. Journal of Hydrology, 231–232, 178–191.

Shepperd, W. D., C. A. Troendle, and C. B. Edminster. 1992. Linking water and growth and yield models to evaluate management alternatives in subalpine ecosystems. In: Getting to the future through silviculture. Proceedings of the National Silviculture Workshop. May 6-9, 1991. Cedar City, UT. U.S. Department of Agriculture, Forest Service, Gen. Tech. Rep. INT-291. 42-48.

Stednick, John D. 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology. 176: 79-95

Stednick, John D. and C. A. Troendle. 2004. Water Yield and Timber Harvesting Practices in the Subalpine Forests of the Central Rocky Mountains. Chapter 7. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 165 – 182.

Storck, P., L. Bowling, P. Wetherbee, and D. P. Lettenmaier. 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest, Hydrological Processes, 12, 889-904.

Storck, P., T. Kern, and S. Bolton. 1999. Measurement of differences in snow accumulation and melt due to forest harvest, Northwest Sci., 73, 87–101.

Swanson, R. H. and G. R. Hillman. 1977. Predicted increased water yield after clearcutting in West Central Alberta. NOR-X-198. Edmonton, AB: Northwest Forestry Research Centre; 40 p.

Swanson, R. H., D. L. Golding, R. L. Rothwell, and P. Y. Bernier. 1986. Hydrologic effects of clear cutting at Marmot Creek and Streeter Watersheds, Alberta. Canadian Forest Service, Northern Forest Centre, Edmonton, Alberta. Information Report NOR-X-278. 27 p.

Swift, L.W., Jr., K. J. Elliot, R. D. Ottmar, and R. E. Vihnanek. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: fire characteristics and soil erosion, moisture, and temperature. Canadian Journal of Forest Research 23:2242-2254.

Thomas, R. B. and W. F. Megahan. 1998. Peak flow responses to clearcutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resources Research 34: 3393-3403.

Tiedemann, A.R., C. E. Conrad, J. H. Dietrich, J. W. Hornbeck, W. F. Megahan, L. A. Viereck, and D. D. Wade. 1979. Effects of fire on water: A state-of-knowledge review. USDA Forest Service General Technical Report WO-10. 28 p.

Toews, D. A. A. and D. R. Gluns. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in Southeastern British Columbia. In; Proceedings of the Western Snow Conference April 15-17, 1986. Phoenix, AZ. Fort Collins, CO.

Troendle, Charles A. 1983. The potential for water yield augmentation from forest management in the Rocky Mountain Region. American Water Resources Bulletin 19(3):359-373.

Troendle, C.A. 1987. The potential effect of partial cutting and thinning on streamflow from the subalpine forest. U.S. Department of Agriculture, Forest Service, Research Paper RM-274. Fort Collins, CO.

Troendle, C.A. 1988. Effect of partial cutting and thinning on the water balance of the subalpine forest. p. 108-116. In: Schmidt, Wyman C. compiler. Proceedings of future forests of the mountain west: A stand culture symposium; 1986 Sept. 29-Oct. 3; Missoula, MT. Gen. Tech. Rep. Int.-243. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 402 p.

Troendle, C.A. and G.S. Bevenger. 1996. Effect of fire on streamflow and sediment transport. Shoshone National Forest, Wyoming. In: Greenlee, J. M., ed. The ecological implications of fire in Greater Yellowstone. Second Biennial Conference on the Greater Yellowstone Ecosystem; 1993 September 17-21; Yellowstone National Park, WY. Fairfield, WA: International Association of Wildland Fire: 139 p.

Troendle, Charles A. and M.R. Kaufmann. 1987. Influences of forests on the hydrology of subalpine forests. p. 68-78. In: Troendle, Charles A.; Kaufmann, Merrill R.; Hamre, R. H. Winokur, Robert P. Tech. Coord. Managementof subalpine forests: Building on 50 years of research. Proceedings of a technical conference; 1987 July 6-9; Silver Creek, CO. Gen Tech. Rep. RM-149. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 253 p.

Troendle, C.A. and R.M. King. 1985. The Fool Creek watershed, 30 years later. Water Resources Research 21(12): 1915-1922.

Troendle, C.A. and R.M. King. 1987. The effect of partial cutting and clearcutting on the Deadhorse Creek watershed. Journal of Hydrology 90: 145-157.

Troendle, Charles A. and Charles F. Leaf. 1980. Hydrology. Chapter III. In: An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources. US Environmental Protection Agency. August 1980. EPA-600/8-80-012 Athens, GA. III.1-III.173.

Troendle, Charles A. and Charles F.Leaf. 1981. The effects of timber harvest in the snow zone on volume and timing of water yields. In Proceedings, Interior West Watershed Management Symposium. (D. M. Baumgartner, Ed.) April 8-10, 1980. 288 p. Washington State University, Pullman, WA.

Troendle, C.A. and J.R. Meiman. 1984. Options for harvesting timber to control snowpack accumulation. In: Proceedings 52nd Annual Western Snow Conference, Sun Valley, Idaho. April 17-19, 1984. p. 86-97.

Troendle, C.A. and J.R. Meiman. 1986. The effect of patch clearcutting on the water balance of a subalpine forest slope. In: Proceedings 54th Western Snow Conference, April 15-17, 1986, Phoenix, Arizona; Fort Collins, CO/USA. Colorado State University. p. 93-100.

Troendle, C. A. and J. M. Nankervis. 2000. Estimating Additional Water Yield from Changes in Management of National Forests in the North Platte Basin. Final report submitted to the Bureau of Reclamation by MATCOM Corporation, Fort Collins, CO. 51p.

Troendle, C. A., J. M. Nankervis, and L. S. Porth. 2003. The impact of Forest Service Activities on the stream flow regime in the Platte River. Final report submitted to the U. S. Forest Service by MATCOM Corporation. Fort Collins, CO. 50 p. plus Appendices.

Troendle, C.A. and W.K. Olsen. 1994. Potential Effects of Timber Harvest and Water Management of Streamflow Dynamics and Sediment Transport. In: Covington, W.W.; DeBano, L. eds. Sustainable ecological systems; 1993 July 12-15; Flagstaff, AZ/USA. Gen. Tech. Rep. RM-247. Fort Collins, CO/USA: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experimental Station: 34-41.

Troendle, C. A. and L. S. Porth. 2000. Predicting the 1.5-, 5-, 10-, and 25-Year Event From the Snow Zones of Colorado and Wyoming. In: Proceedings of the 68th Western Snow Conference. Port Angeles, WA. April 2000. Colorado State University. Fort Collins, CO. pp 41-48.

Troendle, C.A. and J.O. Reuss. 1997. Effect of clear cutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Sciences. I(2), 325-332.

Troendle, C.A., R.A. Schmidt, and M.H. Martinez. 1988. Snow deposition process in a forest stand with a clearing. 78-86. In: Proceedings 56th Annual Meeting Western Snow Conference; 1988 April 19-21; Kalispell, MT. Fort Collins, CO/USA. Colorado State University 9 p.

Troendle, C.A., R.A. Schmidt, and M.H. Martinez. 1994. Partitioning the Deposition of Winter Snowfall as a Function of Aspect on Forested Slopes. In: Eastern/Western Snow Conference; 1993 June 8-10; Quebec City, Quebec/CANADA. Washington, DC/USA: Western Snow Conference; 61: 373-380.

Troendle, C. A. and J. D. Stednick. 1999. A discussion of ``Effects of basin scale timber harvest on water yield and peak streamflow. Journal of the American Water Resources Association. 35 (1) 177-181.

Troendle, Charles A., Marc S. Wilcox, Greg S. Bevenger, and Laurie S. Porth. 2001. The Coon Creek water yield augmentation project: implementation of timber harvesting technology to increase streamflow. Jour. Forest Ecology and Management. 143(2001) 179-187

US-EPA. 1980. An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources. US Environmental Protection Agency. August 1980. EPA-600/8-80-012 Athens, GA.

Van Haveren, B. P. 1988. A reevaluation of the Wagon Wheel Gap Forest Watershed Experiment. Forest Science. 34(1): 208-214.

Van Lear, D.H. and S. J. Danielovich. 1988. Soil movement after broadcast burning in the southern Appalachians. Southern Journal of Applied Forestry 12:49-53.

Van Lear, D.H. and P. R. Kapeluck. 1989. Fell and burn to regenerate mixed pine-hardwood stands: An overview of effects on soil. *in*, Proceedings of pine-hardwood mixtures: A symposium on management and ecology of the type. USDA Forest Service General Technical Report SE-58. p. 83-90.

Verry, Elon S. 2004. Land Fragmentation and Impacts to Streams and Fish in Central and Upper Midwest. In: A Century of Forest and Wildland Watershed Lessons. George G. Ice and John D Stednick, Eds. Society of American Foresters, Washington D. C. (Elsevier Pub.) pp 129-154.

Walstad, J.D., S. R. Radosevich, and D. V. Sandberg. 1990. Introduction to natural and prescribed fire in Pacific Northwest forests. *in*, Walstad, J.D., Radosevich, S.R., and Sandberg, D.V., eds. Natural and prescribed fire in Pacific Northwest forests. Corvallis, OR. p. 3-5.

Wemple BC, Jones JA, Grant GE. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32: 1195–1207.

Wemple B. C., J. A. Jones. 2003. Runoff production on forest roads in a steep, mountain catchment, Water Resour. Res., 39 (8), 1220, doi:10.1029/2002WR001744.

Williams, M.R. and J. M. Melack. 1997. Effects of prescribed burning and drought on the solute chemistry of mixed conifer forest streams of the Sierra Nevada, California. Biogeochemistry 39:225-253.

Wilm, H. G. and E. G. Dunford. 1948. Effect of Timber Cutting on Water Available for Stream flow from a Lodgepole Pine Forest. USDA Technical Bulletin No. 968. 43 pp.

Woodruff, James F. and John D. Hewlett. 1970. Predicting and mapping the average hydrologic response for the Eastern United States. Water Resources Research 6(5): 1312-1326.