Hydrologic Processes in the Pinyon-Juniper Woodlands: A Literature Review

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Abstract

Hydrologic processes in the pinyon-juniper woodlands of the western region of the United States are variable because of the inherent interactions among the occurring precipitation regimes, geomorphological settings, and edaphic conditions that characterize the ecosystem. A wide range of past and present land-use practices further complicates comprehensive evaluations of these hydrologic processes. Heterogeneous vegetative covers make it even more difficult to generalize hydrologic processes and the effects of land management practices on the water balance. Nevertheless, estimates of interception, infiltration, evapotranspiration, soil moisture storage, and hillslope soil erosion of these on-site hydrologic processes have been obtained in plot studies. Estimates of off-site streamflow volumes, sediment yields and transport, and quality of streamflow water are available from the results of watershed-level investigations. Estimates of these respective hydrologic processes are presented in this general technical report.

Keywords: hydrologic processes, pinyon-juniper woodlands, plots studies, watershed-level investigations

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Contents

Introduction

Pinyon-juniper woodlands, the largest forest type in the United States, lie adjacent to and surround the montane forests of the western region. These woodlands—one of the most xeric forest types in the United States—occupy about 48 million acres primarily in Nevada, Utah, Arizona, New Mexico, and Colorado (Larson 1980). Extensive stands are also found in California and Texas with a few stands in southern Idaho, southern Wyoming, and western Oklahoma. Several associations of pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) trees comprise the pinyon-juniper woodlands throughout its range including pure or nearly pure stands of either pinyon or juniper trees and varying mixtures of the two tree genera (Tueller and others 1979, Meeuwig and Bassett 1983, Gottfried and others 1995, West 1999, Jacobs 2008, Pieper 2008). Complete crown closure of overstory trees is rare, but tree roots causing a suppression of understory vegetation often occupy the soils underneath well-developed stands.

Occurring at lower elevations and generally with less annual precipitation and higher evaporation rates than the montane forests, the pinyon-juniper woodlands (seemingly) possess a lower potential to increase streamflow volumes through vegetative management practices when compared to the higher-elevation montane forests (fig.1). However, because of the wide distribution of the woodlands, early investigators felt that vegetative management practices that increase the inherently low streamflow volumes might also increase water supplies to downstream users (Barr 1956, Dortignac 1960). The management practices considered focused largely on clearing (removal) of the comparatively high water-demanding overstory trees by mechanical, chemical, or burning treatments with the conversion of these sites to less water-demanding herbaceous covers. It was thought that reductions in water consumption by herbaceous plants might become recoverable water.

Estimates of the on-site hydrologic processes of interception, infiltration, evapotranspiration, soil moisture storage, and hillslope soil erosion and the off-site processes of streamflow volumes, sediment yields and transport, and quality of streamflow water can be obtained in plot studies and watershed-level investigations, respectively. A review of the literature reporting estimates of these on-site and off-site processes is presented in this report. General hydrologic characteristics of the pinyon-juniper woodlands are characterized initially to present these estimates in some perspective.

General Hydrologic Characteristics

Pinyon-juniper woodlands are found on diverse landscapes including sloping mesas and escarpments, steep canyon, and valley bottoms at middle elevations within semi-arid climates (Tueller and others 1979, Larson 1980, Gottfried and others 1995). Older stands of trees often occupy rocky hillslopes with sparse understories of herbaceous plants (Swetnam and Brown 1992). Developed from a variety of parent materials, soils supporting the woodlands are shallow to moderately deep and well drained with often low fertility levels (Evans 1988, Jacobs 2008, Laycock 1999). Most of the pinyon-juniper woodlands on the Coconino National Forest in north-central Arizona are found on soils belonging to the Alfisol, Mollisol, or Inceptisol Soil Orders (G. Robertson, 2011, personal conversation). Erodability of these soils is a general function of the variable vegetative cover, surface topography, and soil texture and structure encountered. High levels of naturally occurring hydrophobicity in some of these soils (Robinson 2009) can inhibit or even impede the infiltration process and, as a consequence, the linked processes of evapotranspiration. The amount of organic materials on the mineral soil surface also influences the hydrologic characteristics of the woodlands. Infiltration and absorption rates of the soils are affected by the spatial orientation and distribution of surface particles.

Wide fluctuations in weather patterns, low precipitation amounts, and high evapotranspiration rates characterize the pinyon-juniper woodlands (Gottfried and others 1995, Monsen and Stevens 1999, West 1999). Only during the coldest winter months is precipitation generally greater than the evapotranspiration rates. Streamflow is largely ephemeral with only a few permanent streams originating in the woodlands. Streamflow events coincide mostly with the occurrence of streamflow-generating precipitation events with many of these flows associated with high-intensity rainstorms, rapid melting of snow, or rain-on-snow events (Lopes and others 1996, 1999). Snowmelt-runoff produces the greatest amount of annual streamflow volume (fig. 1). Over 70 percent of the annual streamflow originating in the pinyon-juniper woodlands on the Beaver Creek watersheds in

Figure 1—The potential to increase streamflow volumes in the pinyon-juniper woodlands on this typical site in the Coconino National Forest near Camp Verde, Arizona, is not great because of low annual precipitation, high evapotranspiration, and shallow soils.

north-central Arizona (Ffolliott and Baker 1977) occurs as the result of snowmelt-runoff or the occasional rain-on-snow events (Clary and others 1974, Baker 1984, Baker and Ffolliott 2000). Streamflow following torrential thunderstorms in summer months is generally low in volume, variable in velocity, and short in duration. However, summer streamflows frequently produce the highest peaks. Hillslope soil erosion rates, sediment yields and transport, and water quality characteristics are variable throughout the natural range of the woodlands.

Hydrologic Processes

Hydrologic processes in the pinyon-juniper woodlands are influenced by species compositions; structural development and density patterns of the tree overstories; the nature of precipitation events occurring; and decisions made by the people responsible for management of the woodlands. It is not possible to adequately describe the magnitudes and dynamics of these hydrologic processes for all conceivable situations encountered because descriptions for the full spectrum of hydrologic conditions are not available. Furthermore, there are no known studies or investigations where all of the components of the hydrologic cycle have been measured on a single site (Roundy and Vernon 1999). Nevertheless, estimates of the hydrologic processes in the pinyon-juniper woodlands can be obtained from plot studies and watershed-level investigations. Some of these estimates are presented below.

Plot Studies

Estimates of interception, infiltration rates, evapotranspiration, soil moisture storage, and hillslope soil erosion rates have been made in plot studies. While these on-site estimates were obtained mostly from individual studies conducted on different sites, they offer insight to these hydrologic processes in the pinyon-juniper woodlands.

Interception—Interception of precipitation is related largely to the composition, distribution, and density of trees in the overstory and the intensity, duration, and type of precipitation, that is, rain, snow, or a combination of both types of precipitation. Increases in tree canopy coverage reduce the amount of precipitation that eventually reaches the surface of mineral soils (fig. 2). Skau (1964a) estimated that an average of between 10 to 20 percent of the precipitation falling on the pinyon-juniper woodlands of northern Arizona is intercepted by Utah (*J. osteosperma*) and alligator (*J. deppeana*) juniper tree crowns. A comparable level of interception by trees was reported by Collings (1966) in the pinyon-juniper woodlands on the Fort Apache Reservation in eastern Arizona.

Interception losses ranging from 25 to 35 percent have been associated with the canopies of redberry (*J. pinchotii*) and Ashe (*J. ashei*) juniper trees in the woodlands of the Edwards Plateau in west-central Texas (Hester 1996 cited by Thurow and Hester 1997). Elsewhere, reported interception values of western juniper (*J. occidentalis*) trees in the Interior West were less than 10 to over 40 percent depending once again

Figure 2—The relationship between woodland tree canopy and interception of precipitation was studied as part of the Beaver Creek Project within the Coconino National Forest, Arizona. The Beaver Creek watersheds were established in the late 1950s by the Rocky Mountain Forest and Range Experiment Station, the Coconino National Forest, and their cooperators to evaluate land management measures designed to increase water yields from pinyon-juniper woodlands and ponderosa pine (*Pinus ponderosa*) forests (Clary and others 1974). Evaluations of the treatment impacts on other resources, such as wildlife, timber, and forage, were important components of the research.

on the extent of the canopy coverage (Young and Evans 1987, Larsen 1993 cited by Kuhn and others 2007).

The only known attempt to evaluate the effects of clearing tree overstories on interception values was that of Gifford (1975a) who compared interception losses following chaining treatments, where the downed trees were either windrowed or left in-place, with an adjacent site of natural (untreated) woodlands. Gifford found that interception losses from the chained sites were 10 to 70 percent less than the value in the natural site. The differences in interception losses on the chained sites were attributed to the characteristics of the specific site and the year of the measurements.

Precipitation passing directly through tree canopies (throughfall) must also pass through the litter layer beneath the canopies before infiltrating into the mineral soil. Interception losses associated with the litter layers are variable with estimates depending largely on the depth of litter accumulations on the site (Jameson 1966b, Gifford 1970, Scholl 1971). Thurow and Hester (1997) estimated interception losses of throughfall by the litter layer in woodlands comprised of redberry and Ashe juniper trees on the Edwards Plateau exceeding 40 percent. These losses were higher than values reported earlier for western juniper trees (Young and Evans 1987). The differences in these estimates of interception losses were related to the greater buildup of the litter layers beneath the redberry and Ashe juniper trees.

Varying threshold amounts of precipitation are necessary for precipitation to reach the soil surface by flowing down the stems of trees, shrubs, or herbaceous plants (stemflow) during a rainstorm event (Skau 1964a, Collings 1966, Thurow and Hester 1997). However, the magnitude of stemflow in pinyon-juniper woodlands is less than 5 percent.

Infiltration Rates—Infiltration rates are typically greater beneath tree overstories than on sites supporting herbaceous plants because the trees reduce the erosive force of raindrops and the litter accumulation beneath the trees slows the overland flows of water from a site. Early plot studies established "benchmark values" for the range of infiltration rates that can be encountered in pinyon-juniper woodlands. For example, the infiltration rates of soils derived mainly from sedimentary rock, sandstones, and shale in central Utah ranged from 2.1 inches hr^{-1} in the initial 5 minutes following a precipitation event, decreasing to 1.5 inches hr^{-1} after 25 minutes (Williams and others 1969). The infiltration rates of soils developed (collectively) from sedimentary and volcanic rocks, sandstone, and shale in southern Utah decreased from 3.5 inches hr^{-1} in the initial 5 minutes to almost 2.0 inches hr^{-1} after 25 minutes (Gifford and others 1970). These results and findings of other plot studies (Smith and Leopold 1942, Dortignac 1960, Gifford and Tew 1969a, Williams and others 1972, Blackburn and Skau 1974) indicate that infiltration rates vary greatly from site to site. Because of this variability, Gifford (1975b) concluded that in general it is difficult to "pinpoint" the factors that consistently influence the infiltration rates of a site.

Litter can store relatively large quantities of throughfall and, in doing so, can limit the amount of water infiltrating through the mineral soil surface. Nevertheless, the litter layers under pinyon-juniper trees can also contribute to the development of a better soil structure with large pores forming in the soil beneath the litter layers through which infiltrated water can pass (Thurow and Hester 1997). Hester and others (1997) found that the infiltration rates of soils on the Edwards Plateau were higher underneath the canopies of juniper trees than on grassland sites with the litter accumulations beneath the trees the presumed contributing factor. However, this latter situation might not be the case throughout the woodland ecosystems.

The clearing of pinyon-juniper woodlands in establishing herbaceous understories does not always alter infiltration rates. Of 14 sites in central Utah, Williams and others (1969) reported increased infiltration rates on two areas where comparisons were made between cleared and natural sites, while decreased infiltration rates were found on two other sites. There were no statistically significant differences in infiltration between cleared and natural areas on the other sites in the study. Elsewhere in Utah, Gifford and Tew (1969b) observed an increase in permeability of the surface soil on a site that had been cleared of trees six months previously. However, this trend in increased permeability was not observed on a nearby site. Largely similar conclusions were reported in other studies conducted in southern Utah by Gifford (1970) and Gifford and others (1970).

The microflora (crytogamic) crust that forms a cover in some soils in the pinyon-juniper woodlands on the Colorado Plateau can have an impact on hydrologically important soil properties including infiltration rates according to a study by Loope and Gifford (1972). These investigators found that plots with a microflora soil cover in southern Utah often have higher infiltration rates than plots that had been cleared of woodland trees. Loope and Gifford also indicated a possibility of increased soil erosion once the crust had been disturbed by clearing tree overstories.

Pierson and others (2008a) found higher infiltration rates on microsites beneath tree canopies than on the interspace areas situated between tree and large shrub canopies following simulations of artificial rainfall-concentration flows in the Interior West. This finding supported the general observations that infiltration rates are greater beneath tree overstories than on sites supporting herbaceous plants. The amount of plant cover on these study sites was reported to be the main causal factor for these observed differences in infiltration. Reid and others 1999) reported similar results in a pinyon-juniper woodland in the southwestern region. Cline and others (2010) working on rain-fall simulation plots in Utah reported that bare soil areas that were covered with juniper residues generated during a mastication treatment had higher infiltration rates and lower sedimentation rates than sites without a cover of residues.

The site-specific estimates of infiltration rates reported in the literature should be interpreted as largely localized results. Nevertheless, the results of the plot studies reviewed suggest that it is likely that there is neither a consistent increase nor decrease in infiltration rates on sites cleared of trees.

Evapotranspiration—Evapotranspiration is generally the largest route of water outflow from a site. There are no known estimates of the magnitude of evaporation of the precipitation that is intercepted by the trees in the pinyon-juniper woodlands. However, estimates of evaporation of the throughfall that is intercepted by litter layers can be inferred from studies of the depths to which throughfall penetrates into the litter layers.

Skau (1964b) found that the evaporation from soils in the pinyon-juniper woodlands of northern Arizona is generally confined to the upper 10 to 12 inches unless there was severe cracking of the basaltic soils on the site. In a study of the movement of water through the litter accumulations beneath tree overstories in the woodlands of southern Utah, Gifford (1970) found that 3.8 inches of water had penetrated only 1 inch into the litter layer that averaged 1.5 inches in depth beneath closed tree canopies with no water reaching the mineral soil surface. However, evaporation of comparable volumes of throughfall appeared less on sites with largely discontinuous tree canopies in the same area because water on these sites penetrated 59 inches into the soil profile. Thurow and Hester (1997) speculated that the throughfall from low-intensity, short-duration rainstorms in the hill country of eastern Texas will not infiltrate into a soil body because of the high rates of evaporation of the rainfall intercepted by tree canopies and underlying litter.

Transpiration losses from overstory trees have been estimated to account for 80 to 95 percent of the precipitation input into the pinyon-juniper woodlands by other investigators (Lane and Barnes 1987, Weltz

1987 cited by Thurow and Hester 1997, Carlson and others 1990). The magnitudes of the reported transpiration losses depended largely on the composition, structure, and densities of the tree overstory and the amount, intensity, and duration of the precipitation event occurring.

Obtaining reliable estimates of transpiration losses under field conditions is a difficult task (Brooks and others 2003, Shuttleworth 2008). One approach to estimating these transpiration losses is by applying the evapotranspiration tent method outlined by Mace and Thompson (1969). Decker and Skau (1964) enclosed Utah and alligator juniper trees in a ventilated tent of transparent plastic sheeting to estimate transpiration losses from the sample trees. Increased humidity of the ventilation stream was considered to be a direct index of vapor production in this study and, therefore, transpiration rates through conversion. The estimates of transpiration observed by Decker and Skau were variable throughout a day as might be expected. Transpiration rates increased throughout the morning hours, peaked close to noon, and remained at this high level until the middle of the afternoon after which transpiration decreased rapidly into the early night. By linking these fluctuations of daily transpiration rates to the occurrence of trees in a "typical" pinyon-juniper woodland of northern Arizona that were similar in characteristics to the trees sampled, these researchers estimated water losses by transpiration approached the values reported by the investigators, cited in this section.

Dugas and others (1998) estimated a short-term decrease in evapotranspiration rates following the removal of Ashe juniper trees in central Texas. To place the reported reduction in evapotranspiration of only 0.003 inch per day into perspective, the average precipitation in the vicinity of this study was 26.5 inches annually. The lack of a sustained reduction in evapotranspiration losses after the juniper trees were removed was attributed largely to the increased growth of herbaceous plants on the plot.

Estimates of evapotranspiration losses on a watershed-basis can be approximated by an analysis of a simplified water budget (Brooks and others 2003). Ignoring the other components of the hydrologic cycle in such an approximation, the estimates of evapotranspiration are expressed (simply) as the difference between precipitation inputs and streamflow outputs. On the Beaver Creek watersheds located in the pinyon-juniper woodlands, an estimate of annual precipitation falling on the watersheds (the input) is 18.1 inches, while the annual streamflow from these watersheds (the output) averages about 1 inch (Clary and others 1974, Baker 1984). The 1 inch value is equivalent to a 1 inch depth of water covering the total acreage of the watershed. In reality, not all of the areas of a watershed produce the same amount of water. Some sites produce more runoff than others depending on location with respect to the channels, geology and soils and vegetation characteristics. The difference of 17.1 inches is considered an approximation of evapotranspiration. This value is at the high end of the estimates reported above. Evapotranspiration was likely over-estimated in this example, however, because the other components of the hydrologic cycle were not considered in the analysis (fig. 3).

Figure 3—Plot studies to determine the influence of pinyon-juniper woodlands and management treatments on evapotranspiration, soil moisture, and other attributes have been conducted throughout the West, such as this microclimatology study site in the Coconino National Forest.

In separating the components of evapotranspiration, evaporation of precipitation that is intercepted in tree crowns and transpiration losses from the trees themselves are decreased or eliminated (to unknown magnitudes) by clearing the tree overstories. However, evaporation of water from soil surfaces is likely to increase (also to unknown magnitudes) because the cleared site is exposed to increased solar radiation. Magnitude of the combined evapotranspiration processes following a clearing operation is dependent mostly on the characteristics of the site after the operation.

Soil Moisture Storage—Estimates of soil moisture storage in the pinyon-juniper woodlands vary depending largely on the infiltration characteristics of the soil; the magnitudes and sequencing of the recent precipitation events; whether the points of measurement were beneath tree canopies or situated in intercanopy spaces; the topographic position of the measurement point; and the instrumentation and methods applied and sampling protocols followed in obtaining the estimates. Only a few estimates of soil moisture storage have been obtained from plot studies, and, therefore, these estimates should be considered site-specific.

Intermittent measurements of soil moisture storage beneath natural and cleared stands of alligator and Utah juniper trees in northern Arizona were obtained by Skau (1964b) from the beginning of the summer monsoons (June 30) through the end of November in 2 consecutive years with a Veihmeyer tube. He found more water held in storage in the upper 24 inches of clayey and clayey-loam soils on cleared plots in 75 of the 90 comparisons made with plots supporting natural woodland conditions. The differences in the comparisons were considered small, however, ranging from -6.6 to +6.7 percent with only 15 comparisons exceeding ±4.0 percent. Skau concluded that the clearing of overstory trees might have little effect on streamflows insofar as these streamflows are influenced by soil water storage in the upper soil layers. He emphasized, however, that interpretations of the results of this study should be "conditional" because only five measurements were taken beneath each of the tree species on nine sampling dates in each year of the study and that only two types of soil were sampled.

Gifford and Shaw (1973) compared the soil moisture storage of plots on two study areas in natural pinyon-juniper woodland sites in Utah with plots where trees had been cleared by chaining and either windrowed or left in place. These researchers found that the greatest storage of soil moisture occurred on plots where the chained trees had been left in place with the least soil moisture storage on the natural woodland plots. Gifford and Shaw attributed the observed differences in soil moisture storage to changes in microclimate caused by the chaining treatment; differences in the rooting depths on the plots; and the mulching effect of litter on the debris-in-place plots. Also, there was no evidence of deep seepage of soil water on any of the plots in the study (see below).

Average volumetric water content (VWC) in the upper 4 inches of fluvial deposits on small (plot) watersheds of 2.5 to 3.2 acres in area in the pinyon-juniper woodlands of northern New Mexico ranged widely depending mostly on whether the averages calculated were obtained on sites beneath tree canopies or intercanopy sites on grass-dominated hillslopes or valley bottoms (Ochoa and others 2008). Calculations of the average VWC values were based on measurements made with VWC reflectometers inserted horizontally to about 4 inches on each sampling site. The lowest average value of 0.1 (1 percent) was observed in the intercanopy of grass-dominated hillslopes with the highest average value of 0.18 (18 percent) in the intercanopy of the valley bottoms. The reported differences in average VWC values were attributed mostly to the topography of the watersheds that included greater valley areas than hillslope sites. Differences in measurements taken beneath the tree canopies in relation to intercanopy locations were insignificant.

Deep drainage of soil water is generally limited in pinyon-juniper woodlands because of the relatively small portion of a precipitation input that reaches the soil surface and ability of the overstory trees to extract relatively large quantities of soil moisture held in storage (Thurow and Hester 1997). As a consequence, only small amounts of the water percolating through a soil profile have a chance to drain significantly beneath the rooting zone of the overstory trees.

Overland Flows of Water—With exception of the information gleaned from a few infiltrometer studies, there are few estimates of the magnitudes of overland flows of water from the hillslopes of pinyon-juniper woodlands in the literature. Qualitatively speaking, the results of infiltrometer studies suggest that there might be increases in overland flows of water following varying treatment combinations involving the clearing tree overstories, burning of the resulting debris, and seeding of herbaceous plants (Myrick 1969, Gifford 1975b). However, it was hypothesized that any increase in overland flows following the treatments would likely diminish once the seeded plants become established.

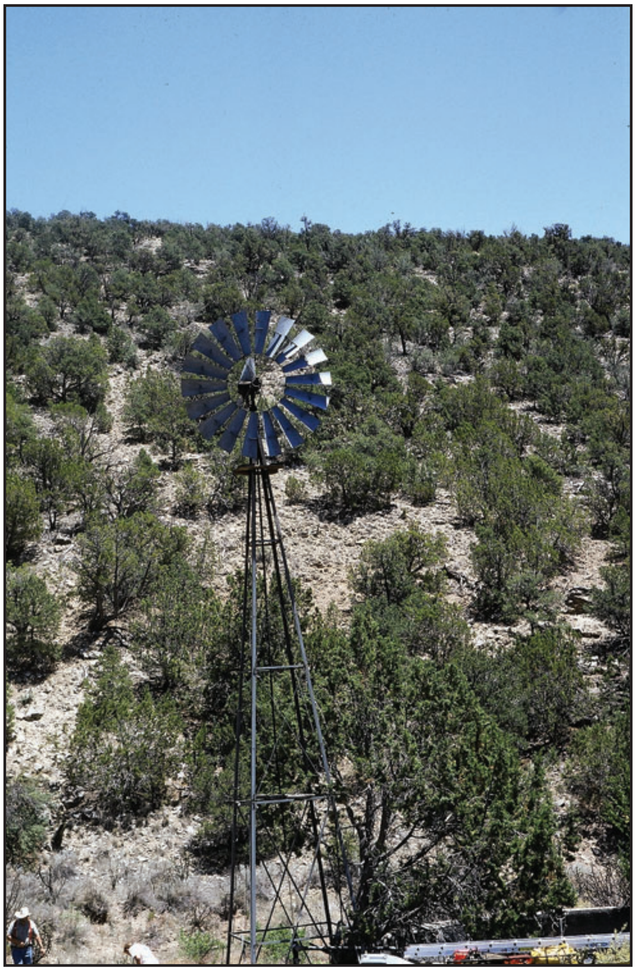

Figure 4—Most of the overland water flows in the pinyon-juniper woodlands originate in the interspace between tree canopies, such as on this hillslope in the Sevilleta National Wildlife Refuge in central New Mexico. The windmill pumps water into a tank for wildlife.

Bolton and others (1991) suggested that the vegetative arrangement and amount of litter that has accumulated on a hillslope in the pinyon-juniper woodlands have a "considerable influence" on the magnitude of overland flows of water. These investigators observed that most of the overland flows in the woodlands of the southwestern region originate in the interspace areas among tree canopies where litter accumulations were less (fig. 4). The litter buildups on a hillslope can also delay the onset of overland flows following a rainstorm. For example, Heede (1987) found that overland flows on "micro-watersheds" in Arizona were disrupted by almost 60 percent as a result of the hummocks of litter that surrounded pinyon and juniper trees.

That litter can hinder the overland flows of water was also reported by Pierson and others (2008a) who measured greater overland flows on plots established in interspace areas between tree and shrub canopies than on plots beneath tree canopies following (artificial) rainfall-concentration flow simulations in the pinyon-juniper woodlands of the Great Basin. Gifford (1970) found that the removal of overstory trees (the primary source of litter buildups) on plots located in the pinyon-juniper woodlands of Utah also tended to increase the overland flows of water in comparison to the flows on plots supporting a tree overstory.

It can be concluded generally, therefore, that on sites where the infiltration rates are "strongly related" to the densities of tree canopies and associated accumulations of litter, overland flows of water originating beneath the tree canopies would be "markedly less" than those on sites dominated by herbaceous plants (Gifford 1975a). This conclusion, if generally true, has implications for clearing woodland trees to increase streamflow volumes.

Hillslope Soil Erosion Rates—The soil particles eroded from one hillslope site are either deposited downslope on another hillslope site or transported into a stream channel to become entrained sediment when water flows in the channel. Unfortunately, limited quantitative information is available to characterize hillslope soil erosion in natural pinyon-juniper woodlands. It was suggested in an early study on the Fort Apache Reservation in eastern Arizona, however, that the rates of soil erosion would probably increase as a result of suppressing herbaceous plants beneath tree overstories (Arnold and Schroeder 1955). In another early study, Dortignac (1956) concluded that soil erosion in the Rio Grande River Basin was related to the condition, density, and extent of herbaceous plant covers with greater soil erosion originating on sites largely devoid of trees.

More recently, Bolton and others (1991) reported that because tree canopies are comparatively dense relative to a cover of scattered herbaceous plants, the denser tree canopies tended to protect the soil surfaces beneath the tree canopies from the erosive impacts of falling raindrops and, therefore, helped to mitigate the detachment of soil particles on a hillslope. Bolton and his colleagues also stated that hillslope soil erosion rates in the pinyon-juniper woodlands are dependent largely on the varying interactions among the vegetation, soil, and commonly encountered rainstorm characteristics.

A conceptual framework formulated by Wilcox and Breshears (1995) supported by plot studies at the Los Alamos National Laboratory in northern New Mexico provides an insight to the patterns of hillslope soil erosion on the landscape-heterogeneity of southwestern pinyon-juniper woodlands. On the basis of observations by these investigators, overland flows of water and concurrent soil erosion rates were greatest on patches of bare mineral soil with the entrained soil particles moving downhill through interconnected intercanopy areas to the canyons below. In a verification of this conceptual framework, Pierson and others (2008a) found that soil erosion following the clearing of pinyon and juniper trees in the Great Basin was greater on plots situated in the interspace among trees and shrubs than on plots beneath these canopies following rainfall-concentration flow simulations.

More quantitative estimates of hillslope soil erosion rates have been obtained in a few plot studies. The rates of soil erosion in the pinyon-juniper woodlands of central Utah ranged from 0.48 to 0.76 tons per acre annually (Williams and others 1969). Results from another plot study, also in Utah, indicated that annual soil erosion rates averaged 0.10 to 0.42 tons per acre (Gifford and others 1970). These results and those from other plots studies conducted in the woodlands of Utah and the Pacific Northwest (Gifford 1973, Blackburn and Skau 1974, Pierson and others 2007, 2008b) report that generally there is little or no consistent decrease or increase in the rates of hillslope soil erosion following the clearing of tree overstories and then seeding the cleared sites with herbaceous plants. However, estimates of soil erosion obtained from plot studies can preclude a "full expression" of the turbulent activity of overland flows of water on a larger hillslope, and, therefore, these estimates obtained from plot studies must be interpreted accordingly. Furthermore, the results obtained from plot studies do not necessarily reflect soil erosion rates for time frames, site conditions, or precipitation patterns other than those associated with these often short-term studies.

A model proposed by Baker and others (1995) describes the combined impacts of water and wind erosion of soils in the pinyon-juniper woodlands and their dependency on annual precipitation amounts. This model was developed initially by Heathcote (1983) with emphasis placed on the linkage of plant cover to the respective rates of soil erosion. Where both water and wind erosion occur under a vegetative cover, there is a compensating effect between the two erosion agents while the erosional effects are additive on bare soil. This model demonstrated that the clearing of trees is likely to increase both water and wind erosion. It also highlighted the relative significance of wind erosion in the pinyon-juniper woodlands—an erosional process that has been largely ignored in the past. Baker and others (1995) report on a study that demonstrated that wind can move significant amounts of soil and ash in a pinyon-juniper woodland site where harvesting slash was burned. Approximately 238 pounds per square foot of soil and ash were collected in a sampler located 1.6 ft above the soil surface in this study.

Watershed-Level Investigations

Expansion of pinyon-juniper woodlands onto landscapes dominated by herbaceous plants impedes streamflow for off-site (downstream) uses according to many investigators (Hawkins 1987, Gottfried and others 1995, Roundy and Vernon 1999, Kuhn and others 2007, Pierson and others 2008a, Tennesen 2008). It has often been thought, therefore, that the clearing of tree overstories might reverse this process and, in doing so, increase downstream flows of water. The replacement of deep-rooted trees and shrubs with shallower-rooted herbaceous species that consume less water would (theoretically) make more water available for off-site use (Clary and others 1974, Ffolliott and Thorud 1975, Davis and Pase 1977). While there was some evidence in the early literature (prior to 1956) that the clearing of woodland trees and replacement with a herbaceous cover might not produce additional water, a recommendation of Barr (1956) and others was that evaluations of alternative conversion treatments to enhance streamflow regimes in the pinyon-juniper woodlands should be made.

A number of methods have been used to increase herbage (forage) production through clearing the competing tree overstories in the pinyon-juniper tree woodlands: mechanical removals, chemical control, and the use of fire. It was suggested by several early investigators (Skau 1964a, Collings 1966, Gifford and others 1970, Gifford 1973, Clary and others 1974) that the same methods of clearing tree overstories might also be suitable for streamflow enhancement. A review of watershed-level investigations to evaluate the effects of clearing tree overstories on streamflow volumes, sediment yields and transport, and the quality of streamflow water by applying these methods follows.

Streamflow Volumes—Extensive areas of pinyon-juniper woodlands have been cleared in the past by chaining or cabling in which a heavy anchor chain or cable was dragged between two tractors (Cotner 1963, Arnold and others 1964, Warskow 1967, Clary and others 1974). Pushing (bulldozing) has also been used to remove the larger trees. However, both of these mechanical methods of pulling trees from the ground leave pits (root cavities) where the trees formally stood (fig. 5). Skau (1961) determined that these pits reduce overland flows of water and, in doing so, streamflow

Figure 5—Mechanical methods of removing pinyon and juniper trees to increase forage and water yields were common throughout the West. This is a typical chaining operation on the Coconino National Forest.

volumes from the cleared watersheds. However, an alternative approach to clearing tree overstories by this heavy equipment is hand-clearing with ax or saw, by using shears mounted on light tractors, or by mechanical mastication to grind up the trees without displacing the base. These latter methods would (in theory) have a minimal impact on reducing the consequent overland flows of water because pitting is eliminated and the increased soil erosion that often occurs with chaining, cabling, or pushing would be minimized. Tree branches left on the site would slow erosion processes. Mastication, depending on the equipment used, may cause some localized soil compaction and reduced infiltration (Cline and others 2010).

Early studies of the effects of clearing pinyon-juniper woodlands on streamflow volumes were undertaken in the basin of the adjacent Corduroy and Carrizo Creeks in eastern Arizona. The tree overstory on Corduroy Creek was cleared on 34,000 acres (25 percent of the basin) by chaining, while the shrubs and litter accumulations beneath the higher-elevation ponderosa pine (*Pinus ponderosa*) trees were burned on 18,000 acres (13 percent of the basin). Carrizo Creek was left undisturbed to serve as a control to evaluate these treatments. Because evaluation of the two treatments on Corduroy Creek considered only their total (overall) effect on streamflow volumes (LeCrone 1959, Collings and Myrick 1966), conversion of the tree overstory to a herbaceous cover could not be isolated as the "sole influence" on the resulting streamflow volumes. This problem was not considered to be important by the investigators, however, because they concluded that the clearing treatment would probably produced no significant changes in streamflow volumes.

Two watersheds less than 100 acres in area on Cibecue Ridge in the same general vicinity as Corduroy and Carrizo Creeks were selected to investigate the possibility that converting tree overstories in the pinyon-juniper woodlands to herbaceous plants would increase streamflow volumes on a smaller-scale. Chaining cleared the tree overstory on one of the watersheds, the resulting slash was burned, and the treated watershed was fenced to exclude livestock and seeded with a mixture of grasses. The other watershed was designated a control. A "parameter model" to predict how components of the hydrologic cycle might change as a consequence of this conversion treatment was used to evaluate this experiment (Robinson 1965, Myrick 1971). The investigators found that streamflow volumes increased significantly on the converted watershed in the first 2 post-treatment years, but then decreased to below the expected (projected) streamflow volumes on the untreated watershed in the following 2 years. One assumed reason for this decrease in streamflow volumes was an increase in transpiration rates attributed to the perennial grasses seeded as a part of the treatment prescription.

The effectiveness of converting tree overstories to herbaceous covers to increase streamflow volumes in the pinyon-juniper woodlands by mechanical methods was also evaluated on Beaver Creek (Clary and others 1974, Baker 1984, Baker and Ffolliott 2000). A clearing treatment similar to that used extensively to increase herbage (forage) production in the southwestern region was applied on a 323-acre watershed. Trees were uprooted by cabling; the smaller trees missed by the cable were felled by power saws. The larger trees were then burned and the cleared watershed seeded with a mixture of forage species. A hand-clearing treatment with the trees felled by power saws was applied later on a second watershed that was 363 acres in area. Pitting and other soil disturbances created by uprooting trees by cabling were largely eliminated by this method (fig. 6). The stumps of alligator juniper, the principal tree species on the watershed, were treated with polychlorinated-benoic acid to reduce subsequent sprouting. Shrub live oak (*Quercus turbinella*) clumps were treated initially with fenuron and later with

Figure 6—Felling trees in pinyon-juniper woodlands with (a) power saws (Beaver Creek), (b) mechanical shears mounted on light tractors (Greene Ranch, Torrance County, New Mexico), or (c) the use of mastication machinery (Dolores Public Lands, Dolores, Colorado), eliminate pitting and other disturbances caused by uprooting trees by cabling.

picloram to reduce their occurrence. Gambel oak (*Q. gambelii*) sprouts were sprayed with 2,4,5-T in the dormant season to control possible re-emergence of these species. No seeding of forage species was done.

The results of investigations in the basin of Corduroy and Carrizo Creeks, at Cibecue Ridge, and on the two Beaver Creek watersheds indicated that the conversion of pinyon-juniper woodlands to herbaceous covers by mechanical means has little long-term effect on streamflow volumes (Clary and others 1974, Baker 1984, Baker and Ffolliott 2000, Ffolliott and Stropki 2008). The reduced overland flows of water caused by pitting where chaining or cabling methods were applied likely compensated for any potential increases in streamflow brought about by the reductions in transpiration losses by the tree removals. Trees in the more open stands on the Beaver Creek watershed converted to a herbaceous cover by hand-clearing were probably too few in number and too scattered in distribution for the treatment to impact the overall loss of water to the transpiration process.

Killing trees with herbicides is another option for converting tree overstories to herbaceous plants. In testing this option to increase streamflow volumes, an herbicidal treatment consisting of a mixture of 2½ pounds of picloram and 5 pounds of 2,4-D was applied by helicopter to a Beaver Creek watershed of 363 acres (Clary and others 1974, Baker 1984, Baker and Ffolliott 2000). This aerial application was sprayed on 281 acres of the watershed with the remaining 82 acres either untreated or where individual trees were hand-treated with the herbicide using a mist-blower. The purpose of this treatment was to lower transpiration losses by killing the trees while leaving the dead trees standing to reduce desiccating windspeeds and impinging solar radiation to control evaporation losses (fig. 7). The treatment also avoided trapping overland flow in pits formed by uprooting trees. The dead trees were harvested for firewood 8 years after the initial treatment; the resulting slash was piled and burned the following year.

Figure 7—Streamflow increased significantly after the aerial application of herbicides on a pinyon-juniper woodland watershed at Beaver Creek. However, the increases were lost once the dead trees, which reduced evaporation, were harvested.

Application of the herbicides on the Beaver Creek watershed was the only known conversion treatment tested to significantly increase streamflow volume. However, while this increase averaged 60 percent by the time when the dead trees were harvested on the watershed, it was less than ½-inch in absolute terms (Clary and others 1974, Baker 1984, Baker and Ffolliott 2000, Ffolliott and Stropki 2008). Furthermore, it was determined that this increase in streamflow volume could be expected to occur only when winter precipitation amounts equaled or exceeded the average (at the time of the experiment) of 9.4 inches (Baker 1984). It must be stated that the large scale application of herbicides on public lands is limited in the southwestern region at this time because many people oppose the use of chemicals for almost any natural resources management purpose, and, importantly, their use is controlled by environmental regulations.

Broadcast burning has been successful in killing trees in pinyon-juniper woodlands for rangeland improvement purposes where trees were dense enough to carry a fire (Cotner 1963, Arnold and others 1964). Individual tree burning (Cotner 1963, Jameson 1966a) has also been applied on a limited scale. From a hydrological standpoint, pits are not created and increases in soil erosion are minimal when these burning treatments are applied carefully. It is unknown, however, if streamflow volumes might increase on a watershed-basis by either broadcast burning or the burning of individual trees. It also is not known if streamflow volumes would change as a result of prescribed burning treatments. While the effects of prescribed burning on some of the hydrologic processes characterizing the pinyon-juniper woodlands have been estimated (Roundy and others 1978, Miller and Tausch 2001, Rau and others 2005, Pierson and others 2008b), this conversion method has not been adequately evaluated in terms of altering streamflow volumes. It is likely that the effects of prescribed burning treatments on streamflow volumes are "hydrologically less" than the effects of a large wildfire, however, because the tree overstories, herbaceous vegetation, and litter are only partially burned with the prescribed low severity fire (Baker 1990, DeBano and others 1995).

Kuhn and others (2007) combined available research findings relating to the impacts of removing juniper trees in the Klamath River Basin of northern California with average precipitation and vegetation information to evaluate the possibilities of increasing streamflow volumes by clearing the tree overstories on a large-scale. Kuhn and his colleagues applied this information to tributaries in the Klamath River Basin that had "significant areas" supporting juniper trees by identifying the areas dominated by these trees; determining the areas with average annual precipitation amounts above an assumed (but not specified) threshold value thought necessary to increase streamflow volumes; and identifying the extent of the overlap between areas dominated by juniper trees and those receiving greater than the threshold precipitation. These investigators found that only 4,438 acres within the 520,000 acres of one of the tributaries in the basin met their feasibility criteria for evaluating streamflow enhancement. No areas in the other three tributaries studied satisfied these requirements. It was determined that there was "no strong evidence" that streamflow volumes would increase "substantially" by even the complete removal of overstory trees. It was further concluded that opportunities for small-scale increases in streamflow volumes could not be adequately evaluated with the available data.

Partial harvesting of pinyon-dominated woodlands is a recent management activity. The objectives of this harvesting are to increase growth of high quality and healthy residual trees, to limit insect caused mortality by reducing stand densities and removing poor quality trees, to provide tree regeneration sites, and to enhance pinyon seed production (Gottfried 2008, Page 2008). The population of pinyon trees throughout the West has declined because of the interaction of drought, overstocked stands, and infestations of the engraver bark beetle (*Ips confusus*). A survey in 2003 and 2004 of five National Forests in Arizona reported that pinyon mortality caused by the beetle ranged from zero to 48 percent on a Forest level and that mortality was positively correlated to stand densities and negatively correlated to elevation on most Forests (McMillan and others 2008). Many pinyon-juniper stands are being converted to essentially pure juniper stands.

The available literature does not include much information from plot or watershed—level research on the impacts of partial harvesting or insect mortality on hydrologic processes in the pinyon-juniper woodlands. However, we know from studies in the higher elevation ponderosa pine watersheds at Beaver Creek (Gottfried and others 2008) and mixed conifer stands at Workman Creek in central Arizona (Rich and Gottfried 1976) that it is necessary to reduce stand densities and to create openings to significantly increase in water yields. If stand densities are reduced significantly by harvesting or insects, it could be possible to increase moisture availability and affect surface runoff at higher (moister) elevations. If dead trees are left standing, it might be possible to duplicate the water yield results from the herbicide treated watershed at Beaver Creek (Ffolliott and Stropki 2008). However, if significant numbers of juniper trees survive, they would likely consume any additional moisture that was previously used by pinyon. Potential surplus moisture is less likely on drier, lower elevation sites where mortality appears to be greater.

Sediment Yields and Transport—Knowledge of sediment accumulations in a stream channel is applied occasionally as a proxy for estimating the magnitudes of hillslope soil erosion on a watershed-basis. Watersheds concentrating large quantities of sediment in their stream channels are generally the watersheds experiencing high rates of soil erosion (Brooks and others 2003). It must be emphasized, however, that not all of the soil particles eroded on a hillslopes reach a stream channel to become sediments. As mentioned earlier, some of the soil particles will be deposited on other hillslope sites before reaching the channel to become sediment. Keeping this point in mind, a few measurements of sediment yields in the southwestern pinyon-juniper woodlands are available.

Total sediment yields have been measured on some of the Beaver Creek watersheds by means of catchment basins to collect bedload materials and a splitting device to sample suspended sediments on the watersheds (Brown and others 1970). Progressively smaller fractions of streamflow are diverted by the splitter to a collection tank where samples are taken for analysis of suspended sediments (fig. 8). Total sediment yields from watersheds supporting natural pinyon-juniper woodlands (based on 13 station-years of measurements) ranged from 0.01 to 0.31 tons per acre annually with an average of 0.10 tons per acre (Clary and others 1974, Ffolliott and Thorud 1975). In contrast, the total sediment yields following the chaining of one of the Beaver Creek watersheds ranged from a trace to 1.1 tons per acre annually with the largest total sediment yields following the historic 1970 Labor Day rainstorm (Thorud and Ffolliott 1973). To place the larger value in perspective, the recurrence interval of this unprecedented rainstorm event was estimated to be 100 to 150 years.

A catchment basin and splitting device had not been installed on the Beaver Creek watershed where trees were felled by power saws, precluding measurements of total sediment yields from this watershed. However, samples of suspended sediment concentrations measured before and after the hand-clearing treatment were not significantly different (Clary and others 1974, Ffolliott and Thorud 1975). The researchers concluded, therefore, that there likely was "no meaningful" change in sediment yields following the mechanical conversion treatments evaluated on the Beaver Creek watersheds.

There were no significant changes in total sediment yields measured with a catchment basin and a splitting device following application of herbicides on one of the Beaver Creek watersheds in comparison to the pre-treatment measurements (Clary and others 1974, Ffolliott and Thorud 1975). While there "appeared" to be a decrease in total sediment yields following the

Figure 8—Bedload materials are collected in a catchment basin and suspended sediments are collected by a splitter at the weir site on an experimental pinyon-juniper watershed at Beaver Creek.

application of this treatment, the evaluation period was "unusually" dry according to the investigators, and, as a consequence, sediment yields from the watershed were likely reduced significantly. The investigators concluded, therefore, that there was no meaningful change in sedimentation as a result of the chemical clearing treatment.

Hansen (1966) defined the **concentration index** as a parameter to be an approximation of the average suspended sediment concentrations originating from (arbitrarily defined) 1-square-mile watersheds in the pinyon-juniper woodlands of northern Arizona. He reported that the concentration index was related significantly to precipitation characteristics, elevation of the watersheds, and litter accumulations on the soil surface of the watersheds. Hansen summarized the suspended sediment concentrations approximated by the concentration index by elevational strata to be 45 to 128,000 parts per million (ppm) on watersheds less than 6,000 ft in elevation and 18 to 1,720 ppm on watersheds 6,000 to 6,500 ft in elevation. The lower concentrations of suspended sediments on watersheds at lower elevations were attributed largely to the lower volumes of streamflow from the lower watersheds to transport sediments.

Sediment rating curves relating suspended sediment concentrations to streamflow discharge (Brooks and others 2003) provide another approach in determining the effects of vegetative management practices on sedimentation processes. Sediment rating curves developed for watersheds in the pinyon-juniper woodlands on Beaver Creek indicated that the mechanical clearing of tree overstories by chaining resulted in increased suspended sediments at selected rates of streamflow discharges because of the soil disturbances caused by uprooting of the trees (Lopes and others 1996, 1999). The highest suspended sediment concentrations (approaching 80 ppm) were associated with the high intensity, short duration rainfall events occurring in the summer, while the lowest concentrations (less than 5 ppm) were attributed to the lower volumes of streamflows generated mostly by the late-winter and early-spring snowmelt-runoff events. There were no changes in the sediment rating curve on the watershed where the herbicidal conversion treatment was applied in relation to the sediment rating curve before the treatment. The researchers reported that the soil surface on the watershed was not disturbed significantly by this treatment since most of the chemical was applied by helicopter.

The primary mover of the sediments that accumulate in stream channels is the infrequent large rainstorm events that produce the intermittent streamflows of sufficient energy to transport sediments that occur throughout the pinyon-juniper woodlands of the western region. The movement of sediments in stream channels, therefore, is episodic in nature. However, the accumulation, storage, and transport of sediments through a stream channel are (collectively) complex processes (Heede 1985, Shen and Julien 1993). Loss of tree overstories by clearing, excessive livestock grazing, or the occurrence of wildfire can result in "large" overland flows of water that become sufficiently concentrated in the stream channels to move sediment accumulations. Regardless of the mechanism, sediments entrained in streamflows are transported further downstream than the larger bedload materials in these events.

Quality of Streamflow Water—Samples of streamflow water collected on the Beaver Creek watersheds before and after clearing of tree overstories by mechanical methods and the application of herbicides provide insight to the changes in the quality of streamflow water that can occur as a result of these conversion practices. Chemical constituents analyzed in these samples included pH, electrical conductivity, total dissolved solids, hardness, silica as SiO_2, calcium, magnesium, sodium, potassium, biocarbonate, carbonate, sulfate, chloride, and fluoride. Iron, manganese, boron, nitrate, and phosphate were also included in the analysis of some of these samples.

Samples obtained from all of the watersheds cleared of tree overstories on Beaver Creek generally exceeded the minimum quality standards—at the time that the samples were obtained—for agricultural irrigation, public water supplies, and aquatic life (Clary and others 1974, Ffolliott and Thorud 1975). However, the iron content in a few of the samples exceeded recommended quality standard for drinking water and aquatic life. All of the samples collected on the watersheds had low sodium absorption ratios. Electrical conductivity values in the streamflow water from the watershed where the hand-clearing treatment was applied were low. While some of the samples obtained on the watershed where the chaining treatment was applied showed a "slight deterioration" of the quality standards specified for irrigation purposes, these samples still exceeded the quality standards for drinking water and aquatic life. Streamflow water from the chained watershed was "moderately hard" while it was "soft" from watershed that was hand- cleared.

The rate of picloram applied on the Beaver Creek watershed treated with herbicides to kill the trees was known to be "excessive" at the time of its application.

However, the rates were applied nevertheless to aid researchers in planned studies of the post-treatment picloram residue in streamflow water. The highest concentration of picloram (0.32 ppm) was detected in the initial samples obtained following the treatment (Clary and others 1974), while the picloram concentrations were less than 0.01 ppm by the spring following its application. It was determined that only 1.3 percent of the applied picloram left the watershed in streamflow water, with 90 percent of this concentration leaving the watershed in the first seven months after its application. No picloram was detected in streamflow water after 3 years.

The conceptual framework and supporting plot studies in the pinyon-juniper woodlands near the Los Alamos National Laboratory reported by Wilcox and Breshears (1995) offer a means for predicting the long-term movement of water, sediments, and unspecified contaminants and nutrients. With respect only to contaminants, low-level contamination covering "many square miles" and localized high-level contamination such as found in landfills were the two primary sources of contaminants considered within this research effort. It was concluded by Wilcox and Breshears that the concentrations of contaminates would be "sufficiently low" not to warrant remedial action in some of the areas studied. At the same time, however, erosional processes could cause depositions of contaminated soil particles in canyon bottoms. The need to improve predictions of the movement of contaminants from pinyon-juniper woodlands on mesa-tops to canyon bottoms led to the development of this conceptual framework.

Conclusions

Estimates of the nature and magnitudes of hydrologic processes in the pinyon-juniper woodlands obtained from a literature review of plot studies and watershed-level investigations of these processes are the focus of this report. These estimates should not be considered "all inclusive" for the full range of hydrologic conditions encountered in the woodlands, however, but only for the sites studied. Nevertheless, the estimates should be useful to hydrologists and watershed managers having responsibilities for sustaining the hydrologic health of the pinyon-juniper woodlands.

The studies and investigations that were reviewed centered ultimately on identifying the potentials for increasing the flows of high-quality streamflows originating on watersheds in the pinyon-juniper woodlands. However, it has been concluded from these plot studies and watershed-level investigations that the potential for increasing streamflow volumes by converting tree overstories to a herbaceous cover is poor (fig. 9). While this conclusion somewhat contradicts the earlier

Figure 9—The potential for increasing streamflow volumes by converting tree overstories to herbaceous covers in the pinyon-juniper woodlands is poor. This 2009 photograph shows tree recovery on a site in the Tonto National Forest near Payson, Arizona, that was mechanically treated in 1958.

recommendations of Barr (1956) and others, it should not necessarily be surprising.

Streamflow improvement in any vegetative type is based largely on the premise that streamflow volumes and, eventually, groundwater aquifers are increased by an amount that is equal approximately to the net reduction in evapotranspiration losses attributed to the conversion treatment implemented on the watershed (Hibbert 1979). However, there is little opportunity to reduce evapotranspiration losses on a watershed-basis where annual precipitation is less than a threshold value of 18 inches (Hibbert 1983) and its total is exceeded by the potential evapotranspiration (Thornthwaite and Mather 1957). This low amount of annual precipitation is not likely to penetrate far enough into the soil to influence the storage of moisture in the soil body that in turn impacts on overland flows of water and, eventually, streamflow volumes. This situation is found throughout most of the pinyon-juniper woodlands in the western region.

A similar conclusion that streamflow volumes are not increased significantly in the pinyon-juniper woodlands by converting tree overstories to herbaceous understories was also reached by Ffolliott and Brooks (1988) in their summary of the opportunities for enhancing streamflow volumes by vegetation management in the Mountain West; by Roundy and Vernon (1999) in their assessment of watershed values (including streamflow regimes) in the pinyon-juniper woodlands of the Interior West; and by Baker and Ffolliott (2000) in their analysis of the opportunities for increasing streamflow volumes through vegetative management practices within the Colorado River Basin.

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