Forest Ecology and Management xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin

Chris B. Zou [a,*], Peter F. Ffolliott [b], Michael Wine [a]

[a] Ecohydrology Laboratory, Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, USA
[b] School of Natural Resources, University of Arizona, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 20 November 2008
Received in revised form 2 August 2009
Accepted 3 August 2009

Keywords:
Colorado River Basin
Hydrological processes
Chaparral shrubs
Pinyon-juniper woodlands
Ponderosa pine forest
Subalpine forests
Water yield

ABSTRACT

The Colorado River Basin has been, and continues to be, the focus of a wide diversity of research efforts to learn more about the effects of natural and human-induced disturbances on the processes and functioning of the basin's upland watersheds. These watersheds are situated at the headwaters of streams and rivers that supply much of the water to downstream users in the western United States. Responses of streamflow to vegetation manipulations have been, and are, one of the research foci in this water-deficient part of the country. The watershed-scale research, led by the U.S. Forest Service and its cooperators, has spanned nearly a century and included an array of vegetation types along a wide range of precipitation gradients. Results from this research have shown that vegetation can be managed to enhance annual water yields while still providing the other natural resource benefits. Analyses of the research results suggest that the effect of vegetation manipulation on streamflow is associated with precipitation–elevational gradient and, therefore, vegetation type. An annual water yield increase between 25 and 100 mm could be achieved by implementing vegetation manipulations in the high elevation subalpine and mixed conifer forests, the ponderosa pine forests (in the Lower Basin), and portions of the low elevation chaparral shrublands. Negligible effects or small increases in water yield were observed for treating sagebrush, pinyon-juniper woodland and desert scrubs. Results from this research have improved our understanding of the basin's hydrology and provided much needed insights to manage forest to mitigate global climate change induced hydrologic impact and meet the increased needs of people living in the basin.

1. Introduction

Impact of vegetation manipulation on streamflow generation was one of the important components in the early experimental watershed research in forest hydrology (Bates and Henry, 1928; Kittredge, 1948; Coleman, 1953). During the past century, studies of different scales, at various locations, and under different climatic conditions demonstrated the tight coupling between vegetation and streamflow production and other hydrological processes (Ice and Stednick, 2004; Sun et al., 2005). However, the direction and magnitude of streamflow change associated with vegetation reduction has long been an issue of debate (Robinson et al., 2003; Wilcox et al., 2005). Both increases and decreases in streamflow production of varying magnitudes were reported when vegetation manipulations were implemented. These different results have been attributed to an array of factors including the vegetation manipulation techniques and the recovering phase, precipitation regime and intensity, evapotranspiration changes, and interactions among all of these factors (Lane and Mackay, 2001; Swank et al., 2001; Brooks et al., 2003; Komatsu et al., 2008). From the manager's viewpoint, it was vital to understand the individual and combined responses to planned vegetation manipulations encompassing the precipitation–elevation gradients to holistically manage the vegetation and water supplies for downstream users.

The Colorado River drains approximately 650,000 km^2 (65 million ha) of virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California before it enters the Gulf of California in Mexico. This drainage area is arbitrarily separated into the Upper and Lower Basins at Lee's Ferry, about 16 km south of the Utah–Arizona border (Fig. 1). The Upper Basin of the Colorado River contains 28.3 million ha and the Lower Basin 36.4 million ha in area. Vegetation types in the basin are closely related to precipitation gradients that (in turn) are associated to elevational gradients. In descending order of precipitation–elevation gradients montane forests are at the "high end" of these gradients, followed by woodlands and shrub communities in the "middle range" of the gradients, and, finally, desert ecosystems at

---

[*] Corresponding author. Tel.: +1 405 744 9637; fax: +1 405 744 3530.
E-mail address: chris.zou@okstate.edu (C.B. Zou).

0378-1127/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2009.08.005

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

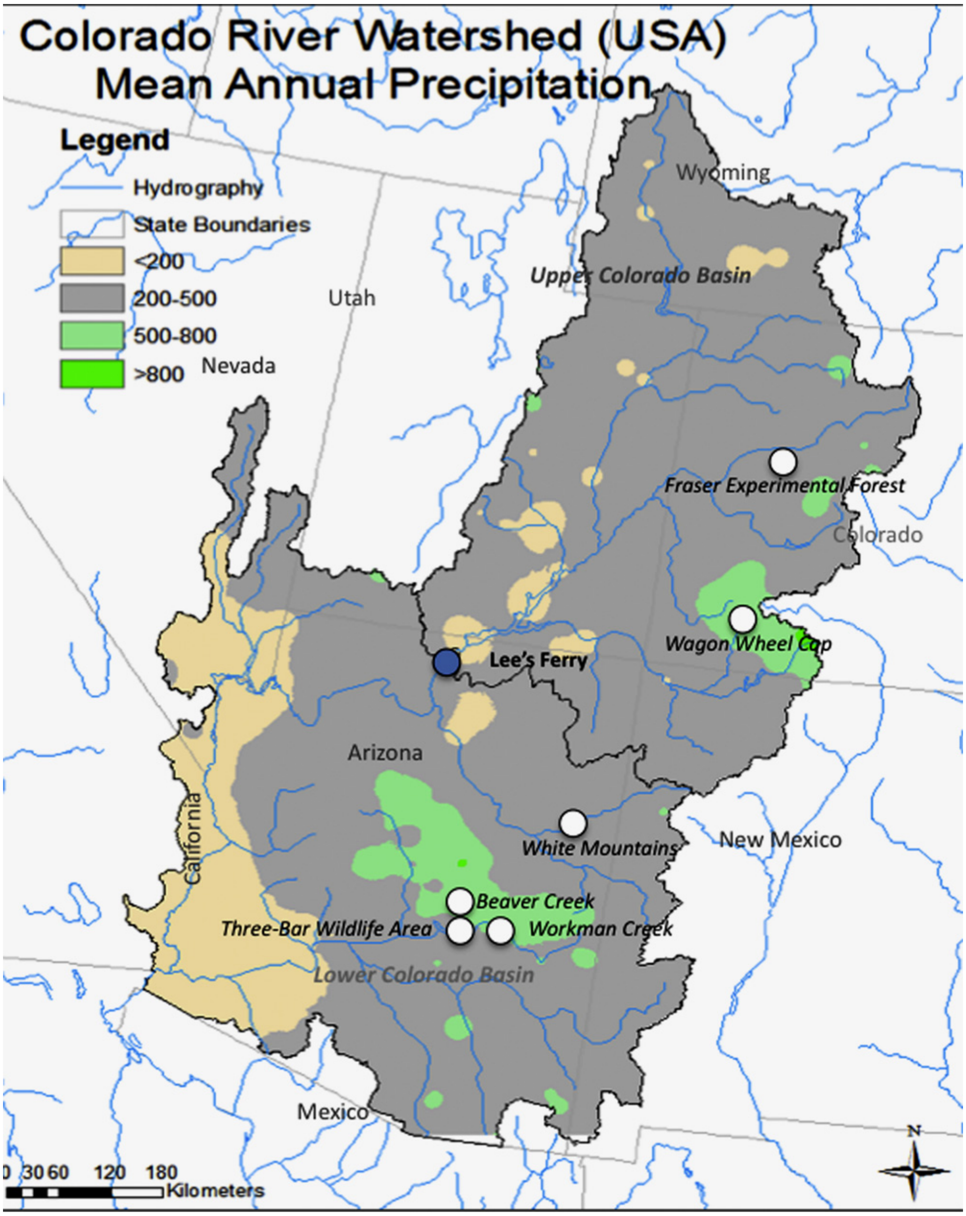

Fig. 1. Mean annual precipitation of the Colorado River Basin. The boundaries of the watershed were determined using the USGS national hydrography dataset. Precipitation was interpolated using Inverse Distance Weighting of Unifed Climate Access Network Cooperative Climate Stations with 1971–2000 Precipitation Normals for the United States. The analysis was conducted using Albers Equal Area Conic Projection NAD 1983. State boundaries were from the USGS.

the “lowest end” of the gradients (Fig. 1). The magnitudes of streamflow responses to vegetation manipulations also follow along these gradients as discussed below.

1.1. Upper Basin

Annual precipitation in the Upper Basin averages 400 mm, most of which is concentrated on the mountain landscapes. The proportion of this precipitation that is converted into streamflow basin-wide is about 65 mm, or 16%. However, precipitation and the resulting streamflow vary greatly from year to year. Annual streamflow amounts between the Upper and Lower Basins at Lee’s Ferry have ranged from about 35% to nearly 165% of the estimated long-term mean streamflow volumes of 1.8 million ha-m. Much of this flow is concentrated in a few spring months when snow melts at the higher elevations (Baker and Ffolliott, 2000). About 4.6 million people are served by the water flows that are available in the Upper Basin, with two-thirds of this water used in the agricultural sector.

Subalpine forests of spruce, fir, Douglas-fir, and lodgepole pine occupy 2.8 million ha at elevations of 2100–3500 m. These forests are situated in a cool, moist climate immediately below the high-mountain alpine zone and receive 500–1400 mm of annual precipitation, two-thirds of which is snow. Ponderosa pine forests are found on 0.6 million ha at lower elevations between 1850 and 2750 m. These forests attain their “best development” on sites that are warmer and drier than those in subalpine forests. Annual precipitation averages 380–635 mm, with about one-half being snowfall. Mountain brush lands dominated by the shrub-form of Gambel oak are located on 1.3 million ha at elevations from 1500 to 3000 m. Sometimes classified as chaparral shrublands, mountain brush ecosystems are comprised of woody plants that are deciduous rather than evergreen. Annual precipitation ranges from 400 to 600 mm less than one-half of it is snow. Big sagebrush

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

occurs on 10.5 million ha of land at elevations up to 3000 m in both basins. Precipitation varies from 200 to 500 mm. Pinyon-juniper woodlands occupy 5.1 million ha of foothills, low mountains, and low plateaus on sites between 1200 and 2300 m. Annual precipitation is 300–450 mm, with some sites receiving up to 500 mm.

1.2. Lower Basin

The Lower Basin receives an average of 330 mm of annual precipitation. The proportion of precipitation converted to streamflow averages 10 mm, nearly six times less than the streamflow in the Upper Basin. Much of the basin is characterized by a cyclic pattern of winter precipitation, dry spring, summer precipitation, and dry fall (Baker and Ffolliott, 2000). Winter precipitation is often snow at the higher elevations. Approximately 20.4 million people benefit from the water flowing in the Lower Basin, with approximately three-fourths of this water consumed in agriculture.

Mixed conifer forests of spruce, fir, Douglas-fir, and ponderosa pine occupy 160,000 ha. These forests are found on sites at elevations of 2100–3000 m that are warmer but not necessarily drier than subalpine forests to the north. Annual precipitation ranges from 630 to more than 760 mm, with one- half or more falling as snow. Ponderosa pine forests occur on 2.4 million ha between 1800 and 2700 m. Between 500 and 630 mm of annual precipitation falls in these forests, nearly equally divided into summer rainfall and winter snow. Pinyon-juniper woodlands occupy 8.1 million ha. Summer rains frequently account for one-half or more of the 300–450 mm of annual precipitation. Chaparral shrublands cover about 1.4 million ha. These sclerophyllous communities, which are limited almost entirely to the Lower Basin, are found at elevations of 900–2000 m and dominated by shrub live oak and other shrub species that sprout prolifically after cutting or fire. Annual precipitation varies from about 380 mm at the lower elevations to over 630 mm at the higher elevations. An area of about 14.5 million ha includes northern desert shrubs dominated largely by sagebrush at elevations of 750–1500 m north of the Colorado and Little Colorado River and at elevations of 50–900 m in southern desert ecosystems. Precipitation in the northern desert shrub type is about 250 mm annually, while precipitation in the southern shrub type averages 150 mm (Fig. 1).

2. Study protocol

Watershed-level experiments to determine or demonstrate the hydrologic response of a watershed (for example, the change in the magnitude, timing, and quality of water regimes) to a prescribed vegetation manipulation (treatment) were the basis for the research results presented in this paper. Manipulations of existing vegetation or replacing one type of vegetation with another were largely the practices evaluated on watersheds representing the array of ecosystems in the Colorado River Basin. These evaluations were based primarily on interpretations of information obtained in paired watershed studies (Brooks et al., 2003; Chang, 2003) widely used in the United States and throughout the world.

In paired watershed studies, two watersheds of similar vegetative, climatic, and physiographic characteristics are instrumented to measure streamflow. One of the watersheds is a control and its characteristics are kept as constant as possible throughout both pre-treatment calibration and post-treatment evaluations for comparison with the other watersheds on which a prescribed vegetative management practice is planned. Once a satisfactory correlation has been achieved (Wilm, 1944; Wilm, 1948; Kovner and Evans, 1954; Reigner, 1964), the planned vegetation manipulation is implemented on the watershed designated for treatment with a calibration regression used to detect (statistically) significant changes in the magnitude, timing, and quality of water regimes. These changes, when they occur, are attributed to the imposed vegetative management practices.

3. Results

3.1. Annual water yield

Early research on the hydrologic impacts of vegetation management practices began in the 1910s, was expanded into the 1930s and 1940s, and continuing in the 1980s to further evaluate the effects of vegetation manipulations on the basin's water resources and other multiple uses. Results from this research have shown that vegetative communities can be managed through properly planned manipulations to enhance annual water yields, at least in the short-run, while still providing the other natural resource benefits required by society in some optimal combinations.

3.1.1. Subalpine and mixed conifer forests

Bates and Henry (1928) conducted the first "experimental watershed study" in the United States at Wagon Wheel Gap, situated at the headwaters of the Rio Grande River in southwestern Colorado. Streamflow was measured on two watersheds from 1911 to 1919 when one of the watersheds was clearcut. Streamflow increased about 25% following this treatment. Many of the later water-balance studies in the high elevation spruce-fir and lodgepole forests were undertaken on the Frasier Experimental Forest in north-central Colorado. A status-of-knowledge publication (Leaf, 1975) presented in-depth discussions of the results of these studies through the early 1970s. Troendle et al. (1987), Ffolliott and Brooks (1988), and other researchers updated this information later. Research conducted in mixed conifer forests at Workman Creek on the Sierra Ancha Experimental Forest in central Arizona indicates that increases in annual streamflow can be obtained by replacing trees with a grass cover that consumes less water on "strategically" located parts of a watershed or reducing the forest overstory densities to lower the consumptive use of water by the trees (Gottfried et al., 1999a). The U.S. Forest Service expanded its watershed research in the mixed conifer forests to Willow Creek and Thomas Creek in the White Mountains of eastern Arizona in the late 1960s to confirm the results obtained from Workman Creek and further test prescribed multiple use forest management treatments (Rich and Thompson, 1974; Ffolliott and Brooks, 1988; Baker, 1999; Gottfried et al., 1999a,b; Baker and Ffolliott, 2000) (Fig. 1). Key findings from these collective efforts include (Table 1):

- Increases in annual water yields of 25–75 mm can often be expected on watersheds supporting high elevation subalpine forests by managing for snowpack redistribution and transpiration reduction in small openings created in the forest overstory.
- Suggested timber harvesting procedures for obtaining water yield increases in the spruce-fir forests are a series of patch cuts, equivalent to five to eight tree-heights in diameter, covering about one-third of the watershed unit. These timber cuts would be scheduled at 50-year intervals. Harvesting in lodgepole pine forests is similar to that in spruce-fir forests except that the patch cuts would be made at 30-year intervals. Thinning of the regenerated forest stands can be scheduled as necessary to meet silvicultural objectives.
- Clearcutting mixed conifer forests on Workman Creek in stages starting on the wettest and progressing to the driest sites increased annual water yields by almost 65 mm, about 75%, for the combined treatments over a 20-year period. Potentials for

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

Table 1
Vegetation types, distribution area, altitude, precipitation and potential increase in streamflow after appropriate vegetation manipulations for the upper and lower portion of the Colorado River Basin.

	Area (10^4 km^2)	%	Altitude (m)	Precipitation (mm yr^{-1})	Streamflow response
Upper Basin	28.3	44	1200–3500	300–1400 (average 400)	Average at 65 mm
Subapline (spruce, fir, pine)	2.8	4.3	2100–3500	500–1400, 2/3 snow	25–75 mm increase with 1/3 patch cuts
Mountain brush lands	1.3	2.0	1500–3000	400 – 600, <1/2 snow	15–45 mm increase, only for 3–5 years without shrub re-growth control
Ponderosa pine	0.6	0.9	1850–2750	380–35, 1/2 snow	Refer to Lower Basin
Pinyon-juniper woodlands	5.1	7.8	1200–2300	300–450	Negligible by mechanical treatment; less than 12.5 mm increase by herbaceous treatment; treatment effect vanished after dead trees were removed.
Lower Basin	36.4	56	50–3000	150 – 760 (average 330)	Average at 10 mm
Mixed conifer forest (spruce, fir, pine)	0.16	0.25	2100–3000	630–760, >1/2 snow	Refer to Upper Basin
Ponderosa pine	2.4	3.7	1800–2700	500–630	6.5–25 mm increase (varied densities); negligible by low to intermediate stocking levels
Pinyon-juniper woodlands	8.1	12.5	1200–2300	300–450	Refer to Upper Basin
Chaparral shrubland	1.4	2.2	900–2000	380–630	Average 100 mm increase where precipitation is over 500 mm.
Big sagebrush (including Upper Basin)	14.5	16.2	50–1500	150–250	12.5 mm increase by conversion of sagebrush to grasses on favorable sites

increasing annual water yields in these forests are generally about 25% less than in the subalpine forests.

- Single-tree selection followed by conversion of mixed conifer to ponderosa pine forest stands by removing other conifer species and thinning to residual ponderosa pine forest to a comparatively low density also increased annual water yields on Workman Creek. This treatment, which affected nearly 85% of the watershed area, resulted in average annual water yield increases of approximately 100 mm, nearly 110%, for 12 years. However, this severe thinning treatment is not currently recommended because of environmental concerns.
- A treatment to bring densities of the mixed conifer forests on Willow Creek to "optimum stocking conditions" by removing mature, over-mature, and high risk trees resulted in a nearly 100 mm, or 55%, increase in annual water yields in the short-term. However, the heavy logging and subsequent wind damage to residual trees compromised the original research objectives. Final treatment conditions on this watershed were similar to a large clearcut rather than to the intended stands of young-growth sawtimber-sized trees. Implementation of a prototypical resource-allocation plan on Thomas Creek involving patch clearcutting with other single-tree and group selection methods increased annual water yields about 45%. The annual streamflow increases were generated by snowmelt or large winter storms, a finding that was similarly observed with other research efforts in the mixed conifer forests.

3.1.2. *Ponderosa pine forests*

Watershed research on water yield improvement in the ponderosa pine forests of the Colorado River Basin was conducted on the Beaver Creek watersheds in north-central Arizona (Brown et al., 1974; Baker, 1982; Ffolliott and Brooks, 1988; Baker, 1999; Baker and Ffolliott, 2000) and in the high elevation ponderosa pine forests on the Castle Creek watersheds in eastern Arizona (Gottfried et al., 1999b); and in the ponderosa pine forests on the Colorado Front Range (Gary, 1975). Results of this research indicated that (Table 1):

- Potentials for increasing annual water yields in ponderosa pine forests are less than in the higher elevation subalpine and mixed conifer forests because of the drier conditions. However, short-term (up to 10 years) increases of 25–75 mm were observed on the Beaver Creek watersheds as a result of varying intensities of tree overstory thinning, alternative patterns of overstory removal, and combinations of these two treatments. Increases of 6.5–25 mm are a more realistic expectation of annual water yield increases within a multiple use management framework, where water, forage, wood, wildlife, and recreation are considered together.
- An average annual water yield increase of 6.5 mm, approximately 30%, remained stable for 20 years after an irregular-block timber harvesting operation and a thinning of the tree overstory on a watershed at Castle Creek. The initial increase in water yields was attributed to reduced evapotranspiration by the residual trees and increased snow accumulations in the created openings. No increase in water yield occurred after a prescribed burn on a second watershed because the fire did not significantly affect the forest overstory conditions or consume much of the litter and duff accumulations on the forest floor (Gottfried and DeBano, 1990).
- Low to intermediate stocking levels in two-thirds of the ponderosa pine forests on the Colorado Front Range generally preclude significant annual water yield increases from these areas regardless of the management emphasis. The only exception is clearcutting, which is not presently a feasible timber harvesting option in the basin.

3.1.3. *Mountain shrub ecosystems*

There is insufficient research in these largely Gambel oak ecosystems to obtain reliable estimates of how vegetation manipulations might influence annual water yields. However, extrapolation of the results from plot studies in Utah (Tew, 1966, 1969; Johnson et al., 1969) suggests that responses of converting mountain brush to a grass cover to reduce the consumptive use of water might be less than that anticipated in the chaparral shrub ecosystems at lower elevations (see below). An annual increase of 15–45 mm in water yield was expected from this type of conversion. However, this increase would be short-lived (only 3–5 years) if shrub re-growth is not controlled (Table 1).

3.1.4. *Pinyon-juniper woodlands*

Effects of vegetation manipulations on annual water yields in the pinyon-juniper woodlands have been studied mostly on the Beaver Creek watersheds (Clary et al., 1974; Baker, 1999; Baker and Ffolliott, 2000). Conversions of the open pinyon-juniper overstories characterizing these woodlands to less water-demanding herbaceous covers of grasses, forbs, and shrubs by cabling, felling,

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

and herbicide treatments resulted in the following responses (Table 1):

- Cabling, pushing, or felling (mechanical treatments) of pinyon-juniper woodlands had a negligible effect on annual water yields. Any water yield increase is thought to be lost to the several-fold increase in transpiration by the increased occurrence of herbaceous plants.
- Herbicidal treatment involving the aerial applications of a mixture of picloram and 2,4-D to kill the trees resulted in a small (but significant) increase in annual water yields of less than 12.5 mm. The test watershed was sprayed with the herbicide mixture from a helicopter to kill trees. The dead but standing trees on the watersheds were then removed after 8 years of post-herbicide evaluation in a second-stage of the treatment. Annual streamflow returned to near pre-treatment levels after the dead trees were removed. However, large-scale conversion treatments with herbicides are currently environmentally unacceptable in the United States.

3.1.5. *Chaparral shrublands*

A research program on the Three Bar Wildlife Area near the Roosevelt Reservoir in central Arizona represented the first major “experimental watershed program” in the chaparral shrub ecosystems of the Colorado River Basin (Hibbert et al., 1974; Baker, 1999; DeBano et al., 1999a; Baker and Ffolliott, 2000). This early program, which was initiated in 1956, was followed later by research on the Whitespar, Mingus, and Battle Flat watersheds in north-central Arizona to further assess potentials for water yield improvement through chaparral to grass conversion practices (DeBano et al., 1999b). Findings from these research efforts include (Table 1):

- Increasing streamflow by vegetation type conversion is possible on “favorable sites” where annual precipitation averages 500 mm or more. The key to increasing annual water yields on these sites is the replacement of deep-rooted chaparral shrubs with shallow-rooted grasses and forbs, which use less water, by applications of herbicides, prescribed burning, or combinations of these methods. Expected average increase is 100 mm in annual water yields on areas receiving more than 500 mm of average precipitation.
- Chaparral shrubs surviving initial conversion treatments and post-treatment re-sprouting have to be controlled. The post-treatment shrub covers should be maintained at about 10% to sustain the observed annual water yield increases. However, concerns about the environmental effects of herbicides and increased recognition of other multiple use values in the chaparral shrublands have restricted large-scale applications of conversion treatments.

3.1.6. *Big sagebrush*

Potentials for increasing annual water yields through vegetative manipulations in big sagebrush ecosystems are poorly defined. Conversions of sagebrush to grasses on “favorable sites” might increase water yields by 12.5 mm, or 15%, according to Sturges (1975), Hibbert (1979), and Ffolliott and Baker (2000). An additional increase of 25 mm might be possible by trapping blowing snow, a common phenomenon in this ecosystem, behind a series of snow fences erected in areas where snowpack water equivalents are 200 mm or more (Tabler, 1971, 1973).

3.1.7. *Semi-desert ecosystems*

Semi-desert grass–shrub ecosystems are the least important water-yielding areas in the Colorado River Basin because of their comparatively low precipitation inputs and high evaporation rates (Baker and Ffolliott, 2000). While annual streamflow averages of up to 15 mm have been observed in these semi-desert shrublands, these amounts are highly variable from year to year and, therefore, cannot be relied upon.

3.2. *Streamflow pattern*

Factors affecting the timing of streamflow in the Colorado River Basin include climatic factors such as the type of precipitation (rain or snow), rainfall intensity, duration, and distribution, direction of storm movement, antecedent soil moisture, and factors affecting evaporation and transpiration. The physical characteristics of the watershed influencing streamflow patterns are its area, shape, elevation, and slope, drainage network, type of soil, and past and present land-use practices (Satterlund and Adams, 1992; Brooks et al., 2003; Chang, 2003). Impacts of these factors – individually or combinations – are site-specific and, therefore, must be evaluated on a watershed-by-watershed basis. Clearing or thinning the vegetation on large portions of watersheds in the higher elevations of the region is likely to increase streamflow and, as a consequence, might increase the stage of flooding when large rainfall events occur. Large clearings and heavy thinnings decrease interception and transpiration losses more than evaporation is increased in many instances.

Effects of vegetation manipulations on the timing of streamflow and peak discharge of stormflow dependent largely on the intensity, pattern, and scheduling of the clearings or thinnings; other manipulations involved in implementing the treatments; and the streamflow generation treatments involved. Depending on the streamflow generation mechanisms, peak discharges can be increased up to 50% when watersheds are completely clearcut or the vegetation overstory is “heavily” thinned (Swank et al., 1989; Satterlund and Adams, 1992; Brooks et al., 2003). However, there could be little impact (effect) on peak discharges, although water yields might be increased, when partial clearcuts (strips, patches, etc.) and “light to moderate” thinnings are sequenced in time and space.

Observations from specific studies are:

- Partial clearcuts and “light to moderate thinnings” on watersheds where snowmelt-runoff is a primary streamflow-generating mechanism tend to “desynchronize” the streamflow with little or no increase in peak discharges (Rich and Gottfried, 1976; Baker, 1982; Troendle, 1983; Troendle and King, 1985; Ffolliott et al., 1989; Swank et al., 1989). A movement toward synchronization of streamflow can be achieved when these treatments are imposed on varying topography, with treatments placed on “cool” sites accelerating streamflow to coincide with the flow from untreated “warm” sites.
- Implementing vegetative manipulations on selected topographic landscapes can either lengthen or shorten seasonal streamflow periods, especially on watersheds where snowmelt-runoff is a main streamflow generation mechanism. Seasonal streamflow regimes from large watersheds with varying topography are delayed or accelerated by prescribing vegetation manipulations to delay or accelerate the initiation of on-site overland flow and then stage the implementation of these practices with respect to the topography of the watershed that either desynchronizes or synchronizes the resultant streamflow.
- Impacts of conversions of lower elevation pinyon-juniper overstories and chaparral shrubs to herbaceous understories on streamflow patterns are generally less than treatments in the higher elevation montane forests (Clary et al., 1974; Baker, 1984, 1999). Rainfall-generated streamflow is often more common than snowmelt generated runoff at these elevations.
- Little is known about changes in the timing of streamflow from watersheds within the semi-desert grass–shrub ecosystems at lower elevation in the region.

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

3.3. Stormflow

Streamflow from watersheds in the Colorado River Basin is often a "stormflow response" following high intensity, short-duration events (Lopes et al., 2001; Brooks et al., 2003). The water table is usually below the bed of the stream in the watershed situations, and, therefore, there is no perennial flow. The Colorado River Basin is situated in environments with one rainy season (mainly summer convectional storms), split rainy seasons (summer and winter), and/or a snowfall season. Much of the streamflow from watersheds in these environments occurs either in the summer rainy season, with intermittent stormflows occurring after the occasional large streamflow-generating event in the dry season; as a result of large late fall-winter rainfall events (frontal storms); or from snowmelt-runoff events in middle-to-late spring and early summer. Streamflow that is generated from these watersheds is "stormflow" when baseflow is absent in either of these latter cases. It becomes necessary to separate stormflow from baseflow when streamflow is perennial.

Seasonal distribution of stormflow: an example:

- Most of the annual water yields from the ponderosa pine forests and lower elevation pinyon-juniper woodlands on the Beaver Creek watersheds originate from stormflows in the winter or early spring as a consequence of streamflow-generating winter rains, snowmelt-runoff, or combinations of these two mechanisms (Solomon et al., 1975; Baker, 1982; Jones and Brazel, 1986; Ffolliott et al., 1989). Late winter–early spring stormflow regimes account for 97% of the annual water yields in the ponderosa pine forests and about 85% in the pinyon-juniper woodlands. Little stormflow is generated in the summer months.

3.4. Low streamflow

Impacts of clearing or "heavy" thinning of vegetation on large portions of a watershed when pre-treatment transpiration rates are comparatively high can often increase low streamflow regimes depending on the "hydrologic characteristics" of the soil and site. Conversely, the impact (effect) can be a reduction in low flows when transpiration rates are low such as the case in late fall or winter. However, "generalizations" for all seasons and conditions are inappropriate.

Observations from specific studies are:

- Clearing or heavily thinning vegetation on large portions of a watershed (occasionally) increases streamflow (stormflow) originating in the "dry season" as a result of streamflow-generating rainfall in the region (Brown et al., 1974; Hibbert et al., 1974; Hibbert, 1979; Baker, 1982). Streamflow influenced by snowmelt-runoff appears to be less affected by these treatments.
- Conversions of chaparral shrubs to grass has "activated" springs on some of the chaparral-dominated landscapes (Hibbert et al., 1974), often resulting in low streamflow in seasons (summer) when the flow was previously nil.

3.5. Extrapolation of watershed-scale studies to the Colorado River Basin

Extrapolation of the results from the watershed-scale studies to increase streamflow from relative small upland watersheds to the larger Colorado River Basin and then to downstream points of water-use involves a series of sequential steps (Ffolliott and Fogel, 2003; Ffolliott et al., 2007). Conditions on the upland watersheds from which results of the studies are to be extrapolated must be characterized in terms of the climatic, physical, vegetation, and social conditions on the watersheds. Areas within larger basin that are not constrained by these conditions are then delineated relative to the possibility of implementing the results of the water yield improvement studies. Increases in streamflow estimated from these treatable areas in the larger river basins are finally routed to downstream points of use in the temporal context of delivering the estimated increases in water supply to these points in the final step of the extrapolation process. While this extrapolation process has been followed in earlier analyses (Thorud, 1974; Ffolliott and Throud, 1975), knowledge of the potentials for water yield improvement in the Colorado River Basin is more comprehensive at this time (Baker, 1999; Baker and Ffolliott, 2000) and methodologies to implement the extrapolation process are more sophisticated.

3.5.1. Conditions on watersheds

Conditions of the upland watersheds studied must be summarized in terms of the climatic, physiographic, vegetative, and other relevant biophysical features and institutional and socioeconomic conditions to provide a basis for extrapolation of the results from these watersheds to the larger river basins. The watersheds, therefore, are characterized by:

- Ownership status – responsible administrating agency on public lands and individual(s) on private lands.
- Climate (weather patterns) – season and annual precipitation amounts and distribution and temperature regimes.
- Vegetation – dominate vegetation communities including main tree overstory species and herbaceous plant species.
- Physiography – geologic formations, topographic features, and soil origin and properties.
- Other key features and conditions of importance to the extrapolation process.

This information is obtained from the literature (Brown et al., 1974; Clary et al., 1974; Rich and Thompson, 1974; Ffolliott and Throud, 1975; Hibbert, 1979; Baker, 1999; Baker and Ffolliott, 2000), earlier resource classifications, and inventory summaries. The information can also be spatially displayed by applying GIS procedures to determine the proportions of the watersheds delineated by the identified conditions. Studies to be extrapolated from the upland watersheds must also be comprehensively described in relation to the vegetation manipulation implemented (clearing, thinning, conversion of tree overstories, etc.) and comparative benefits and costs that are associated with these manipulations. The results of these studies are essentially "case studies" that represent discrete points on a continuum of possible vegetation manipulations. Necessary missing points on this continuum can often be generated through appropriate simulation techniques (Brooks et al., 2003).

3.5.2. Treatable areas on the basin

Vegetative communities on the upland watersheds studied and their respective distributions have been mapped on 15 river basins into which Arizona had been arbitrarily delineated to illustrate application of this general extrapolation procedure within the Colorado River Basin. Precipitation isohyets and land ownership patterns were superimposed on each vegetative community and the total acreage within each precipitation strata determined by ownership for each of the river basins. Following downward adjustments necessitated by constraints to the implementation of a vegetative management practice, the "potentially treatable areas" are combined with the estimates of increases in streamflow obtained from the upland watersheds. Other than ownership, these constraints include climate (weather), physiography, vegetation, and institutional, social,

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

and economic limitations. Still other constraints are included in the extrapolation were necessary.

A few guidelines are presented to indicate how some of these constraints might be evaluated in making the downward adjustments in total areas to determine treatable areas in the Colorado River basin. An analysis by Hibbert (1979) indicated that vegetative management practices implemented in the Colorado River Basin could increase streamflow only in areas receiving at least 450 mm of annual precipitation. Hibbert reasoned that annual precipitation amounts below 450 mm would be effectively used by residual tree overstories and increases in the re-growth of herbaceous plants on the treated area. This finding alone suggests that in the Colorado River Basin, high elevation montane forests and portions of low elevation chaparral communities have the "best potentials" for achieving water yield improvement (Baker, 1999; Baker and Ffolliott, 2000) as mentioned above.

A minimal density of trees is often specified in deciding whether it is feasible to implement, for example, a manipulation in a forest ecosystem on a treatable area. It is assumed in the extrapolation process that the proportion of the area that is stocked to the density level corresponding to the density of the proposed vegetation manipulation represents the proportion of the area that will be impacted by the prescription (Ffolliott and Worley, 1973; Ffolliott, 1978). If this proportion is deemed too small to effectively increase streamflow, the original proposal might be discarded in favor of one that places a larger proportion of the area under the prescribed management practice.

Vegetative manipulations can be implemented in the montane forests of the Colorado River Basin to structure the tree overstories in a manner that "optimizes" snowpack accumulation–melt processes to enhance the role that snowmelt-runoff plays in streamflow generation in many of the higher elevation tributaries (Ffolliott and Baker, 2000). Studies of these vegetation manipulations indicate that aspects representing cooler sites vis-a-vis warmer sites are crucial in planning for the implementation of these manipulations (Ffolliott et al., 1989; Baker, 1999). More snow is retained throughout the winter season on the cooler sites than on warmer sites, and, as a consequence, more snow is available to increase the volume of snowmelt-runoff in the spring. Knowledge of the proportions of cooler and warmer sites on a treatable area, therefore, helps in determining how to either synchronize or desynchronize snowmelt-runoff regimes depending on the watershed management purpose.

4. Discussion and conclusion

Water shortage is expected to exacerbate in a large part of the globe (Tao et al., 2003; Stocker and Raible, 2005), including both southeastern USA (Sun et al., 2008) and southwestern USA (Tao et al., 2003). The impact is particularly severe for Colorado River Basin where various models and multiple evidence indicated that an extra 10–30% reduction in streamflow is projected due to changes in climate (Nash and Gleick, 1991; Christensen et al., 2004; Christensen and Lettenmaier, 2007; Barnett and Pierce, 2009), and this will aggravate water supply shortage in this highly populated region (Barnett et al., 2004; Christensen and Lettenmaier, 2007; McCabe and Wolock, 2007; Barnett and Pierce, 2009) and demand solutions. Vegetation manipulation with a primary goal to increase streamflow generation could potentially be one of the solutions.

Analyses of the watershed-scale research in the Colorado River Basin suggest that the effect of vegetation manipulation on streamflow is associated with precipitation–elevational gradient and, therefore, vegetation type. The best opportunities for increasing annual water yields by implementing vegetation manipulations are concentrated in the high elevation subalpine and mixed conifer forests, the ponderosa pine forests (in the Lower Basin), and portions of the low elevation chaparral shrublands. These vegetative communities are situated on sites with "favorable precipitation regimes" and, in the case of the chaparral shrublands, found close to downstream points of water consumption; therefore, in this latter case, en-route transmission losses are lessened (Baker and Ffolliott, 2000; DeBano et al., 2004; Stednick and Troendle, 2004). However, estimates of increases in streamflow following implementation of vegetative management practices in the Colorado River Basin and elsewhere generally refer to on-site responses at the outlet of the upland watersheds (Bosch and Hewlett, 1982; Douglas, 1983; Hibbert, 1979, 1983; Hornbeck et al., 1993; Whitehead and Robinson, 1993). It is important to point out that the area of such vegetation is less than 9 million ha or about 14% of the total area of the basin. Treatment on the vast pinyon-juniper woodland, sagebrush and desert scrubs does not produce any meaningful increase in streamflow.

Furthermore, the estimates of water yield increase are commonly reported in terms of average weather and hydrologic conditions for a specific period of years that is unlikely to occur every year. These increases are large in some years and small or non-existent in other years depending mostly on the variations in annual precipitation and soil moisture storage on the watersheds. The increases in streamflow from upland watersheds persist only for a few years and streamflow often returns to pre-treatment levels after 10 years or less in the Colorado River Basin (Baker, 1999; Baker and Ffolliott, 2000). It must be expected, therefore, that durations of the estimates of increases in streamflow from the treatable areas within the larger river basins will be similar.

In extrapolating the results obtained from watershed-scale studies such as those conducted in the Colorado River Basin to large river basins elsewhere, it is improbable that all of the treatable areas identified within a river basin can be treated simultaneously since relatively large acreages are involved. A temporal scheduling (sequencing) of vegetation manipulation (treatments) is more likely to occur. As a consequence, the estimated total increase in streamflow from all of the treatable areas within a river basin (in aggregate) will be less than the increase observed on the upland watersheds. It also cannot be assumed that all of the treatable areas identified for treatment are homogeneous in every respect. Impacts of a treatment on a treatable area, therefore, will not be uniform. Finally, allowances must also be made in the extrapolation processes for the transmission depletions or consumptive water-use by streamside vegetation between the outlet of the upland watersheds and downstream reservoirs and other points of water-use.

Current managerial experience and policy implications indicate that to be economically feasible, vegetation manipulations implemented in the Colorado River Basin to improve water yields must also benefit other collateral natural resources and values such as forage production, wildlife habitats, and recreational activities in addition to increasing streamflow (Baker, 1999; Ffolliott et al., 2000). Without these other benefits, implementation of vegetation management practices that enhance streamflow is likely not be acceptable to the public. While applications of the results of this research alone cannot totally alleviate water shortages in the basin, knowledge of these findings should help land-use planners formulate comprehensive strategies to address this challenge. This research has led to a better understanding of the potentials and limitations of vegetation manipulations for enhancing water yields to meet the increasing needs of people living in the Colorado River Basin, elsewhere in the western United States (National Research Council, 2008), and, more generally, throughout the world (Gregersen et al., 2007; Ffolliott et al., 2007).

Acknowledgment

We thank several reviewers for their comments and suggestions that have helped to improve this manuscript. We also thank NASA's LULCC program for providing funding to support the senior author to present this work in IUFRO – 8.01.02 Landscape Ecology and Forest Management conference. Additional support was provided by NIWR/USGS National Competitive Grant Program, Oklahoma Agricultural Experiment Station, Oklahoma Cooperative Extension Service.

References

Baker Jr., M.B., 1982. Hydrologic regimes of forested areas on the Beaver Creek watershed. General Technical Report RM-90. USDA Forest Service, Fort Collins, Colorado.

Baker Jr., M.B., 1984. Changes in streamflow in an herbicide-treated pinyon-juniper watershed in Arizona. Water Resources Research 20, 1639–1642.

Baker Jr., M.B. (compiler), 1999. History of watershed management in the Central Arizona Highlands. General Technical Report RMRS-GTR-29. USDA Forest Service, Fort Collins, Colorado.

Baker, M.B., Ffolliott, P.F., 2000. Contributions of watershed management research to ecosystem-based management in the Colorado River Basin. In: Ffolliott, P.F., Baker, Jr., M.B., Edminster, C.B., Dillion, M.C., Mora, K.L. (Eds.), Land stewardship in the 21st century: The contributions of watershed management. Proceedings RMRS-P-13, USDA Forest Service, pp. 117–128.

Barnett, T.P., Malone, R., Pennell, W., Stammer, D., Semtner, B., Washington, W., 2004. The effects of climate change on water resources in the west: introduction and overview. Climatic Change 62, 1–11.

Barnett, T.P., Pierce, D.W., 2009. Sustainable water deliveries from the Colorado River in a changing climate. Proceedings of the National Academy of Sciences of the United States of America 106, 7334–7338.

Bates, C.G., Henry, A.J., 1928. Forest and Streamflow Experiment at Wagon Wheel Gap, Colorado, supplement 30. US Weather Service, Washington, DC.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55, 3–23.

Brooks, K.N., Ffolliott, P.F., Gregersen, H.M., DeBano, L.F., 2003. Hydrology and the Management of Watersheds. Iowa State Press, Ames, IA.

Brown, H.E., Baker Jr., M.B, Rogers, J.J., Clary, W.P., Kovner, J.L., Larson, F.R., Avery, C.C., Campbell, R.E., 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. Research Paper RM-129. USDA Forest Service.

Chang, M., 2003. Forest Hydrology: An Introduction to Water and Forests. CRC Press, Boca Raton, FL.

Christensen, N.S., Lettenmaier, D.P., 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. Hydrology and Earth System Sciences 11, 1417–1434.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., Palmer, R.N., 2004. The effects of climate change on the hydrology and water resources of the Colorado River basin. Climatic Change 62, 337–363.

Clary, W.P., Baker Jr., M.B., O'Connell, P.F., Johnsen Jr., T.N., Campbell, R.E., 1974. Effects of pinyon-juniper removal on natural resource products and uses. Research Paper RM-128. USDA Forest Service.

Coleman, E.A., 1953. Vegetation and Watershed Management. The Ronald Press, New York, p. 412.

DeBano, L.F., Baker Jr., M.B., Gottfried, G.J., 1999a. Providing water and forage in the Salt-River Basin. In: Baker Jr., M. B. (Eds.), History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29. USDA Forest Service, pp. 13–18.

DeBano, L.F., Baker Jr., M.B., Overby, S.T., 1999b. Managing chaparral in Yavapai. In: Baker Jr., M.B. (Eds.), History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29. USDA Forest Service, pp. 19–25.

DeBano, L.F., Ffolliott, P.F., Baker Jr., M.B., 2004. Fifty years of watershed management in the Southwest: some lessons learned In: Ice, G.C., Stednick, J.D. (Eds.), A Century of Forest and Wildland Watershed Lessons. Society of American Foresters, Bethesda, MD, pp. 155–168.

Douglas, J.E., 1983. The potential for water yield augmentation from forest management in the eastern United States. Water Resources Bulletin 19, 351–358.

Ffolliott, P.F., Worley, D.P., 1973. Forest stocking equations: their development and application. Research Paper RM-102. USDA Forest Service.

Ffolliott, P.F., 1978. A multifunctional inventory approach to multiple use analysis. In: Lund, H.G., LaBau, V.J., Ffolliott, P.F., Robinson, D.W. (Eds.), Integrated Inventories of Renewable Natural Resources: Proceedings of the Workshop. General Technical Report RM-55. USDA Forest Service, pp. 395–402.

Ffolliott, P.F., Baker Jr., M.B., 2000. Snowpack hydrology in the southwestern United States: contributions to watershed management. In: Ffolliott, P.F., Baker, Jr., M.B., Edminster, C.B., Dillon, M.C., Mora, K.L. (Eds.), Land Stewardship in the 21st Century: The Contributions of Watershed Management. Proceedings RMRS-P-13, USDA Forest Service, pp. 274–276.

Ffolliott, P.F., Baker Jr., M.B., Lopes, V.L., 2000. Watershed management perspectives in the Southwest: past, present, and future. In: Ffolliott, P.F., Baker, Jr., M.B., Edminster, C.B., Dillon, M.C., Mora, K.L. (Eds.), Land Stewardship in the 21st Century: The Contributions of Watershed Management. Proceedings RMRS-P-13, USDA Forest Service, pp. 30–36.

Ffolliott, P.F., Brooks, K.N., 1988. Opportunities for enhancing water yield, quality, and distribution in the Mountain West. In: Schmidt, W.C (Ed.), Proceedings – Future Forests of the Mountain West: A stand Culture Symposium. General Technical Report INT-243. USDA Forest Service, Ogden, UT, pp. 55–60.

Ffolliott, P.F., Fogel, M.M., 2003. Connecting upland watershed to larger river basins. Journal of the Arizona-Nevada Academy of Science 35, 71–75.

Ffolliott, P.F., Gottfried, G.J., Baker Jr., M.B., 1989. Water yield from snowpack management: research findings in Arizona and New Mexico. Water Resources Research 25, 1999–2007.

Ffolliott, P.F., Gregersen, H.M., Brooks, K.N., 2007. Integrated watershed management: an approach to natural resources management. Quarterly Journal of International Agriculture 46, 373–394.

Ffolliott, P.F., Throud, D.B., 1975. Water yield improvement by vegetation management: focus on Arizona. National Technical Information Service, PB 246 055. US Department of Commerce, Washington, DC.

Gary, H.L., 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: the status of our knowledge. Research Paper RM-139. USDA Forest Service.

Gottfried, G.J., DeBano, L.F., 1990. Streamflow and water quality responses to preharvest prescribed burning in an undisturbed ponderosa pine watershed. In: Krammes, J.S. (Ed.), Effects of fire management of southwestern natural resources. General Technical Report RM-191. USDA Forest Service, pp. 222–228.

Gottfried, G.J., DeBano, L.F., Baker Jr., M.B., 1999a. Beginning of water studies in the Central Arizona Highlands. In: Baker Jr., M.B. (Ed), History of watershed research in the Central Arizona Highlands. USDA Forest Service, General Technical Report RMRS-GTR-29, pp. 7–12.

Gottfried, G.J., DeBano, L.F., Ffolliott, P.F., 1999b. Creating a basis for watershed management in high elevation forests. In: Baker Jr., M.B. (Ed.), History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29. USDA Forest Service, pp. 35–41.

Gregersen, H.M., Ffolliott, P.F., Brooks, K.N., 2007. Integrated Watershed Management: Connecting People to Their Land and Water. CABI, Oxfordshire, United Kingdom.

Hibbert, A.R., 1979. Managing vegetation to increase flow in the Colorado River Basin. General Technical Report RM-66. USDA Forest Service, Fort Collins, CO.

Hibbert, A.R., 1983. Water yield improvement potential by vegetation management on western rangelands. Water Resources Bulletin 19, 375–381.

Hibbert, A.R., Davis, E.A., Scholl, D.G., 1974. Chaparral conversion: Part 1: Water yield response and effects on other resources. Research Paper RM-17. USDA Forest Service.

Hornbeck, J.W., Adams, M.B., Corbert, E.S., Verry, E.S., Lynch, J.A., 1993. Long-term impacts of forest treatments on water yield: a summary for the northeastern U.S.A. Journal of Hydrology 150, 323–344.

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

Johnson, R.S., Tew, R.K., Doty, R.D., 1969. Soil moisture depletion and estimated evapotranspiration on Utah mountain watersheds. Research Paper INT-67. USDA Forest Service.

Jones, R., Brazel, A.J., 1986. Problems associated with the variability of southwest precipitation and seasonal snowpacks. Western Snow Conference 54, 12–17.

Kittredge, J., 1948. Forest Influences. McGraw-Hill Book Co., New York, NY.

Komatsu, H., Kume, T., Otsuki, K., 2008. The effect of converting a native broad-leaved forest to a coniferous plantation forest on annual water yield: a, paired-catchment study in northern Japan. Forest Ecology and Management 255, 880–886.

Kovner, J.L., Evans, T.C., 1954. A method for determining the minimum duration of watershed experiments. Transactions of the American Geophysical Union 35, 608–612.

Lane, P.N.J., Mackay, S.M., 2001. Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. Forest Ecology and Management 143, 131–142.

Leaf, C.F., 1975. Watershed management in the Rocky Mountain subalpine zone: the status of our knowledge. Research Paper. RM-137. USDA Forest Service.

Lopes, V.L., Ffolliott, P.F., Baker Jr., M.B., 2001. Impacts of vegetative management practices on suspended sediment from watersheds of Arizona. Journal of Water Resources Planning and Management 127, 41–47.

McCabe, G.J., Wolock, D.M., 2007. Warming may create substantial water supply shortages in the Colorado River basin. Geophysical Research Letters 34, L22708, doi:10.1029/2007GL031764.

Nash, L.L., Gleick, P.H., 1991. Sensitivity of streamflow in the Colorado Basin to climatic changes. Journal of Hydrology 125, 221–241.

National Research Council, 2008. Hydrologic Effects of a Changing Forest Landscape. National Academy Press, Washington, DC.

Reigner, I.C., 1964. Calibrating a watershed using climatic data. Research Paper NE-15. USDA Forest Service.

Rich, L.R., Gottfried, G.J., 1976. Water yields resulting from treatments on the Workman Creek Experimental Watersheds in central Arizona. Water Resources Research 12, 1053–1060.

Rich, L.R., Thompson, J.R., 1974. Watershed management in Arizona's mixed conifer forests: the status of our knowledge. Research Paper RM-130. USDA Forest Service.

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005

Robinson, M., Cognard-Plancq, A.L., Cosandey, C., David, J., Durand, P., Fuhrer, H.W., Hall, R., Hendriques, M.O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M., Zollner, A., 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. Forest Ecology and Management 186, 85–97.

Satterlund, D.R., Adams, P.W., 1992. Wildland Watershed Management. John Wiley & Sons, Inc., New York.

Solomon, R.M., Ffolliott, P.F., Baker Jr., M.B., Gottfried, G.J., Thompson, J.R., 1975. Snowmelt runoff efficiencies in Arizona watersheds. Resource Report 274. Agricultural Experiment Station, Tucson, Arizona.

Stednick, J.D., Troendle, C.A., 2004. Water yield and timber harvesting practices in the subalpine forests of the Central Rocky Mountains. In: Ice, G.C., Stednick, J.D. (Eds.), A Century of Forest and Wildland Watershed Lessons. Society of American Foresters, Bethesda, MD, pp. 168–169.

Stocker, T.F., Raible, C.C., 2005. Water cycle shifts gear. Nature 434, 830–832.

Sturges, D.L., 1975. Hydrologic relations on undisturbed and converted big sagebrush lands: the status of our knowledge. Research Paper RM-140. USDA Forest Service.

Sun, G., McNulty, S.G., Moore Myers, J.A., Cohen, E.C., 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. Journal of the American Water Resources Association 44, 1441–1457.

Sun, G., McNulty, S.G., Lu, J., Amatya, D.M., Liang, Y., Kolka, R.K., 2005. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. Journal of Hydrology 308, 258–268.

Swank, W.T., DeBano, L.F., Nelson, D., 1989. Effects of timber management practices on soil and water. In: Burns, R. M. (Ed.), The scientific basis for silvicultural and management decisions in the National Forest System. General Technical Report WO-55. USDA Forest Service, pp. 79–106.

Swank, W.T., Vose, J.M., Elliott, K.J., 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. Forest Ecology and Management 143, 163–178.

Tabler, R.D., 1971. Design of a watershed snow fence system and first-year snow accumulation. Western Snow Conference Proceedings 39, 50–55.

Tabler, R.D., 1973. Evaporation losses of windblown snow and the potential for recovery. Western Snow Conference Proceedings 41, 75–79.

Tao, F.L., Yokozawa, M., Hayashi, Y., Lin, E., 2003. Terrestrial water cycle and the impact of climate change. AMBIO 32, 295–301.

Tew, R.K., 1966. Soil moisture depletion by Gambel oak in northern Utah. Research Note INT-54. USDA Forest Service.

Tew, R.K., 1969. Converting Gambel oak to grass reduces soil-moisture depletion. Research Note INT-104. USDA Forest Service.

Thorud, D.B., 1974. The Arizona Watershed Program in review—conclusions and recommendations. Arizona Watershed Symposium 18, 58–60.

Troendle, C.A., 1983. The potential for water yield augmentation from forest management in the Rocky Mountain region. Water Resources Bulletin 19, 359–373.

Troendle, C.A., Kaufmann, M.R., Hamre, R.H., Winokur, R.P., tech. coords. 1987. Management of subalpine forests: building on 50 years of research. General Technical Report RM-149. USDA Forest Service.

Troendle, C.A., King, R.M., 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. Water Resources Research 21, 1915–1922.

Whitehead, P.G., Robinson, M., 1993. Experimental basin studies—an international and historical perspective of forest impacts. Journal of Hydrology 145, 217–230.

Wilcox, B.P., Owens, M.K., Knight, R.W., Lyons, R.K., 2005. Do woody plants affect streamflow on semiarid karst rangelands? Ecological Application 1155, 127–136.

Wilm, H.G., 1944. Statistical control of hydrologic data from experimental watersheds. Transactions of the American Geophysical Union 2, 616–622.

Wilm, H.G., 1948. How long should experimental watersheds by calibrated? Research Note 2. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

Please cite this article in press as: Zou, C.B., et al., Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecol. Manage. (2009), doi:10.1016/j.foreco.2009.08.005