Estimating the WATER SUPPLY BENEFITS from Forest Restoration in the Northern Sierra Nevada

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Executive Summary

Approximately two-thirds of California's water—including drinking water for 23 million people—originates in the Sierra Nevada as snow and rain. A number of interrelated factors, including historic land management practices, climate change, drought, and a growing population, are threatening the capacity of the Sierra Nevada to meet current and future demands for water. To address this issue, The Nature Conservancy explored whether increased investment in Sierra Nevada restoration may be a valuable strategy for increasing and enhancing California's water supply. This report examines the extent to which investing in forest and meadow restoration could increase water supply and improve the timing of water availability. We focused our analysis specifically on restoration at the watershed-scale on national forests in the northern Sierra Nevada.

Using syntheses of over 150 studies on the relationship between forest harvest and water yield, we estimated the potential water yield impacts from mechanical thinning to restore a forest's ability to store snow and use water more efficiently. Our analysis suggests that, if the current scale of forest restoration is increased three-fold, there could be up to a 6 percent increase in the mean annual streamflow for individual watersheds. In the Feather River, the watershed with the greatest area available for thinning, we estimated thinning might produce ~97,000–285,000 acre feet of additional runoff. We used a cost-benefit analysis to compare the costs associated with this increased pace of forest restoration to the economic value of water supply benefits to downstream hydropower, agricultural, and urban water users. We found that the economic benefits from increased hydropower generation and water uses are sufficient to cover between one-third and the full cost of thinning, assuming a low or high water response to forest thinning.

A firefighter douses flames during the 2013 Rim Fire, the largest wildfire recorded in the Sierra Nevada. © Justin Sullivan/Getty Images

Meadow restoration also has the potential to modify downstream water supply, particularly the timing of flows. Healthy, restored meadows may hold water during periods of high runoff and release it later in the season than would occur in a degraded meadow. We reviewed the only study to date that quantified the shift in water timing from meadow restoration to understand the potential of restoration to improve water supply timing. Given the lack of research, we did not extrapolate these findings to meadows across the northern Sierra Nevada.

In this preliminary assessment, we made some generalized assumptions that require further research and data collection to validate. Future research should quantify more precisely the water yield response from ecologically based forest thinning, especially at a large watershed scale, and more precisely calculate the economic value of increased water supplies for individual watersheds. Constrained public agency capacity and budgets make accelerating thinning challenging, but these findings suggest that investment by hydropower generators and downstream water users may be a cost-effective power production and water procurement strategy and can help to overcome funding barriers. Given the many other non-water benefits of such restoration efforts—including fire risk reduction and fish and wildlife benefits—our assessment suggests that investing in Sierra Nevada forest restoration deserves consideration as a cost-effective water supply strategy for California.

LEFT: Snow covers the ground in a thinned forest stand at Independence Lake Preserve. © Simon Williams, The Nature Conservancy

Introduction

Large-scale forest and meadow restoration is needed across the Sierra Nevada to reduce the risk of mega-fires and improve ecosystem health. Mega-fires are large, severe wildfires that burn larger and hotter than historic fires, and have more "lasting unwanted human, economic, and environmental consequences."[2] The largest recent example in California is the 2013 Rim Fire, which burned more than 250,000 acres with 33 percent of the areas burned at high severity, indicating complete mortality of live vegetation.[3] Forest restoration efforts are underway across national forests in the Sierra Nevada, but indicators show the scale of restoration lags far behind what is necessary to reduce unnaturally high fuel loads and the risk of mega-fires.

The U.S. Forest Service (USFS) forest restoration goal is 500,000 acres per year across the state of California and restoration of 50 percent of accessible, degraded meadows over the next 15–20 years.[3] However, the current USFS approach largely limits forest thinning to areas where costs can be offset by harvesting some timber, leaving large areas with dense, small trees of little commercial value untreated, and limiting capacity for thinning at the necessary scale to allow for more managed wildfire. Because forest and meadow restoration both have the potential to create water quantity and timing benefits to downstream water users and hydropower utilities, the economic value of these benefits should be considered as a potential way to help offset the costs and deliver restoration at sufficient scales.

Fire suppression and logging practices in the Sierra Nevada have resulted in large areas of forest that are overly dense with small trees and brush. These dense forests may alter streamflow patterns and reduce available water supplies. Dense forest cover intercepts snow thereby reducing snow storage on the ground. In addition, dense forests may intercept, evaporate, and transpire more water into the atmosphere. Restoring a forest's ability to store snow and reducing evapotranspiration by thinning the vegetation may release more water as runoff while simultaneously decreasing the risk of mega-fires and promoting healthier forest conditions. Modeling estimates for the Sierra Nevada predict a 1–16 percent increase in streamflow following forest thinning, depending on the assumptions made about the type, scale, and timing of forest treatment.[4,5,6] Recent estimates from Arizona predict a gain in mean annual runoff of 0–3 percent for six years after thinning for the entire watershed area, but a 1–9 percent increase in the sub-watershed that supplies water to the city of Phoenix.[7]

Wet meadows can function like a sponge by storing water, reducing peak flood flows, and releasing cold water in the summer when water is limited. Healthy meadows also provide habitat for rare and endangered species and valuable summer pasture for livestock grazing. The USFS meadow restoration goal is, "to improve their habitat function and ability to hold water longer into the summer and deliver clean water when most needed."[8] It is estimated that over 50 percent of meadows in the Sierra have been severely degraded through historic land-use practices, diminishing their current and long-term capacity to serve as vital water storage sites and habitat for meadow-dependent wildlife. In many cases, restoration involves channel realignment or "pond and plug," where practitioners reconnect the stream channel and floodplain to increase flooding of the meadow, thus recharging the groundwater. This summer timing may be valuable for downstream users because it augments the water supply when water and electricity demand are high and streamflow is low.

Despite the significant need for forest restoration and the abundance of hydropower in the northern Sierra Nevada, there have been no attempts to estimate how an increase in forest and meadow restoration across the northern region could impact water quantity, timing, and downstream water users. Abundant data are available on the water yield impact of forest harvest. Using these data, we estimated the potential water supply benefits of an increase in mechanical forest thinning on national forests in the northern Sierra Nevada. Based on these projections, we compared the costs associated with forest restoration to the potential economic value of water supply benefits for downstream water users. Unlike forests, few studies have been completed to measure the potential water supply benefits of meadow restoration. In order to characterize the potential for benefit, in this analysis we evaluated the one study available as the basis for further investigation. The premise of this analysis is that increased investment in forest restoration by downstream water users could help to overcome constraints in agency capacity and catalyze forest and meadow restoration at a scale that is sufficient to significantly improve the health and water-holding capacity of the Sierra Nevada.

"People look to the forests with hope when there is a drought and when there are floods."[1]

Colorado School of Mines students, Paul Micheletty (left) and Erik Wortman (right), with Dr. Terri Hogue's hydrology research group study the impact of forest thinning and prescribed fire on water yield in the Sagehen Experimental Forest. The students remove litter from the end of a snow core, measure the depth of the snowpack, and weigh the core to estimate the snow water equivalent. © Alicia Kinoshita

Methods

We analyzed 11 watersheds in the northern Sierra Nevada, the majority of which flow to a large rim reservoir. These include the American River, Bear River, Cosumnes River, Feather River, Lassen Foothill Creeks (Battle, Butte, Deer, and Mill), Mokelumne River, Truckee River, and Yuba River (Figure 1). The Truckee River flows into Nevada, and all other watersheds flow into California. The watershed delineation for all of the watersheds, except the four creeks in the Lassen Foothills, is approximately equivalent to the eight-digit hydrologic unit (fourth-level sub-basin) from the Watershed Boundary Dataset for California.[9] For watersheds with large dams, we used the unimpaired streamflow estimates from the California Department of Water Resources to estimate the streamflow. For all other watersheds, we used the U.S. Geological Survey (USGS) stream gauge at the watershed outlet.

Forest restoration areas

We summarized the past 10 years (2002–2012) of mechanical thinning and prescribed fire in the watersheds by compiling data from the Forest Service Activity Tracking System (FACTS) geodatabase, which provides an estimate of the existing pace and scale of forest treatments.[10] We removed areas of overlapping treatment in subsequent years to avoid double counting (Appendix A). To identify watershed-scale areas for future forest thinning, we used the Forest Service's analysis of operable thinning areas,

FIGURE 1. Study area watersheds in the northern Sierra Nevada.

those that are considered logistically feasible.[11] Additionally, the USFS budget often limits operation to areas with merchantable timber to offset the cost of the restoration. We selected two scenarios, C and D, which are the least constrained of the four modeled by the USFS for the Sierra Nevada. The primary difference between these two scenarios is that Scenario C requires merchantable timber to offset restoration costs, while D does not. We used Scenario D to estimate the water yield and economic benefits of forest restoration.

Before and after photos of forest thinning at Sagehen Experimental Forest. © Scott Conway, U.S. Forest Service

Currently, USFS mechanical treatment areas are constrained by legal, administrative, operational, and budgetary constraints. Because of this, only 25 percent of national forest in the Sierra Nevada is available for mechanical thinning, with the exception of the Lassen, Plumas, and Tahoe National Forests in the northern Sierra Nevada, which had 75 percent of their sub-watersheds available.[12]

Forest thinning and water yield

To estimate potential per-acre water yield benefits of forest thinning, we relied on existing peer-reviewed literature from studies across a range of conifer forest ecosystems. Brown et al. (2005) compiled results from three synthesis papers on paired watershed studies by Bosch and Hewlett (1982), Stednick (1996), and Sahin and Hall (1996).[13,14,15,16] Bosch and Hewlett (1982) recorded the maximum increase in water yield in the first five years after treatment for 94 paired watershed studies, while Sahin and Hall (1996) built on the Bosch and Hewlett (1982) study and recorded the average increase in the same time period. Brown et al. (2005) added 72 studies to Bosch and Hewlett (1982), bringing the total number to 166 studies. Despite this extensive literature on the relationship between forest harvest and water yield, there are no empirical studies completed yet on the effect of ecologically based forest thinning on water yield in the Sierra Nevada. These synthesis studies show a linear increase in water yield with increases in the percentage of forest removed regardless of the forest type or the precise logging method. Based on these studies, we used the average increase in water yield as a low estimate of water yield change, and the reported maximum increases to estimate the high end: 22–40 mm for 10 percent reduction in forest basal area (i.e., the area of tree trunks) or 0.14–0.41 acre-foot (AF) per acre of forest treated.[17,18]

We estimated the level of thinning based on existing ecological guidelines from the USFS and on-the-ground examples of thinning projects. Recent ecological guidelines for forest thinning in the Sierra Nevada emphasize the need for spatial heterogeneity with patches and gaps that replicate historic conditions when fire was more common.[19,20] The guidelines do not specify precise targets for forest conditions, but recent instances in which thinning practices followed these guidelines in the Sierra Nevada have reduced basal area 20–31 percent.[21,22,23] Research indicates that the minimum area that must be treated with strategically placed mechanical thinning and prescribed fire to reduce high-severity wildfire from moving easily across the landscape and minimizing ecological effects (a primary objective of these thinning efforts) is 10–30 percent of the watershed area.[24,25,26,27] Based on these ecological thinning guidelines and the area needed for management of wildfires, we assumed a 20–31 percent reduction in basal area and that the watershed area treated is proportional to the basal area removed.[28]

Based on the literature, we assumed the impact of forest thinning on water yield would occur in the winter and spring during the main precipitation period and encompassing the peak in snowmelt runoff (December to May) over a 7-year period. This 7-year duration of thinning treatments is because water yield increases will only persist until the forest regrows. In the Sierra Nevada, two studies found increased understory growth seven to eight years after thinning, in the absence of prescribed burning.[29,30] If prescribed fire occurs within 10 years after thinning, the effective duration of thinning extends to 15–20 years. We did not estimate differences in water yield due to combined thinning and prescribed fire, or differences from thinning on north- and south-facing slopes. We also did not estimate the delay in the date of the peak runoff due to thinning.[31]

Economic costs and benefits of restoration

For the economic valuation, we used a cost-benefit analysis, estimating the costs of implementing forest restoration and the economic value of the predicted increases in water quantity (Table 1). Unless otherwise noted, all estimates are presented in 2012 dollars. For costs, we relied on existing literature and expert opinions, estimating net cost of forest restoration costs as $1,000 per acre. This value accounts for potential revenues from sale of timber and biomass.[38]

We considered the potential impacts of changes in water quantity and timing on three downstream water uses: hydropower, irrigation,

BOX 1. Meadow restoration and water timing

The current understanding of meadow degradation is that streambank erosion and channel incision, where the stream within the meadow no longer connects with its floodplain, causes a meadow to become drier. Once in this new state, the meadow sometimes will not return to a functional wet meadow for centuries, even when the disturbances are removed.[32] The fluvial geomorphic processes within a meadow determine its functionality and restoration potential. The relationship between the depth of the channel bed and the meadow floodplain elevation affects the groundwater recharge potential (Figure 2). This simplified description of meadow water storage becomes complicated by additional groundwater inputs, differences in porosity, characteristics of the bedrock below a meadow, regional groundwater flows, and consideration of upstream and downstream channel and streamflow changes. There are 14 different hydrogeomorphic meadow types ranging from dry to wet.[33] These types provide a starting point for understanding restoration potential and the surface and subsurface flow paths within a meadow.

In the northern Sierra Nevada, Bear Creek, Clark's Creek, and Last Chance Creek "pond and plug" restoration efforts showed raised water tables post-restoration, but these studies did not quantify the shift in summer flow. American Rivers (2012) used five studies showing groundwater depth change with meadow restoration to calculate increase in acre-feet stored at 0.2–1.0 AF/acre restored.[34] In contrast, a study of the Bear Creek meadow "pond and plug" found a loss in summer flow in the restored reach, perhaps due to increased evapotranspiration and increased groundwater discharge that was not included as surface streamflow.[35]

There is only one peer-reviewed study that quantified the post-restoration flow change in the summer. Tague et al. (2008) studied the Trout Creek meadow restoration, which used a channel realignment technique and biotechnical engineering, and found an additional 11 percent flow in June (0.5 AF/acre) and 24 percent in July (0.7 AF/acre) post-restoration.[36] A critique of the Trout Creek study indicated an additional tributary flowing into the study site between the upstream and downstream gauge should be isolated from the results.[37] Additionally, in dry years the restored meadow increased late summer flow, but in normal and wet years there was less of an effect of restoration on flow timing. Due to the lack of research on meadow impacts on streamflow, we do not project the potential water benefits across the northern Sierra Nevada or estimate the economic benefits of a shift in water timing from winter to summer.

FIGURE 2. Meadow restoration approaches in the Sierra Nevada reconnect incised stream channels with the floodplain by realigning and re-creating new channel dimensions or by "plug and pond" techniques that slow down the water and increase groundwater recharge.

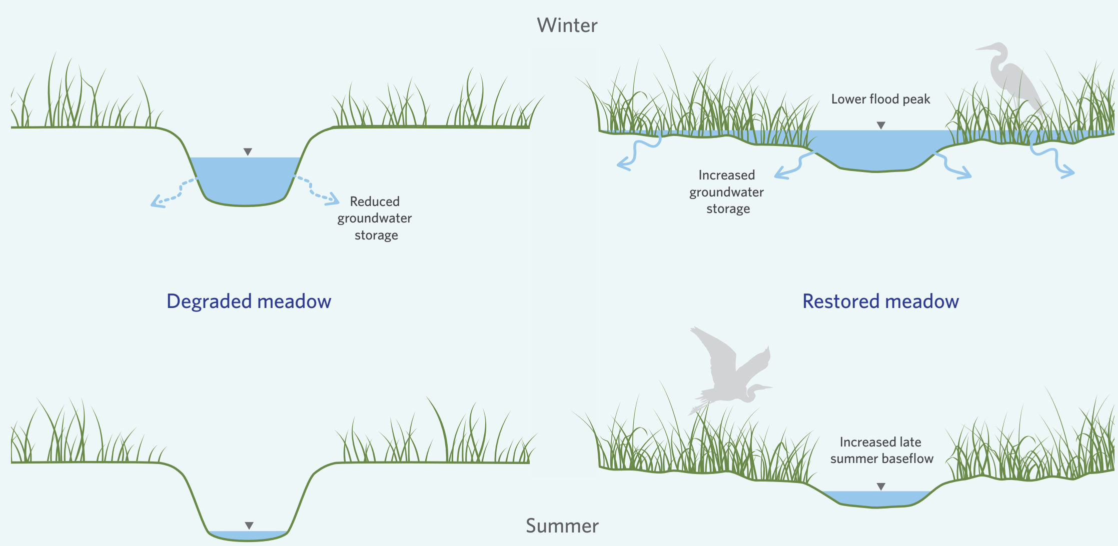


TABLE 1. Summary of model assumptions for downstream water users.

Model Assumption	Hydropower	Irrigation	M&I
% change in acre feet (AF)	25%	70%	20%
Value of water	$0.06/MWh	Winter: $63/AF	
		Summer: $150/AF	$150/AF

and municipal/industrial water supply. We first assessed the presence or absence of each use within each watershed. For hydropower, we estimated the change in production at the watershed level by collecting information on the head and megawatts of installed capacity for each facility, and back-calculating each facility's reliable flow. We then calculated an adjusted head for each facility by multiplying the share of the total drainage area by the original head, and finally we summed all the adjusted heads for each watershed. The adjusted watershed head and change in flow due to forest restoration treatment were used to derive the kilowatt power rating and the additional power production. For the base-case scenario, we assumed that only 25 percent of increased water yield would actually be used to produce hydropower. If there was limited storage and increases in water yield occur when hydropower facilities were operating at full capacity, it may not be possible to utilize incremental flows for additional electricity production. The actual hydropower increase would depend on the specific hydropower infrastructure within the watershed, such as the unused hydropower generating capacity and the availability of upstream storage.

To approximate the net economic benefit to hydropower, the additional generation was multiplied by $0.06 per kilowatt-hour (kWh) for the net financial value of incremental power production.[39,40] The net financial benefit of additional water supply to a power utility is the difference in cost between generating hydropower from that water and the price at which the utility would alternatively have to procure the power on the wholesale market. Because hydropower generation has very low variable costs, estimated at $0.06 per megawatt-hour (MWh), ($0.00006/kWh),[41] we estimated the value to power utilities of additional hydropower production as a typical $0.06/kWh wholesale market clearing price. Any policies or economic conditions that raise the wholesale market price of electricity, now set by carbon-based fuels, would increase the value of hydropower to the utility because the difference in price between wholesale market prices and the near-zero cost of incremental hydropower generation would increase. Further, small-scale hydropower (less than 30 megawatts) may have unique value to utilities in future years in complying with California's renewable energy portfolio standard (RPS), should it be increased.

For irrigation, we assumed 70 percent of any additional flow resulting from restoration would flow downstream and be available for use. This reflects the average use of water by irrigation both in the U.S. and globally. For the remaining 30 percent, we assumed that municipal and industrial uses would use 20 percent, and that 10 percent would be channel losses or other riparian environmental uses (Table 2). In most western basins, municipalities typically have limited access to surface water. Since seasonal timing affects demand for irrigation water, we used a range of $62.50/AF for winter and $150/AF for summer.[42,43] We estimated that water used for municipal/industrial purposes would be valued at the high end of this range, or $150/AF (Table 1). Generally, municipal/industrial demand pay a rate for water that equals or exceeds that of agricultural or environmental prices. These figures represent long-term average pricing and will be lower than prices paid in drought conditions where some farmers are curtailed.

To calculate the benefit-cost ratio (BCR), we made several assumptions. First, we assumed that all restoration activities occur in the first year. This is not a realistic timeline, but it allowed us to easily compare total costs and total benefits over the length of life of each restoration activity. Second, we assumed a discount rate (i.e., the rate at which future economic costs and values are discounted) of 5.0 percent, which is the midpoint between the range of 3.0 percent and 7.0 percent recommended by the U.S. Office of Management and Budget.[44] Third, we assumed the timing of the increased water yield would occur during the peak in snowmelt runoff (December to May) over a 7-year period.

We reported the low and high estimates for the BCR using the low and high values for water-quantity changes found in the literature. All other parameters were set conservatively with respect to demonstrating cost recovery for forest thinning. Given the relative uncertainty in the input parameters, we also conducted a sensitivity analysis of five key variables: the discount rate; value per AF of summer irrigation and municipal/industrial water; value per kWh of electricity; cost of forest thinning; and percentage of water yield available to hydropower generation. For each parameter, we maintained the original values of the other parameters in the model and reported the BCR based on the low and high water quantity response range as is reported for the base-case scenario before modifying the variables. For forest thinning, we modified each variable in the sensitivity analysis in the following way: increased the value of water by 33 percent from $150/AF to $200/AF in the summer only; increased the net financial benefit per kWh of electricity by 50 percent from $0.06/kWh to $0.09/kWh based on projected energy price increases by some economists[45]; decreased the cost of forest thinning per acre by 50 percent from $1000 to $500, consistent with expected treatment costs for some forest watersheds in the Sierra Nevada[46]; increased the water yield available for hydropower from 25 percent to 100 percent; and changed the discount rate from 5 percent to 3 percent and 7 percent.

Results

Forest restoration areas

From 2002–2012, the scale of forest thinning and prescribed fire in the study area was 468,364 acres, or 46,836 acres per year (Figure 3). The amount of treatment ranged from 0.2–12 percent of the watershed area (Figure 4). The USFS land covers more than 40 percent of the watershed area in 7 of the 11 watersheds. The only watershed where the USFS land represents less than 20 percent of the watershed area was the Bear River. We estimated that from 2013–2023 there are 1,117,483 acres under Scenario C and 1,309,774 acres under Scenario D that meet the criteria for operable forest restoration and water yield increase in the northern Sierra Nevada (Figure 4). This operable thinning area represents, on average, a two-fold increase for Scenario C and a three-fold increase for Scenario D in restoration compared to areas treated to date (Figure 5). The greatest percentage, 30 percent of the watershed, and acreage of operable area, 694,593 acres, was in the Feather River watershed.

FIGURE 3. Past forest thinning and prescribed fire use by the U.S. Forest Service from 2002-2012 (a) compared to the hypothetical forest thinning area (b) based on USFS criteria for operability.

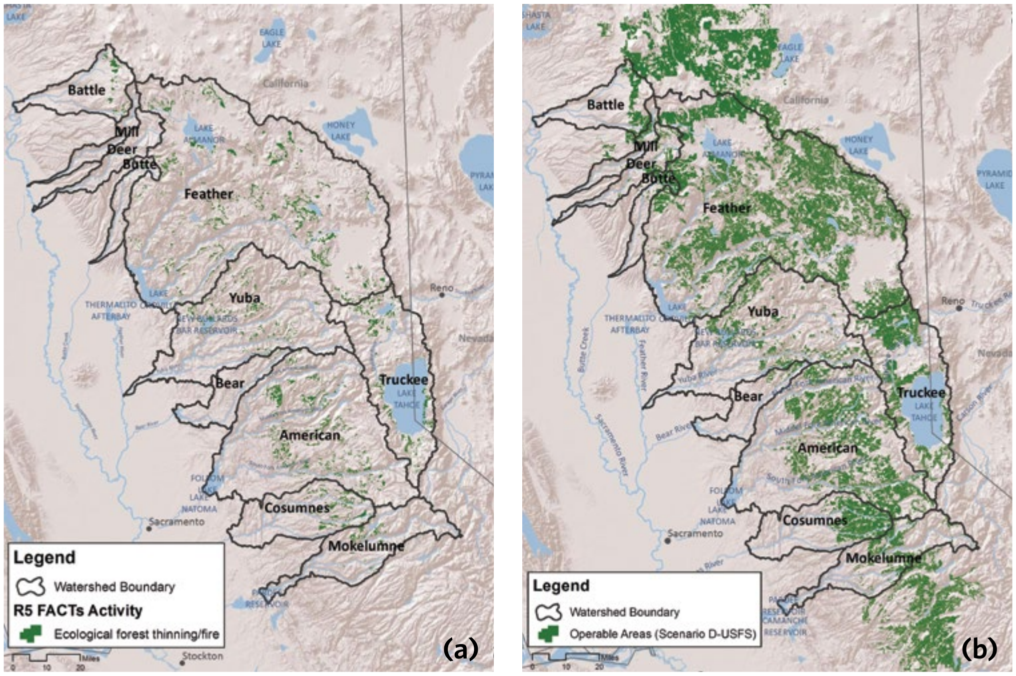
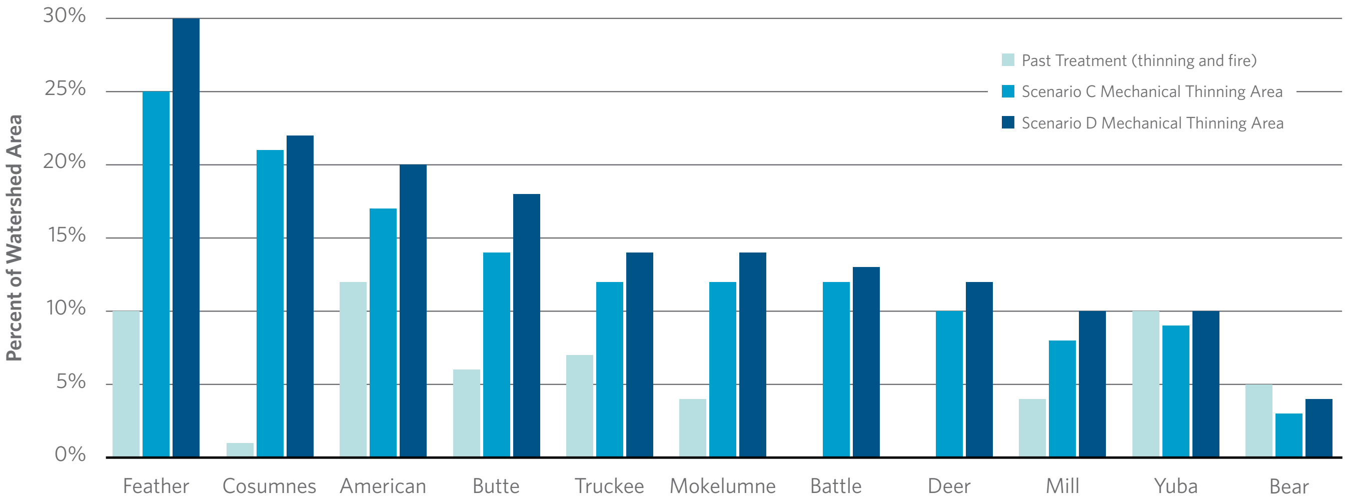


FIGURE 4. Past forest restoration from 2002-2012 compared to the mechanical thinning area in Scenario C and D.



Forest thinning and water yield

The estimated increase in water yield from forest thinning across all 11 watersheds was 0–6 percent of the average annual streamflow based on the gauge records across the watersheds from 1980–2000 (Figure 6, Table 2). The greatest increase in water yield was in the largest watershed, the Feather, and ranged from ~97,000–285,000 acre feet (Figure 7).

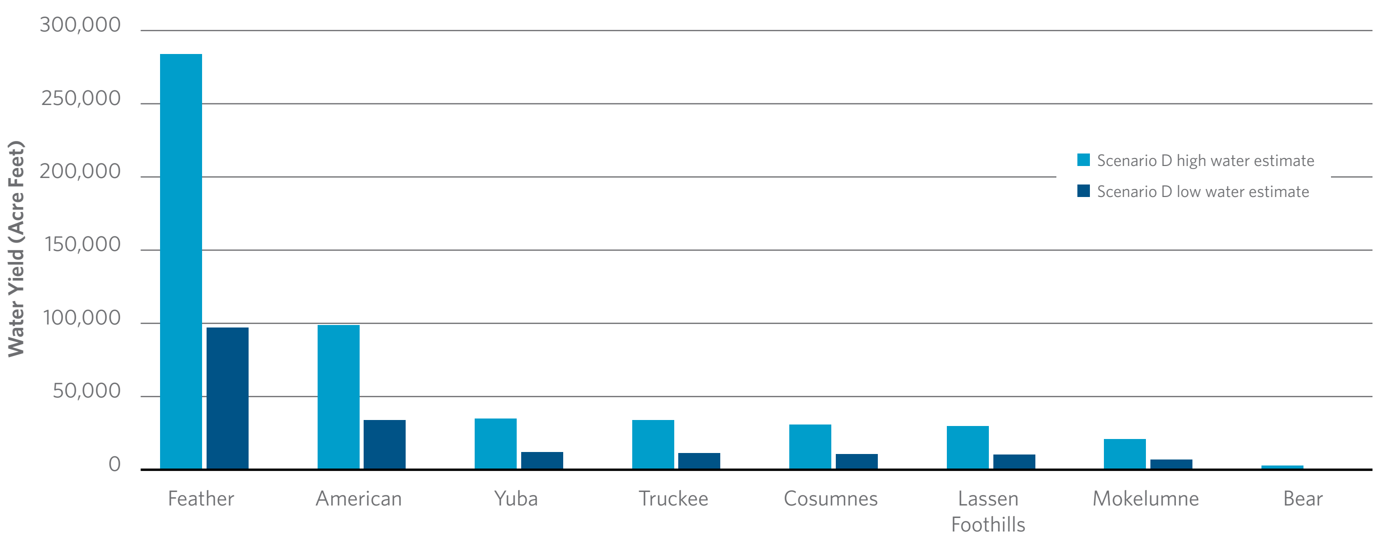
TABLE 2. Estimated water yield from forest thinning by percentage, sorted by mean annual streamflow.

Watershed	Watershed area (acres)	USFS area (%)	Stream gage (ID)	Mean streamflow (AF/yr)	Water Yield from Forest Thinning (% of mean annual streamflow)	
Feather	2,306,498	61	DWR	4,682,603	2%	6%
American	1,191,856	52	DWR	2,882,849	1%	3%
Yuba	860,756	48	DWR	2,448,314	0%	1%
Battle	236,367	22	11376550	1,240,086[b]	1%	2%
Butte	96,665	25	11390000			
Deer	141,978	49	11383500			
Mill	85,075	54	11381500			
Mokelumne	370,108	54	DWR	793,675	1%	3%
Truckee[a]	606,833	43	10346000	640,016	2%	5%
Cosumnes	340,565	32	DWR	488,852	2%	6%
Bear	180,368	7	11424000	327,248	0%	1%

[a] The Truckee Watershed excludes the surface area of Lake Tahoe.

[b] Streamflow combined for Lassen Creeks.

FIGURE 5. Estimated increase in water yield with an average three-fold increase in the amount of forest thinning on national forests



Economic costs and benefits of restoration

The study results suggest that increased water yield from forest thinning could provide economic benefits that may, in some cases, fully offset the cost of forest restoration (Table 3). Even small increases in water yield likely have real economic value for downstream water users. The BCR of forest thinning for the low water response under Scenario D was from 0.06–0.34 with an average of 0.17 across all watersheds. A BCR of 0.17 means 17 percent of the thinning costs could be recovered by the economic benefits of the increased water supplies. For the high water yield response estimates, the range was 0.18–1.01 with an average of 0.51. Variables having the greatest impact to the model in decreasing order of impact were the cost of thinning, the water yield available to hydropower, and the value of hydropower.

A key indicator of a higher BCR was presence of hydropower in a watershed; all watersheds with hydropower had higher BCRs than those that did not. Considering only watersheds with hydropower capacity, the low range BCR was 0.11–0.34 with an average of

TABLE 3. Benefit-cost ratios (BCR) from forest thinning, Scenario D, sorted by BCR.

Watershed	Hydro-power	Costs	Economic benefits of water yield increases			
			Low water yield		High water yield	
	(Y/N)	($m)	($m)	(BCR)	($m)	(BCR)
Mokelumne	Y	50	17	0.34	50	1.01
Butte	Y	17	5	0.30	15	0.87
Bear	Y	7	2	0.28	5	0.83
Yuba	Y	85	20	0.23	58	0.68
American	Y	241	50	0.21	148	0.61
Feather	Y	695	142	0.20	415	0.60
Truckee	Y	83	9	0.11	26	0.31
Battle	N	32	2	0.06	6	0.18
Deer	N	17	1	0.06	3	0.18
Cosumnes	N	76	5	0.06	13	0.17
Mill	N	9	1	0.06	2	0.17

0.24, and the high range BCR was 0.31–1.01 with an average of 0.70. Benefits to hydropower accounted for approximately 69 percent of total benefits in watersheds with hydropower capacity.

Evaluating the impact of each variable in the sensitivity analysis, we found, as expected decreasing the cost of thinning by 50% resulted in a 50% increase in BCRs. Increasing the water yield available to hydropower from 25 percent to 100 percent effectively tripled the average BCR for watersheds with hydropower (Table 4). Again, for watersheds with hydropower, increasing the value of hydropower from $0.06 to $0.09 per kWh resulted in an average increase in BCRs of 37%. Increasing the value of summer water for irrigation and municipal/industrial by 25% has a relatively small effect on BCRs; this reflects the model set-up, since only summer values were adjusted, yet water yield benefits from thinning were assumed to occur in winter. Finally, adjusting the discount rate resulted in minimal overall changes for both adjusted rates used.

TABLE 4. Sensitivity analysis of the forest thinning economic model (average values in parentheses).

Base case value	Parameter change	Thinning BCR range (All 13 watersheds)		Thinning BCR range (7 Hydropower watersheds)	
		Low water yield response	High water yield response	Low water yield response	High water yield response
Base case	Base case	0.06-0.34 (0.17)	0.17-1.01 (0.51)	0.11-0.34 (0.24)	0.31-1.01 (0.70)
Cost of thinning: $1,000/acre	$500/acre	0.12-0.69 (0.35)	0.35-2.01 (1.02)	0.21-0.69 (0.48)	0.62-2.01 (1.40)
Water available to hydropower: 25%	100%	0.06-1.19 (0.52)	0.17-3.50 (1.51)	0.25-1.19 (0.78)	0.72-3.50 (2.28)
Hydropower net benefit/ kWh: $0.06	$0.09	0.06-0.48 (0.23)	0.17-1.42 (0.68)	0.13-0.48 (0.33)	0.38-1.42 (0.96)
Summer irrigation and municipal/industrial: $150/AF	$200/AF	0.06-0.34 (0.17)	0.17-1.01 (0.51)	0.11-0.34 (0.24)	0.34-1.01 (0.70)
Discount rate: 5%	3%	0.06-0.37 (0.19)	0.19-1.08 (0.55)	0.11-0.37 (0.26)	0.33-1.08 (0.75)
Discount rate: 5%	7%	0.06-0.32 (0.16)	0.16-0.94 (0.47)	0.10-0.32 (0.22)	0.29-0.94 (0.65)

Perazzo Meadow © Kristen Podolak, The Nature Conservancy

Discussion

This assessment is a first attempt at calculating the water supply benefits from watershed-scale forest restoration in the northern Sierra Nevada. These watershed level results suggest that the economic benefits from water yield increases may be an important argument in favor of additional forest restoration investments. Nevertheless it is important to emphasize that such actions do not represent a solution to California's water crisis, but rather a sensible investment in forest management that is likely to create benefits for water users downstream.

There are several key assumptions, however, that need further modeling and testing. As stated earlier, there are no empirical studies completed yet on the relationship between ecological forest thinning and water yield in the Sierra Nevada, although there are three research projects underway (Kings River Experimental Watershed, Sagehen Project, and Sierra Nevada Adaptive Management Project) and one proposed (Sierra Watershed Ecosystem Enhancement Project). The results from these empirical studies can inform future water benefit models. This assessment assumed all forest thinning has an identical impact on increasing water yield, but there are likely differences in the yield related to differences in elevation, precipitation, aspect, and forest type.

It is also unclear if the results from paired watershed studies on small scales in the western United States are representative of the large watershed-scale treatment in the Sierra Nevada analyzed in this study. There are likely differences between paired watershed studies conducted at the small-scale (i.e., less than 25,000 acres, most less than 500 acres) and landscape-scale forest thinning, which raise caution in extrapolating from the former to the latter. Scaling up the water benefits from small-scale forest studies to landscape-scale watersheds would require larger-scale studies. There is more complexity in land use, wetlands, and stream networks as the scale increases from small paired-watershed to large watersheds with varied topography and climate gradients.

The economic valuation could be improved by estimating water benefits on a monthly basis to match the implementation schedule and cost with future benefits. We assumed the increased water from forest thinning would occur in the winter when stream flows and hydropower generation are typically at their peak, and the economic values may be less than assumed depending upon storage capacity and hydropower generation capacity. More water in the summer would likely have a higher hydropower value, but this would require storing the water in reservoirs above the hydropower facilities and we did not incorporate reservoir storage and spilling. The model could also be improved by acquiring information on watershed-specific water use for irrigation and municipal/industrial uses.

For forest restoration, we used an average cost per acre for all watersheds due to lack of specificity in the available data at the watershed level. More specifically, we were not able to account for certain key variables known to affect costs such as stand type and age. Other factors that could make it difficult to increase the pace and scale of forest restoration as modeled in this study, include: planning and regulatory hurdles, insufficient biomass and small-wood infrastructure to handle the thinned material, and lack of social license.

Conclusion

In this assessment, we envisioned a scenario of increased forest restoration in 11 watersheds in the northern Sierra Nevada and estimated the potential water quantity benefits to downstream water users. Using a cost-benefit analysis, we found that potential economic benefits from forest thinning, largely from the potential for increased hydropower production, are real, and in some cases may be sufficient to fully offset the cost of thinning in select watersheds. We estimated that the pace and scale of forest restoration to achieve these benefits; however, would need to be increased, on average, three-fold compared to the actual efforts observed from 2002–2012. Whether hydropower utilities and other water users would invest in forest restoration is likely to depend on a number of factors, including the likelihood that activities would occur at a sufficient scale to generate measurable results.

Even with the narrow focus on water quantity, the results suggest that there could be economic benefits for hydropower, irrigation, and municipal/industrial water users from investments in forest restoration in northern Sierra Nevada watersheds. While it can be challenging to coordinate different economic users who benefit from restoration, in this study we found that the water quantity benefit to any of the three individual water uses, but especially to hydropower, could motivate them to invest in restoration. Although we modeled a range of increased water yield, even the conservative increase in water yield from forest thinning could provide economic value to hydropower facilities. Meadow restoration also has potential for benefit by shifting the water timing from winter to summer, which likely would have economic water benefits, but more study on the water effect is needed.

Key variables affecting the economic benefits estimated in this study are the cost per acre of thinning, the percentage of water yield increase available to hydropower, the water yield increase per acre of treatment, and the price per kWh. We used conservative values for these variables and found that, in some watersheds, the cost of forest treatment may be fully offset by the revenue benefit to the downstream users alone. Thinning forests is not the answer to California's water crisis, but it may be a sensible economic approach to forest and water management. In sum, there are potential water supply benefits from watershed restoration in the northern Sierra Nevada, warranting an increased research effort to quantify the costs and benefits, and consideration by downstream beneficiaries like hydropower and water utilities.

Truckee River © Elizabeth Carmel, www.TheCarmelGallery.com

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Appendix

Decoding the U.S. Forest Service FACTs database: We used the R5 FACTs database to determine the acres of forest thinning and prescribed fire from 2002–2012 on U.S. Forest Service Land in the Northern Sierra Nevada. The FACTs database was accessible on the web for R5.

1. Added a field that assigned either "thinning," "prescribed fire," or "NULL" based on associated Activity Codes (a crosswalk table was used to assign activity codes).

   See FACTS_LANDFIREEventType_XWalk.xlsx provided by the Landfire Team for description of codes. We selected these codes to represent mechanical forest thinning and prescribed fire. Mechanical forest thinning codes = 1136, 1150, 1153–1154, 1160, 4150–4154, 4210, 4220, 4511, 4512, 4521, 4530, 4580, 6101, 6103–6105, 6107, and 6130

   Prescribed fire codes = 1111, 1112, 1113, and 6101.

2. Intersected the FACTs data with the AU watershed analysis unit GIS layer. This is a layer that shows the ~HUC8 watersheds.

3. Created a new GIS layer from the R5 dataset that produced a "flat" layer of unique polygon geometries. This was done because many polygons in the R5 dataset are identical; however, they are stacked upon one another, an artifact of numerous merge processes over time. Layer is created by running "Delete Identical" using the "shape" option. This new layer was re-intersected with the R5 dataset to create a unique ID combination between "Activity Code" and new polygon ID.

4. Exported GIS attribute table to .dbf file and opened within Excel environment. Ran a "sort" and then removed duplicates based on polygon ID, activity code (4-digit number), and acreage. Once completed, pivot table was developed to sum acreages.

5. Created a new worksheet in Excel that filters the attributes by "TNC_Activity" (i.e., selects for "Ecological forest thinning" and "Prescribed fire").

6. Used the pivot table to sum acres by activity code and watershed.

BACK COVER: Martis Valley in the Truckee River watershed. © Elizabeth Carmel www.TheCarmelGallery.com


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