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Water yield response to forest treatment patterns in a sierra nevada watershed

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A R T I C L E I N F O

Keywords:
Runoff
Forest Treatments
MIKESHE
Sagehen
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A B S T R A C T

Study region: Sierra Nevada
Study focus: Snow dominated forests serve as source water supplies to much of the western United States. In recent years, these forests have experienced an increase in both drought and wildfire, which threaten critical water resources. By reducing forest density, treatments offer a promising solution to reducing fuel loads and potentially increasing surface water yield. However, the amount of fuel load reduction necessary to produce a change in water yield is not well-characterized. The objectives of the current study are to: 1) calibrate a distributed parameter, fully-integrated and physically-based hydrologic model to available watershed data and evaluate predicted hydrologic changes for a range of fuel treatment scenarios in a heavily forested experimental basin in the Sierra Nevada (Sagehen Creek basin near Truckee, California, USA), and 2) determine the extent (threshold) of forest treatments necessary to produce substantial changes, i.e. a 25% increase, in surface runoff.
New hydrological insights for the region: Using DHI's physically-distributed code, MIKESHE, to develop the model for Sagehen Basin, twenty forest treatment scenarios with varying canopy density reductions (CDRs) and areas of treatment were simulated for a five-year period. Statistical testing showed that significant change in runoff occurred for every developed scenario at the annual scale (99% confidence interval). Surface water yield is highly correlated with precipitation patterns, however, treatments have a compounding effect over the years and the basin has a more dramatic response to higher treatment intensities. Increasing treatment CDR was more effective at increasing water yield than increasing treatment area. Results suggest that as forest managers implement fuel treatments, water yield response depends on: 1) the degree to which treatments are implemented by either area or CDR, 2) future climate variability including extended periods of drought, and 3) basin storage conditions and how this might buffer disturbance response in the basin.

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1. Introduction

The western United States is experiencing larger and more severe droughts caused by highly variable climate, especially precipitation and temperature changes (Cook et al., 2007; Svoboda et al., 2002). Drought conditions are more likely if precipitation deficit occurs with warm conditions, which have increased in the last decade and are likely to persist and worsen due to anthropogenically-driven climate change (Diffenbaugh et al., 2015; Lehner et al., 2017; Williams et al., 2022). Although it is not unusual for multi-year droughts to occur, the 2012–2015 drought in California was noted to be the worst in the last 1200 years (Diffenbaugh et al., 2015; Goulden and Bales, 2019; Griffin and Anchukaitis, 2014). Impacted forests of the Sierra Nevada are shown to be especially vulnerable during periods of drought because of how highly dependent the region is on precipitation (Levy et al., 2020; Vilanova et al., 2023). Two consequences of drought are particularly concerning, including an increase in wildfire severity and burn extent (Parks et al., 2016; Crockett and Westerling, 2018), and a decrease in water supply due to declining snowpack in mountainous regions (Chavarria and Gutzler, 2018; Fritze et al., 2011; Middelkoop et al., 2001).

Forest treatments and wildfire mitigation measures, such as reducing forest density, offer a promising solution to reducing wildfire risk and severity. Recent research has also focused on the ancillary benefits of fuel treatments where the primary aim is reduction of forest density (Agee and Skinner, 2005; Stephens et al., 2012). These potential benefits include wildfire fuel reduction, increasing forest heterogeneity which improves habitat quality and landscape connectivity (North et al., 2009), and potential increases in streamflow (Zou et al., 2010). More studies on forest treatment practices are being undertaken to determine if they provide the co-benefit of enhancing water yield and can offer a viable solution for water management in Mediterranean regions such as the Sierra Nevada (Tague et al., 2019)

Multiple approaches to forest treatment, such as prescribed burns and mechanical fuel management, have been shown to increase surface water yield (Bari et al., 1996; Hubbart et al., 2007; Stednick, 1996). The relative amount of increase in water yield depends on climate, forest type and the degree of vegetation removal, with vegetation removal primarily reducing evapotranspiration (ET) in watersheds (Bosch and Hewlett, 1982; Sun et al., 2005). Goeking and Tarboton (2020) found that even though forest cover loss *can* increase water yield, this is not always the outcome, and the conditions where water yield is not affected are uncertain. Bart et al. (2016) showed a decrease in annual streamflow in a Sierra Nevada watershed after a stand replacing disturbance where trees were replaced with shrubs that have higher Leaf Area Index (LAI) and transpiration rates (Bart et al., 2016). Predicting the impacts of forest treatment on water budget partitioning is especially challenging in snow-dominated alpine systems such as the Sierra Nevada due to precipitation-driven surface runoff and the relative consistency of ET despite forest treatments (Boden et al., 2023).

The impact of forest treatments on hydrologic behavior are often investigated through empirical studies or use of hydrologic models (Bari et al., 1996; Bosch and Hewlett, 1982; Dung et al., 2012; Hubbart et al., 2007; Saksa et al., 2017; Stednick, 1996). Because hydrologic models allow a system to be well-constrained, they can help isolate environmental model parameters and processes on simulated system responses, like streamflow, and can be better distinguished from sources of environmental “noise” (e.g., climate) during the modelling process. Physically-based distributed models are generally more advantageous compared to traditional lumped models because 1) they account for greater heterogeneity in watershed conditions and spatial variability of factors controlling hydrologic response (DHI, 2023; Ma et al., 2016; Prucha et al., 2016) and 2) model parameters can be adjusted to account for post-disturbance processes (Goeking and Tarboton, 2020; Kurzweil, 2021; Zhang et al., 2008). Thus, physically-based distributed models are typically well-suited for simulating integrated hydrologic response to forest disturbance and can enhance current understanding of the linkage between the two (Goeking and Tarboton, 2020). For example, Saksa et al., 2017 used a hydro-ecologic model to replicate a historical treatment performed in 2012 in a Sierra Nevada basin to better understand the effect on the entire water balance and not just discharge alone. Other studies have shown how forest treatments have affected water yield (Goeking and Tarboton, 2020), even hypothetical simulated treatments (Povak et al., 2022; Sun et al., 2015), however none have compared how water yield may be altered by treatments emphasizing canopy density reduction (CDR) versus treatments emphasizing size of area treated. Here, we use historical forest treatment and runoff data from a basin to calibrate a physically distributed hydrologic model, much like Saksa et al., 2017 and others (Grayson et al., 1992; Silberstein, 2006). However, this study is novel because it does *not* replicate a historic treatment, but rather tests a variety of forest treatments emphasizing CDR and area treated (that range from 20 percent to 100 percent in both area and CDR) to assess water yield response.

Currently, limited research exists on quantifying the hydrologic impacts of both area treated, and the intensity of the treatment (which we define as canopy density reduction; CDR) of various forest treatment types. To address this knowledge gap, this research seeks to answer the following questions: 1) for CDR applied to 100% of our study basin's area, what CDR threshold will produce a 25% increase in water yield, and 2), how do a variety of treatments, that vary in area and CDR, affect streamflow in the basin? To address the first question, we hypothesized that the entire basin (100% area) will need to experience at least a 50% CDR to see a 25% increase in water yield. To address the second question, we hypothesized that treatments focusing on a higher CDR would be more effective at increasing water yield than those focusing on treating a larger area. We chose a threshold of 25% to be certain that the change was outside the bounds of uncertainty in the model and to be large enough to be observable.

Specific objectives of this work are to: 1) parameterize a distributed, integrated hydrologic model to capture a range of fuel treatment scenarios in the Sagehen Basin, and 2) determine the extent (threshold) of forest treatments necessary to produce significant changes in surface runoff. Our results and findings support forest and water managers as they assess watershed response to different treatment strategies for a drought-prone and uncertain future.

2. Methods

2.1. Site description

Sagehen Basin is within the Sagehen Experimental Forest in Lake Tahoe National Forest, roughly 18 km northwest of Truckee, California. Sagehen Creek flows into Stampede Reservoir and ultimately connects with the Truckee River. The watershed domain evaluated in this study is approximately 36 km^2 with the pour point located near the intersection of California State Route 89 and Sagehen Creek (Fig. 1), upstream of the Stamped Reservoir. In recent work, observational streamflow data (2012–2020) from Sagehen showed little response in water yield to a range of forest treatments (Boden et al., 2023).

The basin lies within the eastern slopes of the Sierra Nevada with an elevation ranging from 1877 m to 2662 m. This Mediterranean climate has cold, wet winters and warm, dry summers. Temperature can vary from −10–4 degrees Celsius in December and 3–26 degrees Celsius in July with an annual precipitation of approximately 838 mm – 80% of that being snowfall (University of California at Berkeley, 2022). There are 13 vegetation species alliances in the Sagehen watershed (Table 1) (USDA, 2008). The basin is primarily composed of Mixed Conifer – Fir Alliance, which covers approximately 48% of the basin area. The Red Fir Alliance follows as the second highest percent area (approximately 19%), followed by the Eastside Pine Alliance (approximately 16%). For a detailed description of each alliance see Region 5 – Resource Management (usda.gov)(USDA, 2022a). The dominant species is the Jefferey Pine and is seen in multiple alliances.

In 2016 and 2018, the US Forest Service applied strategically placed area treatments (SPLATs) to approximately 27% of the watershed in the form of mechanical and manual vegetation removal and prescribed burn. The goal of the Sagehen SPLAT project, also known as the Sagehen Project, was to modify wildfire behavior by reducing hazardous fuel loads, enhance habitat for wildlife species, create heterogenous forest conditions, enhance the ecological role of fire, and restore declining aspen stands (USDA, 2013). These treatments consisted of silvicultural prescriptions such as variable thin, legacy tree treatment, suppressed cut, dense cover area, early seral opening, decadent feature enhancement, and fire/fuel prescriptions such as pile burn, surface fire, and lop and scatter (USDA, 2013). Fig. 2, adapted from Boden (Boden et al., 2023), illustrates the treatment locations, type, and year. There are four treatment locations that are hatched in the figure where LAI was analyzed for this study (Reference 2.4 Scenarios).

Soil profiles in the basin are well drained and moderately acidic (Soil Survey Staff et al., 2022) and are typically represented by gravelly, sandy loam and cobbly, loamy sand (Johnson and Needham, 1966). The surficial geology of the area consists of Quaternary

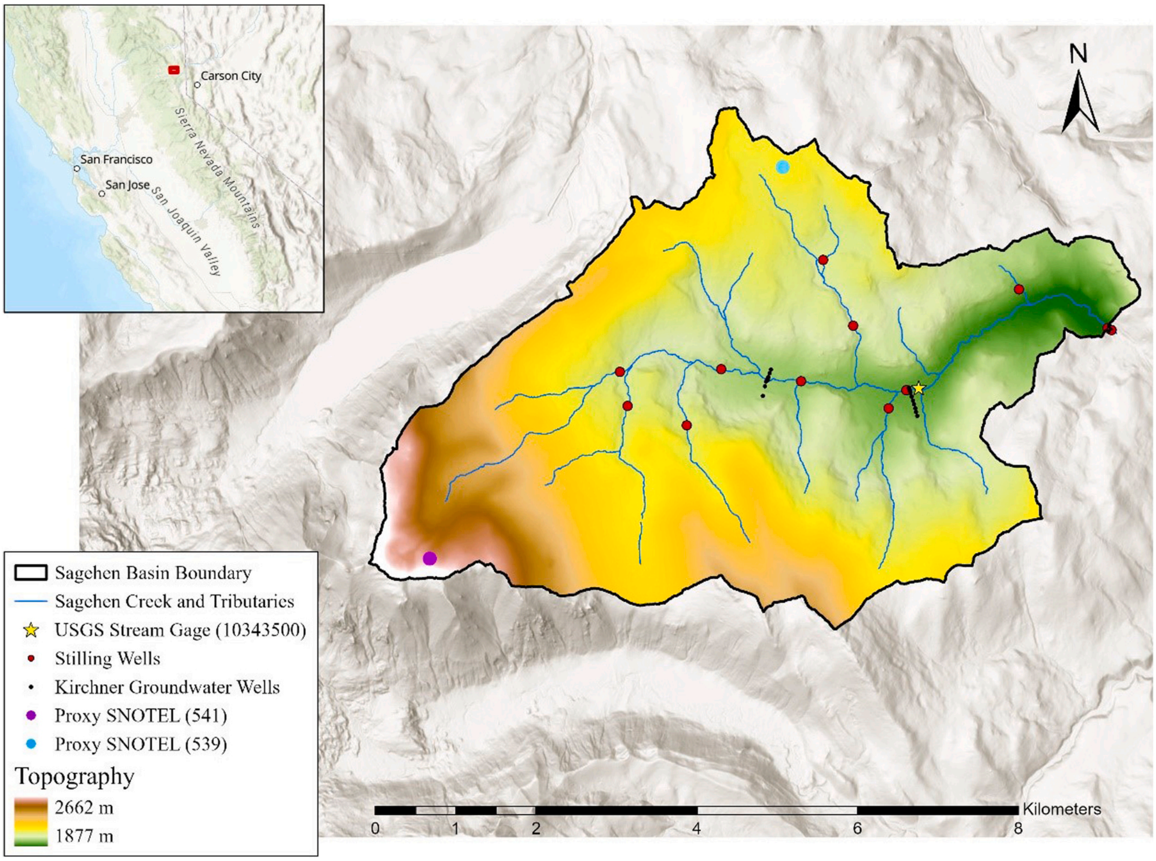

Fig. 1. Site Map of Sagehen Basin.

Table 1
Sagehen basin vegetation.

Species	Percent
Mixed Conifer – Fir Alliance	48.65%
Red Fir Alliance	18.68%
Eastside Pine Alliance	16.09%
Upper Montane Mixed Chaparral Alliance	7.46%
White Fir Alliance	4.39%
Lodgepole Pine Alliance	2.27%
Subalpine Conifers Alliance	0.93%
Wet Meadows (Wet Grasses and Forbs) Alliance	0.49%
Annual Grasses and Forbs Alliance	0.44%
Huckelberry Oak Alliance	0.26%
Willow – Aspen Alliance	0.15%
Big Sagebrush Alliance	0.12%
Willow (Riparian Scrub) Alliance	0.09%

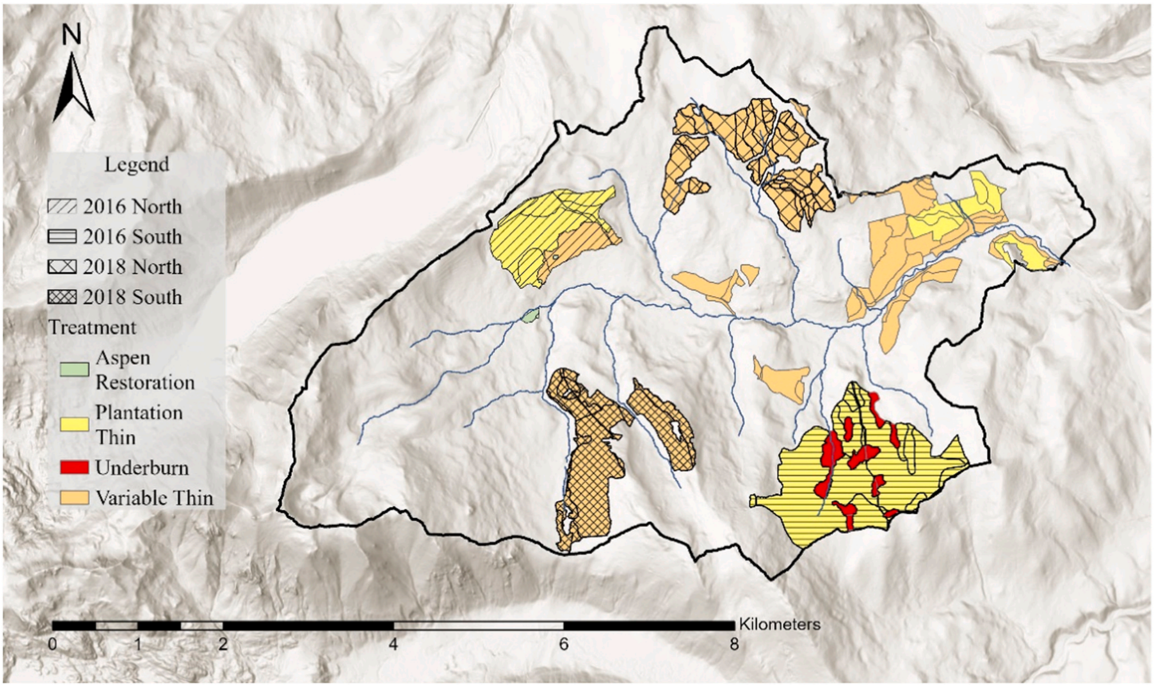

Fig. 2. Map of 2016 and 2018 SPLAT locations showing treatment type and which treatment areas were analyzed for change in LAI.

alluvium and glacial deposits that vary in thickness from 15 m near Sagehen Creek in the lower elevations to a few meters or less on the hillslopes and ridgelines. Deposits near the creek have measured hydraulic conductivities in the range between 10^{-6} to 10^{-4} meters per second, creating conditions conducive to hyporheic exchange (Manning et al., 2012). The deposits cover Tertiary andesite and volcaniclastic rocks that cover Mesozoic granodiorite (Sylvester and Raines, 2017). These two lower geological layers are likely greater than 400 m thick and host a groundwater aquifer with circulation to depths of at least 100 m (Brumm et al., 2009). This groundwater-surface water exchange supports springs, two large fens, Sagehen Creek, and numerous tributaries, where at least 85% of the creek is derived from groundwater during seasonal snowmelts (Urióstegui et al., 2017). The western portion of this basin contains several geologic faults that run northwest to southeast. Within the basin and along Sagehen Creek are several low-gradient fens. The fens, a type of groundwater-dependent-ecosystem, are fibric soil material (peat) with a high saturated moisture content, specific yield, and hydraulic conductivity (Brown et al., 2011).

2.2. Model development and data

The Danish Hydrologic Institute's (DHI) hydrologic modelling software, MIKESHE, is capable of simulating responses of ecohydrological processes (Ma et al., 2016), and has been used to predict streamflow response resulting from landcover change (Kurzweil, 2021; McMichael and Hope, 2007). LAI is often used to represent vegetation density in physically-based models (DHI, 2023; Kurzweil,

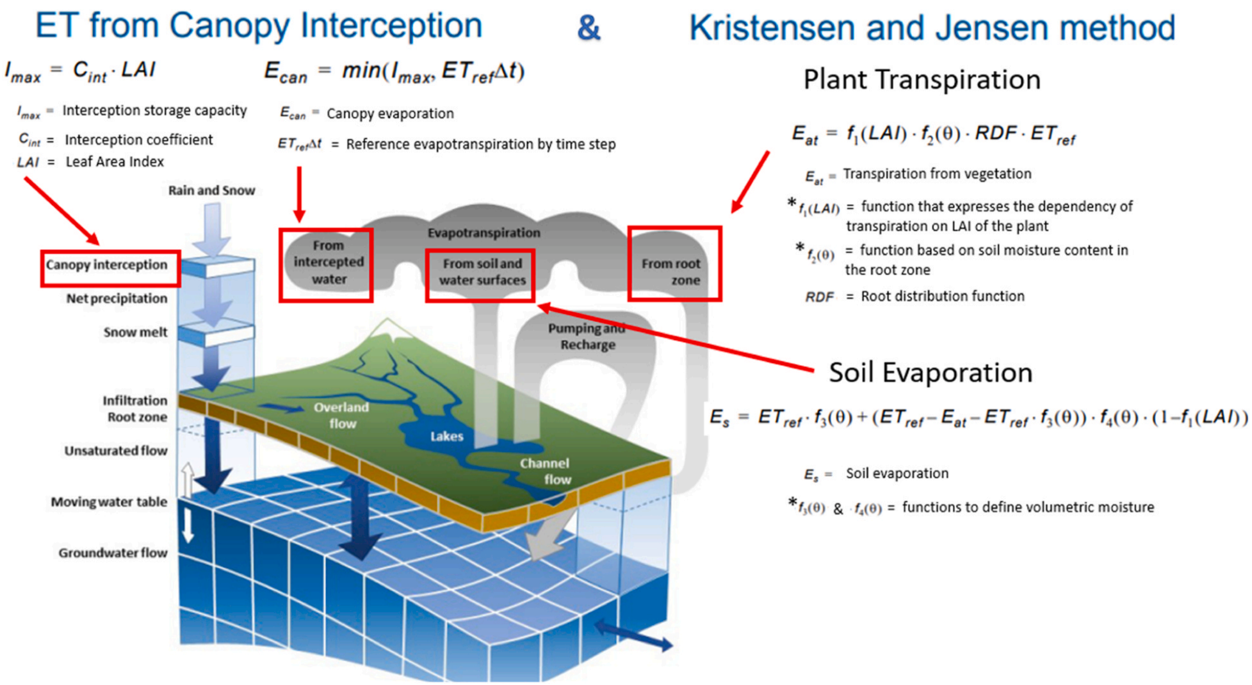

Fig. 3. Adapted from MIKESHE Manual (manual), showing how LAI effects the water balance. * For a more detailed description of these functions, reference the manual (DHI, 2023).

2021; Schneider et al., 2023; Tague and Band, 2004). In the current study, LAI and root depth were modified to simulate and represent the change in forest structure due to forest treatments. The MIKESHE software coupled with the comprehensive river network modelling package, MIKE HYDRO, was selected due to 1) its ability to account for spatially-distributed, time-varying data and model inputs that are used to define coupled hydrologic processes including channel flow, surface runoff, unsaturated flow groundwater flow, actual ET (including transpiration, soil evaporation, snow sublimation, ponded evaporation, etc.), and importantly snowpack/melt dynamics since Sagehen Basin's hydrologic system is strongly snow-melt driven and 2) because it accounts for dynamic and quantitative vegetation change (via LAI).

The MIKESHE modeling software uses LAI to calculate canopy interception and canopy evaporation using the Kristensen and Jensen method (Fig. 3). This is advantageous when analyzing and modifying LAI to simulate forest treatments or in our approach, using canopy reduction as a proxy. Fig. 3 was modified from the MIKESHE manual (DHI, 2023) to highlight MIKESHE's components and interactions with LAI, illustrating how LAI affects water budget partitioning and ultimately water yield. The equations included in the figure illustrate how each component is a function of LAI. More background on how MIKESHE integrates LAI is outlined in the MIKESHE manual and Kristensen, 1975 (DHI, 2023; Kristensen and Jensen, 1975).

Simulation specifications for water movement included the following: Finite Difference for Overland Flow (OL) and Saturated Flow (SZ), a MIKE HYDRO River model for the Rivers and Lakes (OC) network, Richards Equation for the Unsaturated Flow (UZ), and the Kristensen and Jenson method for Evapotranspiration (ET). Table 2 includes a list of the parameters.

2.2.1. *Streamflow data*

Sagehen Basin contains one USGS stream gauge (10343500) and 12 stilling wells installed as part of prior research (Boden et al., 2023) (Fig. 1). The USGS stream gauge measures daily discharge for the period of record of water year (WY) 1954 to current. The stilling wells (installed in 2012) collect continuous 15-minute total pressure measurements which were then converted to discharge using rating curves developed for each channel reach.

2.2.2. *Model domain, grid discretization, and topography*

The model domain coincides with Sagehen Basin delineated at the stilling well located near the intersection of California State Route 89 and Sagehen Creek (Fig. 1). The model requires regularly spaced, square finite difference grid cells, so a 100 m grid was selected based on the available data and a 1 m resolution DEM from a 2014 USFS Tahoe National Forest Lidar flight, was used to define topography (OpenTopography, 2022).

2.2.3. *Climate*

Hourly precipitation, potential evapotranspiration (PET), and temperature were obtained for Sagehen using the North American Land Data Assimilation System (NLDAS) (NASA, 2012). An area-weighted extraction method was used to obtain gridded climate products for the Sagehen Basin domain, over the period 2000–2022. Climate data NLDAS zone 37 was obtained. NLDAS was chosen for this application because of its high temporal resolution and period of record. NLDAS has a spatial resolution of 196 km^2. To assess the reliability of NLDAS, we compared precipitation to the two Proxy SNOTEL sites by aggregating annual totals and visually inspecting data trends. We observed that the annual NLDAS precipitation falls within the range of precipitation at both sites and follows the observed trend. Statistics at the seasonal scale of both the NLDAS and the observed data were compared and found to be similar. The two SNOTEL sites capture lower and higher elevation precipitation values, so we would expect that a representative average would fall between the two sites.

Table 2
Model parameters.

	Parameter	Data Set	Temporal Resolution	Spatial Resolution
Forcing Data	Model Domain	Open Topography (OpenTopography, 2022)	-	1 m
	Topography	Open Topography (OpenTopography, 2022)	-	1 m
	Precipitation	NLDAS (NASA, 2012)	hourly	196 km^2
Additional Input Data for Study Purpose	Temperature	NLDAS (NASA, 2012)	hourly	196 km^2
	PET	NLDAS (NASA, 2012)	hourly	196 km^2
	River Morphology	Open Topography (OpenTopography, 2022),	-	1 m
	Vegetation	Forest Service (USDA, 2008)	-	100 m
	LAI	MODIS (Myneni et al., 2015)	4 day	500 m
	Root Depth	Forest Service – FEIS (Zouhar, 2015)	-	-
	Soil distribution	USDA Soil Survey (Soil Survey Staff et al., 2022)	-	-
	Subsurface geology	USGS National Geologic Map Database (Sylvester and Raines, 2017)	-	-
Empirically Derived Parameters	Temperature Lapse Rate	SNOTEL (539, 541) (USDA, 2022b)	hourly	-
	Precipitation Lapse Rate	SNOTEL (539, 541) (USDA, 2022b)	hourly	-
	Melting Temperature	SNOTEL (539, 541) (USDA, 2022b)	hourly	-

2.2.4. Vegetation

Time-varying LAI for each species alliance was extracted from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) (Myneni et al., 2015) using an area-weighted extraction method. Root depth for each alliance was derived by taking the average rooting depth of the top three species.

2.2.5. Streamflow network

The MIKE HYDRO River network modelling package was used to characterize the river network including tributaries in the basin. The stream network was delineated using the ArcHydro package from ArcGIS Pro using a 1 m resolution LiDAR DEM. Cross sections were placed approximately every 500 m in the MIKE HYDRO River network due to the basin's topography and model efficiency. The cross-section bank and invert profiles were adjusted to ensure flow to the lowest topography. No hydraulic structures within Sagehen Creek were implemented into the model because the hydraulic structures are minor and none of them divert or store water.

2.2.6. Unsaturated zone (UZ)

The spatial distribution and selection of soils was determined using the surficial geology (Sylvester and Raines, 2017) and the United Stated Department of Agriculture (USDA) web soil survey and was simplified to three soil types: one for the fens, the river alluvium, and the surrounding area. Richards Equation was used to simulate the unsaturated zone (UZ), which uses the Van Genuchten formula for soil moisture-pressure relationships. Systematic manual calibration of the soil profile was required as detailed knowledge of the soil stratigraphy was not present (DHI, 2023).

2.2.7. Saturated zone (SZ)

Three layers were implemented for the saturated zone (SZ): an aquifer, a weathered bedrock, and a lower bedrock – as additional layers help simulate baseflow values (Brumm et al., 2009; Manning et al., 2012; Welch and Allen, 2014). Systematic manual calibrations were conducted by testing various depths to lower levels of the different saturated zone layers and implementing various hydraulic properties, e.g., hydraulic conductivity. Reference Table SI.1 (in the Supplemental Information) to see the parameters and their values.

2.3. Calibration and validation

The model was calibrated using a multi-step approach. We first manually calibrated the MIKESHE snowmelt parameters to ground-based snow water equivalent (SWE) from two Snow Telemetry (SNOTEL) sites: Independence Camp (539) and Independence Lake (541). Next, we manually calibrated the remaining MIKESHE modules to observed stream discharge at the USGS gauge (10343500). Supplementary discharge data from 1) distributed sub-basin stilling wells and 2) groundwater depth data (Kirchner et al., 2020) were used to get an approximation of subbasin flows and groundwater levels near the fens (Fig. 1).

During calibration and validation periods the model output (S, simulated) was evaluated using observed data (O, observed) and Pearson's R-correlation (r), Nash Sutcliffe Efficiency (NSE) and percent bias (PBIAS) (Eqs. 1–3, respectively).

$$r = \frac{\sum(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum(O_i - \overline{O})^2 \sum(S_i - \overline{S})^2}} \tag{1}$$

$$NSE = 1 - \frac{\sum(S_i - O_i)^2}{\sum(O_i - \overline{O})^2} \tag{2}$$

$$PBIAS = 100*\frac{\sum(S_i - O_i)}{\sum O_i} \tag{3}$$

These objective functions were computed first using the MIKESHE statistics on the hourly timestep, and then using the 'hydroGOF' package (Zambrano-Bigiarini, 2020) in the statistical software R at the daily and monthly timesteps (Tables 3 and 4). The annual

Table 3
Model calibration statistics for the objective functions for multiple timesteps.

Time Period		Observed Data	Objective Function	Timestep		
				Day	Week	Month
WY 2011–2021	SWE	SNOTEL - Independence Camp (539)	R	0.92	0.92	0.93
			NSE	0.8	0.81	0.82
			Pbias	13.4	13.4	13.4
	SWE	SNOTEL - Independence Lake (541)	R	0.94	0.94	0.95
			NSE	0.85	0.85	0.86
			Pbias	5.0	5.0	5.0
WY 2011–2021	Flow	the USGS gauge (10343500)	R	0.72	0.77	0.85
			NSE	0.28	0.41	0.66
			Pbias	0.7	0.7	0.7

Table 4
Model validation statistics for the objective functions for multiple timesteps.

Time Period		Observed Data	Objective Function	Timestep		
				Day	Week	Month
WY 2003–2010	SWE	SNOTEL - Independence Camp (539)	R	0.92	0.92	0.93
			NSE	0.73	0.73	0.75
			Pbias	-27.2	-27.2	-27.2
	SWE	SNOTEL - Independence Lake (541)	R	0.94	0.94	0.95
			NSE	0.84	0.84	0.85
			Pbias	-19.1	-19.1	-19.1
WY 2003–2010	Flow	the USGS gauge (10343500)	R	0.67	0.73	0.8
			NSE	0.43	0.51	0.59
			Pbias	-28.2	-28.2	-28.2

timestep was not included as the sample size of the annual timestep (n=8) was considered too small for an accurate representation of model performance. Mccuen, Knight, and Cutter (2006), explain how NSE is sensitive to time intervals if the sample size is small. Monthly R and NSE values of 0.7 and 0.5 were considered acceptable for flow model performance and an annual PBIAS value of plus or minus 15.0 was considered acceptable for flow (Moriasi et al., 2015). PBIAS was the focus for the study as the objective is quantitative. A calibration period of WY 2011 to WY 2021 was evaluated for flow as seen in Table 3. This calibration period contains a wide range of climate conditions and is also used for assessment of the developed scenarios.

A validation period of WY 2003 to WY 2010 was evaluated (Table 4). This validation period does not experience the range of climate conditions as the calibration period and generally underpredicts flow (Table 4).

2.3.1. SNOTEL SWE

Sagehen Basin has two SNOTEL sites immediately adjacent to the basin at two distinct elevations. The slope, aspect, and elevation were analyzed for the existing SNOTEL sites, and proxy locations similar to those characteristics were chosen within the Sagehen Basin. SWE data from the two SNOTEL sites were used to manually calibrate the model which was simplified to two grid cells representing each site with OC and SZ turned off. The parameters that were sequentially calibrated to SWE are as follows: Degree-day coefficient, Minimum Snow Storage, Maximum Wet Snow Fraction, Initial Total Snow Fraction, Initial Wet Snow Fraction, Temperature Elevation, and Precipitation Elevation.

2.3.2. Streamflow and groundwater depth

The UZ was simplified to a two-layer approach to decrease computation time when adjusting certain calibration parameters and then the full Richards Equation was implemented. The model was calibrated to streamflow at USGS gauge 10343500 by manually adjusting the hydraulic parameters. Because of the complex nature of the basin's geology, the stilling wells were used as a reference to help determine hydraulic properties, however, they were not used in calibration. Well data from Kirchner (2020) was not used in calibration but was used as a reference to approximate characteristics of the fens and of the underlying groundwater.

Table 5
Grouped scenarios showing the percent of LAI reduction and the percent of the basin area treated.

Scenario Group	Scenario Name	LAI Reduction 2016–2021	%-Area of Basin Treated
Control	Baseline	0%	0%
Low CDR Treatment Scenarios	10% Area Treatment	-25%	10%
	20% Area Treatment		20%
	40% Area Treatment		40%
	60% Area Treatment		60%
	80% Area Treatment		80%
	100% Area Treatment		100%
High CDR Treatment Scenarios	10% Area Treatment	-100%	10%
	20% Area Treatment		20%
	40% Area Treatment		40%
	60% Area Treatment		60%
	80% Area Treatment		80%
	100% Area Treatment		100%
Low Area Treatment Scenarios	20% CDR Treatment	-20%	25%
	40% CDR Treatment	-40%	
	60% CDR Treatment	-60%	
	80% CDR Treatment	-80%	
	100% CDR Treatment	-100%	
High Area Treatment Scenarios	20% CDR Treatment	-20%	100%
	40% CDR Treatment	-40%	
	60% CDR Treatment	-60%	
	80% CDR Treatment	-80%	
	100% CDR Treatment	-100%	

2.4. Scenarios

The modeled forest treatments are summarized in Table 5. Similar to other studies, we use historical data to calibrate the MIKESHE model (Saksa et al., 2017). However, our scenarios do not replicate historical treatments but capture varying area and CDR. The historical treatments were analyzed to help choose a minimum CDR value. The scenarios use the assumption that a prescribed LAI reduction is constant for the harvest (treatment) year (2016) and five years after (2017–2021). In other words, it was assumed that no significant vegetation recovery occurred after the forest treatment. The scenario period captures a variety of climate variability that ranges from year to year and captures years that correspond to historic wet (WY 2017) and dry years (WY 2020–2021). In this study, we consider a 25% reduction LAI to be a relatively low CDR and we consider 25% area to be a relatively low treatment area. Scenarios are grouped as follows and they were named to represent the variable that was held constant (e.g. the Low CDR scenarios had a constant variable of a 25% LAI reduction):

1) **control (Baseline) scenario**, which provides characterization of water yield that is not affected by forest treatment,
2) **five Low CDR scenarios**, which apply a constant treatment CDR via a constant percent reduction of LAI (-25% LAI) to a varying area percentage of the basin (20, 40, 60, 80, and 100%),
3) **five High CDR scenarios**, which apply a constant treatment CDR via a constant percent reduction of LAI (-100% LAI) to a varying area percentage of the basin (20, 40, 60, 80, and 100%),
4) **five Low Area Treatment scenarios**, which apply a varying CDR of treatment via varying percent reduction of LAI (-20%, −40%, −60%, −80%, and −100%) to a constant treatment area (25% area),
5) **and five High Area Treatment scenarios**, which apply a varying CDR of treatment via varying percent reduction of LAI (-20%, −40%, −60%, −80%, and −100%) to a constant treatment area (100% area).

LAI reduction factors for the Low CDR scenarios were chosen by observing four treated SPLAT areas. Two of the areas had treatments in 2016 and two of the areas experienced treatment in 2018. The areas are identified as: 2016 South, 2016 North, 2018 South, and 2018 North (Fig. 2). To see treatment meta data, reference Table SI.2. The 2016 South treatment area experienced the greatest ET reduction of all the SPLAT areas (Boden et al., 2023). The average monthly LAI values, taken from MODIS (Myneni et al., 2015), were calculated for ten years before the treatment (baseline), the harvest (treatment) year, and for two years after the treatment. The standard deviation for the baseline values were computed and the percent change was calculated by comparing the baseline to the harvest and post-harvest years for the growing season, May through October. Post-treatment reductions in LAI fall below the standard deviation of baseline LAI for several months of the growing season (July, August), and it was assumed that treatment occurred during the summer of the harvest year (June through September) (Figure SI.1).

LAI was also analyzed for two areas that were not treated in the same harvest year and compared to 2016 South data. The two areas that were not treated showed an increase in LAI while 2016 South observed a decrease in LAI. These results suggest that the reduction in LAI was due to forest treatment. Based on the percent decrease in 2016 South for the month of October in the harvest (treatment) year, a reduction factor of 25% in LAI was selected for the Low CDR scenarios (See Table SI.3). It was assumed that October would be the first month after treatments, as we assumed that treatment occurred during the summer months, and the most representative of LAI before any vegetation restoration.

For the High Area Treatment scenarios, 100% of the basin's area was chosen to consider the extent of treatments that would be necessary for the entire basin to see an increase in water yield. Even though it may be unrealistic, nor recommended, to treat the entire basin at 100% CDR, we use this as an upper boundary condition representing clear cutting of the entire basin.

2.4.1. Baseline scenario

A non-harvested (without forest treatment) simulation for 2005–2021 was executed to create a Baseline scenario to compare against the developed scenarios. Nine extra years were simulated in this scenario to give a better statistical representation of the modeled basin and to include two years for model "spin-up". Since Jeffery Pine is the dominant species in Sagehen ("Sagehen experimental forest," 2005), this vegetation type was applied across the entire basin, where LAI and root depth were assumed equivalent to that of Jeffery Pine (Rose et al., 2003). In this scenario, the monthly LAI timeseries values were chosen by taking the average LAI value for 2005–2015 for each month and applying those monthly values for each year. In this Baseline scenario, no LAI or rooting depth reductions were applied.

2.4.2. Low CDR treatment scenarios

For the Low CDR Treatment scenarios, a 25% LAI reduction was applied to 20% of the basin's area and each simulation after increased the area of treatment by 20% until 100% of the basin was treated. The basin was split into ten elevation bands and within each elevation band, a random 25% of the grid cells were chosen to be treated where LAI and root depth were set to zero (complete removal and no plant activity). These areas were distributed by elevation as elevation of treatment affects hydrologic response (Goeking, 2020) and to ensure treatment areas were well distributed across each elevation band. We started application of treatments at the lower elevation of the basin and as the treated area increased, we moved the application to higher elevations of the basin. For example, a treatment representing a 25% LAI reduction to 20% of the basin's area would be the bottom 20% of the basin and 25% of those cells treated.

2.4.3. High CDR treatment scenarios

For the High CDR Treatment scenarios, a 100% LAI reduction was applied to 20% of the basin's area and each simulation increased the area of treatment by 20% until 100% of the basin was treated. The basin was split into ten elevation bands and within each elevation band, a random 25% of the grid cells were chosen to be treated where LAI and root depth were set to zero (complete removal and no plant activity).

2.4.4. Low area treatment scenarios

For the Low Area Treatment scenarios, a range of LAI reduction values (i.e., treatment CDRs) were simulated starting with 20% and incrementally increasing the reduction by 20% until 100% LAI reduction was applied to 25% of the basin area. For each treatment CDR, random grid cells were selected to cover the percent CDR, and LAI and root depth were set to zero.

2.4.5. High area treatment scenarios

For the High Area Treatment scenarios, a range of LAI reduction values (i.e., treatment CDRs) were simulated starting with 20% and incrementally increasing the reduction by 20% until 100% LAI reduction was applied to the entire basin (100% area). For each treatment CDR, random grid cells were selected to cover the percent CDR, and LAI and root depth were set to zero.

2.4.6. Scenario statistics

Hydrologic indicators were analyzed to understand the effect of the simulated forest treatments, including 1) annual water yield, 2) seasonal water yield, and 3) annual runoff ratio. Daily flow was converted to runoff depth, and absolute change and percent change from the Baseline scenario were calculated annually for each water year (WY) and season, and for runoff depths and runoff ratios. Basin seasons are defined as: winter (October-February), melt (March-June) and summer (July- September). Statistics for the 10-year Baseline scenario were computed and the absolute change was compared to the standard deviation of the Baseline scenario. The results and runoff patterns were then compared to climate variables, such as precipitation and snow water equivalence (SWE).

3. Results

Runoff statistics for the Baseline scenario model simulation are highlighted in Table 6. All water budget changes presented and discussed were calculated as scenario minus baseline (change = scenario – baseline). The first standard deviation of the baseline that was measured across all years was initially compared with the absolute change in the forest treatment scenarios to determine if there was a substantial change in runoff. No scenario had a larger annual absolute change in runoff than the Baseline scenario when compared to one standard deviation. However, on the seasonal scale multiple scenarios for the winter and summer seasons observed a larger annual seasonal change in absolute runoff than the Baseline scenario when compared to one standard deviation. In the summer season, four High CDR Treatment scenarios (40–100% area treated) and three of the five High Area Treatment scenarios (60, 80, and 100% LAI reduction) experienced a larger absolute change than the Baseline when compared to one standard deviation. Additionally, in the winter season, every scenario group had at least two scenarios that experienced a greater absolute change than one standard deviation in WY 2017.

A Kruskal Wallis Rank Sum Test (KW) was applied to all treatment scenarios (Table SI.4). All treatments were found to be significantly different above the 99% confidence level for the entire period both annually and for each season. A Pairwise-Wilcoxon Rank Sum Test (PW) was applied to all treatments to compare each scenario's runoff to Baseline scenario runoff (Table SI.4). Ultimately, we observed that all treatments were significantly different above the 99% confidence interval for the entire time period, both annually and for every season except for the Low CDR treatment at 20% area (25% CDR and 20% Area) in the melt season and the Low Area treatment at 20% CDR (20% CDR and 25% Area) in the melt season.

All scenarios show an increase in runoff above the Baseline scenario (Table 7 and Table SI.5). The greatest increase in runoff occurs for the 100% High CDR and High Area Treatment scenario (100% LAI reduction for 100% of the area) for the year 2017 (255.7 mm; 22.4%). The smallest increase in runoff occurs for the 20% Low Area Treatment scenario (20% LAI reduction for 25% of the area) for the year 2016 (3.8 mm; 1.5%). Generally, the greatest annual absolute changes from the baseline are observed in 2017 and the smallest annual absolute changes are in 2016.

From a seasonal perspective, the greatest deviations from baseline vary between melt season and winter/low flow by year. The smallest deviations are seen in the summer/dry season for every year. The greatest deviations are observed in 2017 for the winter/low flow season, 2019 for the melt season, and 2020 for the summer/dry season.

Table 7 shows absolute change (rather than percent change) because small changes in runoff produce skewed (high) values in percent change, which is misleading during low-flow periods. Percent changes in runoff for each scenario are presented in Table SI.5

Table 6
Baseline statistics for runoff [mm] (WY 2007–2021).

Runoff [mm]	Mean	Minimum	Maximum	Standard Deviation	25th Percentile	75th Percentile
Annual	250	117	1117	264	123	263
Winter	56	39	178	36	40	50
Melt	174	60	905	224	67	178
Summer	19	14	34	7	15	20

Table 7
Annual absolute change from baseline by scenario.

Absolute Change [mm]		Annual Depth [mm]	Low CDR					High CDR					Low Area					High Area				
Percent Area		Baseline	20	40	60	80	100	20	40	60	80	100	25	25	25	25	25	100	100	100	100	100
Percent CDR		Baseline	25	25	25	25	25	100	100	100	100	100	20	40	60	80	100	20	40	60	80	100
Annual	2016	262	5.6	11.4	16.4	23.1	29.8	30.2	63.4	98.5	127.0	161.8	3.8	9.3	18.0	28.6	38.5	23.1	47.9	81.0	118.2	161.8
	2017	1142	14.6	29.8	41.9	53.5	63.4	55.4	115.8	169.9	211.3	255.7	14.8	27.6	41.8	58.3	72.7	50.9	97.6	148.1	199.6	255.7
	2018	289	9.1	20.0	30.3	40.1	48.3	39.4	86.6	132.8	166.9	206.5	10.8	20.4	32.3	45.8	57.6	38.7	72.6	114.9	157.3	206.5
	2019	378	12.2	24.9	35.4	46.3	55.0	48.5	102.2	151.3	189.4	229.3	14.2	25.6	38.4	53.5	66.5	44.7	83.9	129.5	177.1	229.3
	2020	150	9.9	16.0	20.2	22.9	26.1	34.0	59.1	80.8	96.3	118.3	6.4	10.5	16.2	23.2	29.5	21.0	39.4	62.8	89.2	118.3
	2021	134	9.8	16.0	20.4	23.3	26.0	36.8	64.2	88.5	105.6	126.2	6.0	10.5	16.5	24.1	31.2	20.8	40.2	65.6	93.5	126.2
	Average	**392.5**	**10.2**	**19.7**	**27.4**	**34.9**	**41.4**	**40.7**	**81.9**	**120.3**	**149.4**	**183.0**	**9.3**	**17.3**	**27.2**	**38.9**	**49.3**	**33.2**	**63.6**	**100.3**	**139.2**	**183.0**
Winter	2016	50	3.3	4.6	5.2	5.6	5.8	12.5	20.1	25.6	28.7	31.2	1.1	1.9	3.0	4.9	6.6	4.7	8.8	15.4	22.8	31.2
	2017	191	10.5	22.3	32.4	41.9	49.4	41.7	90.9	136.7	172.4	208.8	12.3	22.7	34.6	48.4	60.4	39.9	77.2	118.5	162.0	208.8
	2018	81	5.1	8.9	11.8	13.9	16.2	18.0	33.4	48.8	62.7	80.0	3.7	6.1	10.1	14.8	19.2	12.8	24.7	40.1	57.2	80.0
	2019	49	4.3	6.2	7.3	8.0	8.2	15.4	24.7	31.3	34.7	36.2	1.9	3.3	5.0	7.1	9.1	6.7	12.2	19.9	28.0	36.2
	2020	51	3.9	5.9	7.3	8.2	8.6	13.6	22.9	30.0	33.7	36.1	2.3	3.7	5.6	7.9	10.0	7.0	12.5	20.1	28.1	36.1
	2021	44	3.9	6.0	7.3	8.2	8.6	15.8	26.5	34.8	39.3	42.4	1.7	3.2	5.2	7.7	10.1	6.8	12.8	21.9	31.5	42.4
	Average	**77.7**	**5.2**	**9.0**	**11.9**	**14.3**	**16.1**	**19.5**	**36.4**	**51.2**	**61.9**	**72.5**	**3.8**	**6.8**	**10.6**	**15.1**	**19.2**	**13.0**	**24.7**	**39.3**	**54.9**	**72.5**
Melt	2016	190	0.5	4.1	8.0	13.9	20.2	11.5	33.8	60.9	85.3	116.7	1.7	5.9	12.8	20.6	28.1	15.2	34.0	57.6	84.3	116.7
	2017	917	1.3	3.8	5.3	6.9	9.0	7.0	14.7	20.3	24.9	32.6	0.6	2.5	4.0	5.8	7.4	6.9	14.4	20.7	25.7	32.6
	2018	186	2.2	8.5	15.4	22.7	28.5	15.2	43.7	72.0	91.1	112.6	6.3	12.9	20.3	28.2	34.9	23.0	43.1	67.0	89.2	112.6
	2019	301	6.0	15.7	24.6	34.5	42.6	27.0	67.7	107.4	140.9	178.3	11.2	20.6	31.1	43.2	53.3	34.6	66.4	101.0	137.3	178.3
	2020	81	4.3	7.4	9.6	11.0	13.4	14.1	26.1	37.4	47.7	65.8	3.2	5.3	8.3	12.0	15.3	10.8	21.4	33.7	48.5	65.8
	2021	72	4.2	7.5	10.0	11.6	13.6	14.9	28.0	40.9	51.9	67.8	3.5	5.9	9.2	13.4	17.1	10.9	22.0	34.9	49.9	67.8
	Average	**291.2**	**3.1**	**7.8**	**12.1**	**16.8**	**21.2**	**14.9**	**35.7**	**56.5**	**73.6**	**95.6**	**4.4**	**8.9**	**14.3**	**20.5**	**26.0**	**16.9**	**33.5**	**52.5**	**72.5**	**95.6**
Summer	2016	22	1.9	2.7	3.2	3.6	3.9	6.1	9.5	12.0	13.1	14.0	1.1	1.6	2.2	3.1	3.8	3.2	5.1	8.1	11.2	14.0
	2017	35	2.7	3.8	4.3	4.7	5.0	6.7	10.2	12.9	14.0	14.4	1.9	2.5	3.2	4.1	5.0	4.2	5.9	9.0	11.9	14.4
	2018	21	1.8	2.6	3.1	3.4	3.6	6.2	9.5	12.0	13.1	14.0	0.9	1.4	2.0	2.8	3.5	2.9	4.8	7.8	10.9	14.0
	2019	29	2.0	3.0	3.6	3.9	4.2	6.2	9.9	12.6	13.8	14.8	1.1	1.7	2.4	3.2	4.1	3.4	5.3	8.6	11.7	14.8
	2020	19	1.8	2.7	3.3	3.7	4.0	6.3	10.2	13.4	14.9	16.4	0.9	1.5	2.3	3.3	4.2	3.2	5.5	9.0	12.5	16.4
	2021	17	1.6	2.5	3.0	3.5	3.8	6.2	9.7	12.8	14.4	16.0	0.8	1.4	2.1	3.1	3.9	3.0	5.4	8.7	12.1	16.0
	Average	**23.8**	**2.0**	**2.9**	**3.4**	**3.8**	**4.1**	**6.3**	**9.8**	**12.6**	**13.9**	**14.9**	**1.1**	**1.7**	**2.4**	**3.3**	**4.1**	**3.3**	**5.3**	**8.5**	**11.7**	**14.9**

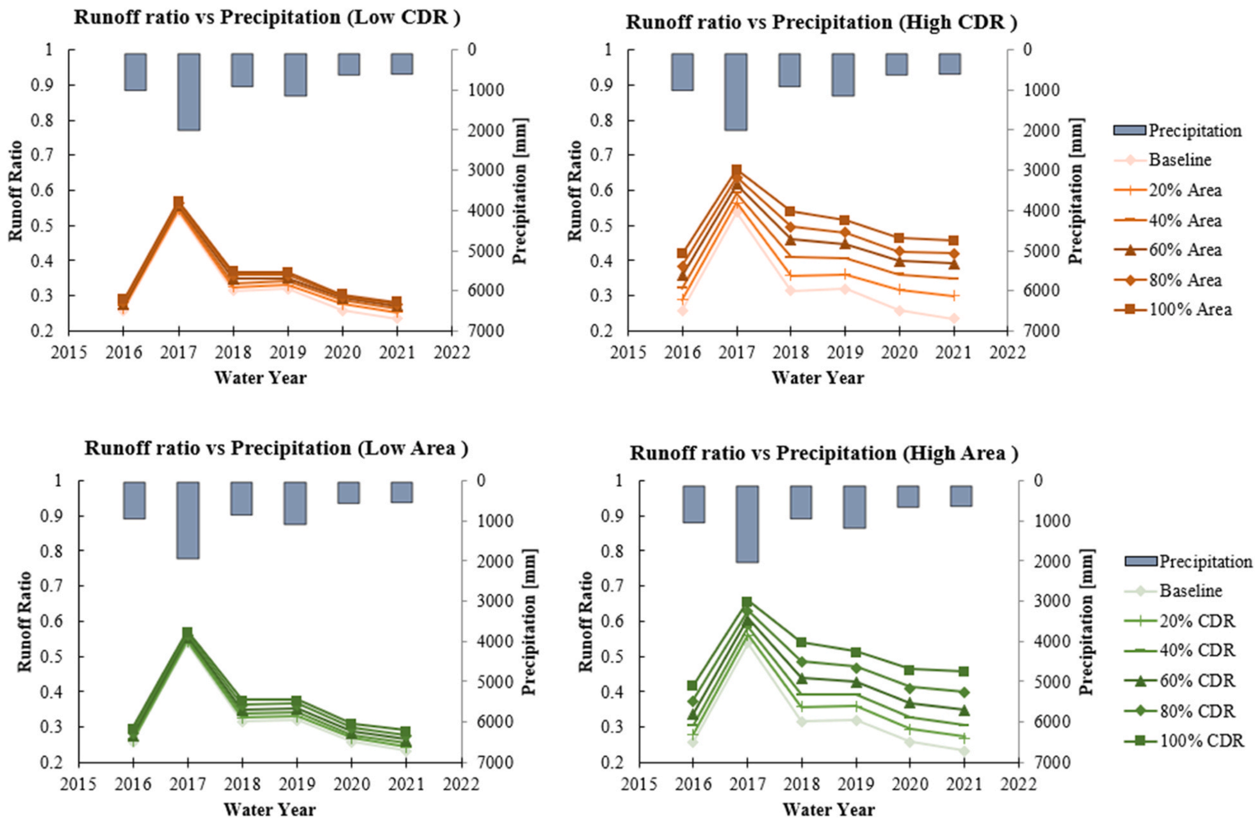

Fig. 4. Runoff Ratio for Baseline and Canopy Density Reduction (CDR) Treatment Scenarios Compared to Precipitation. Treatment was applied at the start of WY 2016.

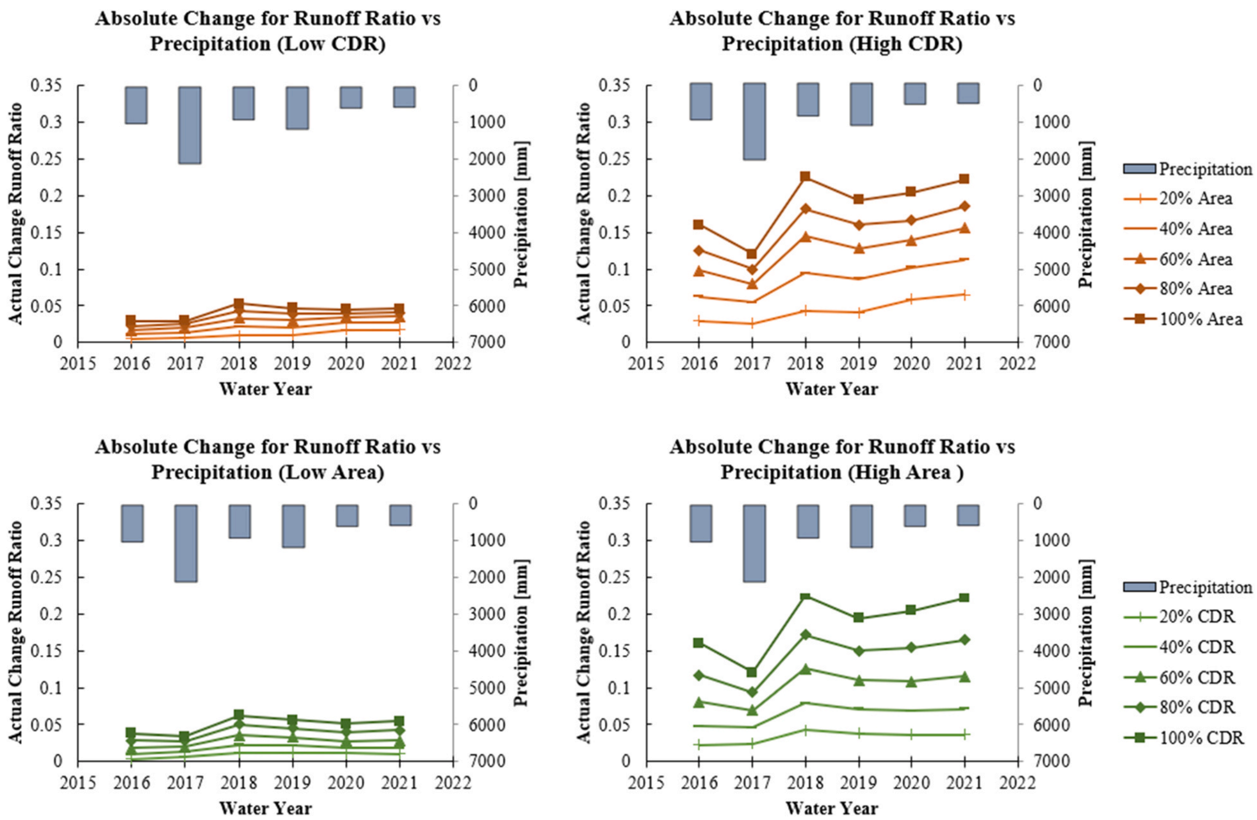

Fig. 5. Absolute Change in Runoff Ratio from Baseline to Scenario Compared to Precipitation. Treatment was applied at the start of WY 2016.

and could be a more viable metric to use if comparing one year at a time since runoff magnitudes are in a more similar range of values.

3.1. Low CDR and low area treatments

In the Low CDR and Low Area Treatment scenarios, for each year, absolute change in annual runoff generally increases linearly as area increases (all years experience an R^2 greater than 0.95) (Table 7, Figure SI.2, and Figure SI.3). The largest average absolute change increase was seen for 25% of the basin area treated at 100% CDR (49.3 mm; 16.9%). The smallest average absolute change increase was seen for 25% of the basin area treated at 20% CDR (9.3 mm; 3.2%). In 2017, the largest average absolute change increase was seen for 25% of the basin area treated at 100% CDR (72.7 mm; 6.4%). For the same scenario and year, the winter/low flow season experienced the largest overall seasonal deviation (60.4 mm; 31.7%). In 2016, the smallest average absolute change increase was seen for 25% of the basin area treated at 20% CDR (3.8 mm; 1.5%). For the same scenario and in 2017, the winter/low flow season experienced the smallest overall seasonal deviation (0.6 mm; 0.1%). Generally, summer/dry season shows the smallest average increase in absolute change and the melt season shows the greatest average increase in absolute change.

3.2. High CDR and high area treatments

In the High CDR and High Area Treatment scenarios, for each year, absolute change in annual runoff generally increases linearly as the CDR or LAI reduction increases (all years experience an R^2 greater than 0.98) (Table 7, Figure SI.4, and Figure SI.5). The largest average absolute change increase was seen for 100% of the basin area treated at 100% CDR (183.0 mm; 64.9%). The smallest average absolute change increase was seen for 100% of the basin area treated at 20% CDR (33.2 mm; 11.3%). In 2017, the largest average absolute change increase was seen for 100% of the basin area treated at 100% CDR (255.7 mm; 22.4%). For the same scenario and year, the winter/low flow season experienced the largest overall seasonal deviation (208.8; 109.5%). In 2021, the smallest average absolute change increase was seen for 100% of the basin area treated at 20% CDR (21.0 mm; 14%). For the same scenario and in 2018, the summer/dry season experienced the smallest overall seasonal deviation (2.9 mm; 14.0%). Generally, summer/dry season shows the smallest average increase in absolute change and the melt season and winter/low flow season vary by treatment for the greatest average increase in absolute change.

3.3. Runoff ratio

Runoff ratio, calculated as annual runoff depth divided by annual precipitation, describes the percent of precipitation that becomes surface runoff. It is also an indicator of how other water budget components (such as infiltration and ET) may impact the basin water budget. Within any given WY, we observed an increase in the amount of precipitation available to runoff as CDR and area of treatment increased – in other words, runoff ratio increased as treatment increased; therefore, the amount of precipitation going to the other water budget components decreased (Fig. 4).

Over time, runoff ratio decreases as precipitation decreases, reinforcing the notion that runoff in Sagehen is precipitation dominant and the given treatment levels show little influence on annual variability in runoff (Fig. 4). For the High CDR (with areas of 40% or larger) and High Area Treatments (with a CDR of 40% or larger) in 2018, precipitation is lower than surrounding years, yet the runoff ratio is higher than the following year, 2019, for each treatment excluding the baseline scenario. Extremely wet conditions in 2017, allowed for a relatively high runoff ratio in 2018. This suggests that antecedent storage (groundwater) conditions are likely influencing runoff.

When considering the absolute change in runoff ratio from baseline to each scenario (Fig. 5), there is a cumulative effect observed on the percent of precipitation that becomes runoff over time with higher treatments as seen in the High CDR and High Area Treatments. For example, the absolute change in runoff ratio has a greater average increase from CDR to CDR and area to area in 2021 than it does in any of the previous years.

The basin's response to precipitation increases as treatment CDR and area increases and the basin shows a greater response and change in runoff ratio for higher treatments. Observe the change in values in the 100% scenario vs the 20% scenario – the 20% scenario has a much more buffered response to precipitation.

4. Discussion

4.1. Hydrologic modeling and water yield threshold

The first objective of this study was to parameterize a distributed, integrated hydrologic model to capture a range of fuel treatment scenarios in the Sagehen Basin. The calibrated MIKESHE model adequately reproduced flow behavior in the Sagehen Basin for a period that contained historic wet and dry years. However, the system was noted to be extremely sensitive to soil and subsurface hydraulic properties, so much of the difficulty in reproducing peak flows and flow timing is attributed to data gaps, and limited characterization of the subsurface, both UZ and SZ; particularly around the fens. The second objective was to determine the extent (threshold) of forest treatments necessary to produce significant changes in surface runoff. All treatment scenarios demonstrated statistically significant increases in runoff on the annual scale for the simulation period. We hypothesized that we would need to treat the basin at a 50% CDR to see a 25% increase in water yield. Results showed a 25% increase in average annual runoff when the entire basin (100% of the modeled area) was treated with a CDR between 40% and 60%, which is consistent with our hypothesis. We also observed a 25%

increase in water yield when 20–40% of the basin area was clear-cut (100% CDR). Therefore, forest and water managers would need to apply a high degree of forest treatments to also observe a substantial increase in annual water yield (Bari et al., 1996; Dung et al., 2012; Saksa et al., 2017; Stednick, 1996; Zou et al., 2010). However, even though the majority of treatments did not produce an average annual runoff increase of 25%, a 10 mm increase in runoff depth (as seen in the 'Low CDR, 20% area' treatment scenario) results in around 345,000 cubic meters for downstream users in the Truckee region. Despite all treatments producing significant changes in runoff on the annual scale, none of the scenarios generated a change in runoff that fell outside of one standard deviation of the annual Baseline runoff. Due to the wide fluctuation in runoff for these ten years, the standard deviation in runoff is abnormally high as compared to observed historic statistics (Table SI.6). If absolute change in runoff were to exceed the standard deviation it would need to be more than double the average runoff.

4.2. Area vs CDR treatment

Relative to Baseline, the greatest (and most significant) increases to annual runoff depth were observed in the High CDR Treatment scenarios. Thus, to maximize the potential co-benefits of fuel treatments (e.g., healthier, more-fire resilient forests *and* increase in water yield), we found that it is more effective to have a high CDR treatment than a larger treatment area (reference Table 7 and SI.5, High CDR and High Area Treatments), which is consistent with our hypothesis.

Although there is a growing amount of literature that characterizes water yield changes to post disturbance and climate (Goeking and Tarboton, 2022, 2020; Zhang et al., 2017), there is a paucity of literature that characterizes water-yield changes to forestry practices – such as comparing treatment area with treatment CDR and this study helps to fill that knowledge gap (Bosch and Hewlett, 1982; Reinhart and Eschner, 1962; Swanson and Hillman, 1977; Trimble et al., 1987). For example, Reinhart and Eschner (1962), evaluated four different forest practices that varied in treated area and CDR but did not have a methodology to define if the result was impacted by the treatment CDR or treatment area. The present study is novel in that it provides quantifiable characterization for treatment area and treatment CDR with respect to water yield.

4.3. Variability in post-treatment runoff change controlled by climate and subsurface

The greatest deviations in post-treatment runoff correlate with precipitation and SWE. WY 2019 had higher winter precipitation and SWE (Figure SI.7 and Figure SI.7) that contributed to higher melt season runoff (Table 7). WY 2017 was a historic wet year, and all scenarios have the highest runoff ratio for this year implying that total streamflow response is affected most by climate (Fig. 4); but for higher treatments, 2017 does not experience the greatest absolute change in runoff ratio from the Baseline scenario (Fig. 5) which may imply that consecutive treatments have a greater impact on the increase of water yield than climate may have. This may also suggest that wetter years are less sensitive to forest treatment as streamflow response is more sensitive under dry conditions (Hou et al., 2021; Zhang et al., 2017). Sierra Nevada water resources are highly dependent on precipitation (Levy et al., 2020; Vilanova et al., 2023), so consecutive treatments could offer a potential solution to combat a decrease in water supply during a prolonged drought.

Over time, runoff ratio decreases as precipitation also decreases (Fig. 4) and stays highly correlated which agrees with findings from Boden et al., (2023). However, more work is needed to fully understand the implications of forest treatment in the Sierra Nevada region under longer-term climate conditions and to isolate and separate the influences of climate and forest harvesting on runoff.

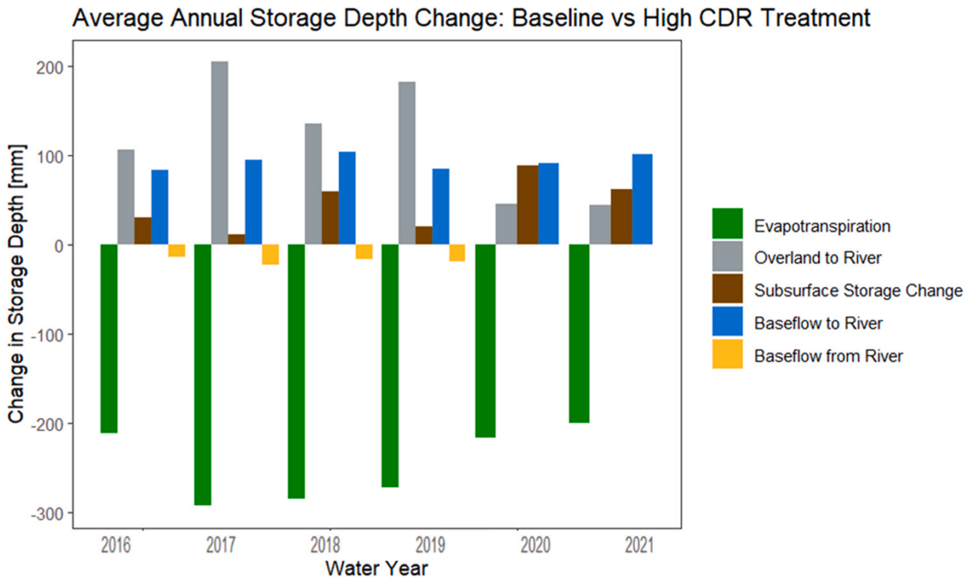

Fig. 6. The change in water balance parameters from Baseline to 100% Area and 100% CDR Treatment scenario.

For high treatments, in 2018, precipitation was lower than surrounding years, yet the runoff ratio is higher than the following year, 2019, once treatments are implemented. Since 2017 was very wet, 2018 allows for a relatively high runoff ratio (Fig. 4). This suggests that antecedent storage (e.g., groundwater) conditions may also be contributing to runoff. We implemented the MIKESHE water balance tool and grid calculator to further investigate this hypothesis (Fig. 6 and 7).

ET and overland flow are the two water budget components contributing the most to variability in post-disturbance runoff until WY 2020 where baseflow to river supersedes overland flow to river (Fig. 6). Subsurface storage change and baseflow to river have a greater increase during drier years (WY 2020–2021) when overland flow does not increase as much. It is important to understand that the system compensates for a loss in ET with increased overland flow and too high of an increase in overland flow could cause an increase in erosion which could affect ecosystem stability and decrease water quality. Baseflow from river (often described as a "losing stream"), occurs when a stream channel's height is above the groundwater table and the stream contributes to groundwater. The basin experiences this during the first couple years of treatment which would be expected as the system experiences more overland flow. On the contrary, baseflow to river (often described as a "gaining stream"), occurs when groundwater contributes to streamflow (e.g., during periods of low flow, when the groundwater table is more saturated). It is possible to see both gaining and losing river characteristics in a year because of seasonal trends in runoff. All WYs' experience an increase in subsurface storage, but the drier years (WY 2018, 2020, and 2021) see the greatest increase and therefore this finding supports our speculation that antecedent groundwater conditions are contributing to runoff. Wet years create moist antecedent conditions that may buffer the effects of drought in the following years. A possible contribution to this effect may be from the basin's fens as they support surface water-to-groundwater exchange that helps to sustain the ecosystem (Sampath et al., 2016). Another opportunity for future work could involve evaluating the relationship between the system's groundwater, fens, and runoff, since fens are highly sensitive to changes in groundwater flow that are caused by hydrologic disturbances (Drexler et al., 2013).

Fig. 7 illustrates that there is a net increase in the head of the SZ in the highest treatment scenario (100% area and 100% CDR) relative to the Baseline scenario. Interestingly, the amount of increase appears to be correlated with the elevation gradient first and then with distance away from Sagehen Creek. Understanding where the SZ increases first could support management in 1) choosing strategic placements for treatment and 2) predicting where they will first see increases in water yield. This also shows where the basin is being most affected which could support a further analysis of how treatment could impact runoff based off basin characteristics such as elevation, elevation gradient, aspect, surficial geology, and vegetation.

The basin does seem to lose its buffering capacity with the addition of forest treatment which then produces wide fluctuations in annual flows (Fig. 4) and its increase in overland flow (Fig. 6). The basin's runoff response increases with increased treatment. For example, if all trees were removed, such that ET decreases and overland flow increases, it would be expected that the basin would have a more dramatic response to precipitation.

4.4. Regional implications

A large portion of California's water supply comes from the Sierra Nevada (Kattelmann et al., 1983). Forest and Water managers in the Sierra Nevada region are concerned with the changing climate that produces more severe drought, as this drought stress could make current Sierra forests susceptible to 1) higher fuel loads (Crockett and Leroy Westerling, 2018; North et al., 2009) and 2) a decrease in water resources, as the region is highly dependent on precipitation (Levy et al., 2020; Vilanova et al., 2023). In Sagehen basin, Boden et al., 2023, found no significant increases in water yield after single-application forest treatment and found the basin to be precipitation dependent (Boden et al., 2023). Through the development of a hydrologic model for the Sagehen basin, we found that the lack of vegetation recovery that could be observed through consecutive yearly forest treatments offer a solution for an increase in water yield in this basin, as we saw an increase in water yield despite a decrease in precipitation. However, while consecutive yearly treatments (continuous maintenance) present a potential water supply solution, this practice may have limited feasibility from a forest management standpoint.

The complexity of this sub-alpine, Mediterranean forest's subsurface produced uncertainty in the study. The evaluation of groundwater vulnerability could lead to better surface numeric models as other studies in this region have shown (Brumm et al., 2009; Urióstegui et al., 2017). In this region, surface water yield is heavily buffered and influenced by groundwater-surface exchange (Fig. 6) (Rademacher et al., 2005). Thus, studies and modeling efforts in this region are encouraged to have an adequate understanding of the subsurface as it could better support forest and water management in planning forest treatment placement.

We quantified water yield for a range of treatments that varied in area and CDR in a Jeffrey Pine Forest, a species native to the Sierra Nevada region (Rose et al., 2003). This species' unique water utilization could differ from other species so this study's results are limited in transferability to other (non-Jeffery Pine dominant) forest types. Additionally, future efforts in understanding if the forest's vegetation will respond with Jeffrey Pine regrowth or conversion will help better quantify water yield for the years following forest treatment (Bart et al., 2016).

4.5. Model uncertainty, limitations, and opportunities to expand on work

Uncertainties arise when modelling complex hydrologic systems such as Sagehen Basin. The surficial geology was considered; however, little was known about the interaction of the subsurface with the fens such as groundwater or river exchange. General fen characteristics (i.e., subsurface depth, hydraulic conductivity, specific yield) were evaluated but may not capture the specific nature and behavior of the fens within Sagehen. Fault lines and springs were not evaluated, and it is unclear how they may contribute to the model's performance.

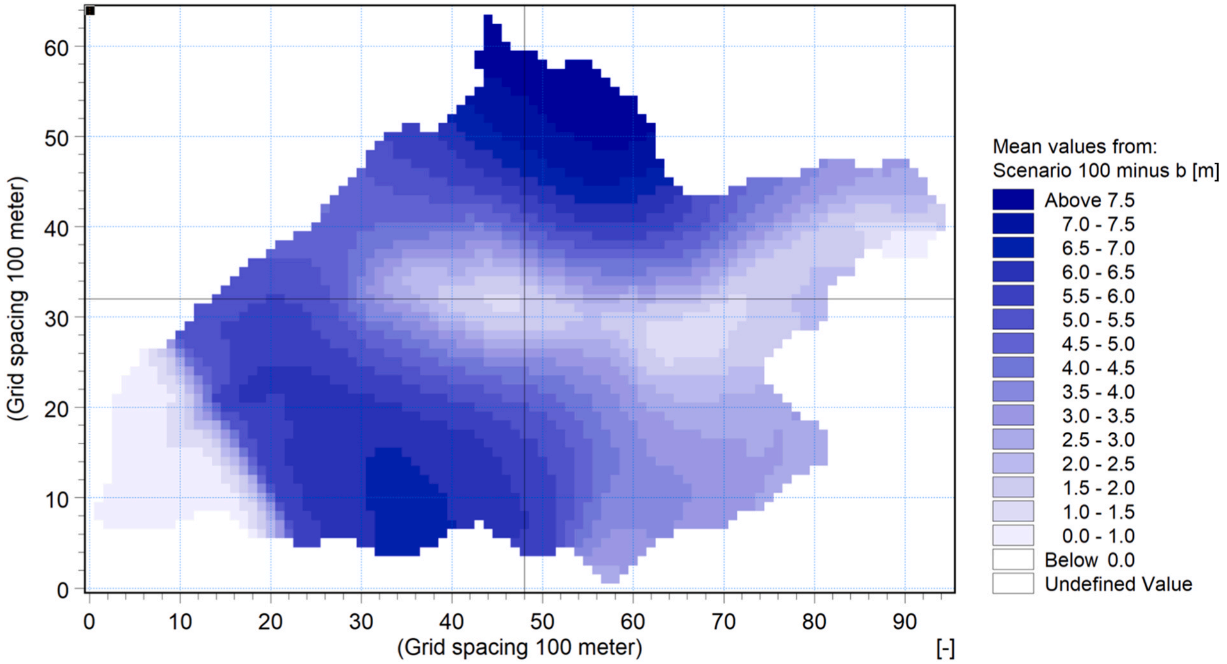

Fig. 7. The average change between Baseline and 100% Area and 100% CDR Treatment scenario in subsurface head during the simulation period.

This study largely focuses on annual and seasonal totals for the entire basin and not for individual tributaries. As seen in Fig. 7, Sagehen tributaries experience the greatest changes in runoff under harvesting scenarios. Thus, it will be critical to better characterize how forest treatments effect the watershed on a sub-basin scale, as too great an increase in flow in the tributaries could be detrimental to the ecosystem. For example, high flows could cause erosion which could decrease water quality and create unsuitable habitat for aquatic organisms.

Model calibration statistics were excluded on the annual time scale as the sample size, or number of years for calibration, were small (n = 8). The model could have benefitted from a larger annual sample size as the study focused on annual totals to improve accuracy and confidence; however, the annual sample size was limited due to the period of available data, a model spin-up period and the need for a validation period. Despite uncertainty with the annual statistics, the daily, weekly, and monthly statistics were acceptable (Moriasi et al., 2015) giving us confidence in the model's performance.

This study focuses on the change in vegetation/canopy density (LAI and root depth) for a Jeffery Pine Forest and how this affects ET in the Sagehen Basin system. Therefore, other factors that could be affected by forest treatments such as the change in crop coefficient (DHI, 2023; Richard G. Allen et al., 1998), soil compaction (Patiño et al., 2021), and forest regeneration (Bart et al., 2016) could be considered in future work. The forcing parameters of ET include reference ET, climate, canopy interception and evaporation, plant transpiration, and soil evaporation (covered in the Kristensen Jenson method). LAI and root depth do not affect reference ET or climate but impact canopy interception/evaporation and plant transpiration.

This study also lacks detailed subsurface data. Looking specifically at soil characteristics such as soil moisture, investigating well data outside of the fens, and understanding how surficial geology impacts hydrological features (faults and springs) would help illuminate the full water balance story and how those factors may impact forest treatment.

Capturing vegetation recovery is difficult (and little existing literature presents quantifiable metrics to represent post-disturbance vegetation recovery); however, we know removal of vegetation creates growth opportunities for ground cover species that contribute to transpiration. For this study, we assume little to no post-disturbance forest recovery (e.g., plants coming back after vegetation is removed). Since we observed that ET has a strong control on runoff change after harvest, post-harvest recovery will likely mute some of the changes in runoff that we observed. Considering post-harvesting vegetation recovery into forest-hydrology models is a challenging but important consideration for future efforts.

High CDR and High Area Treatments are unlikely to occur in management designing and are not beneficial for maintaining forest resources. Consecutive forest treatments with High CDR or High Area are also unlikely as these may not be economically feasible or realistic. These more intense treatments may increase runoff the most but at an expense on the ecology of the forest system. Higher runoff increases opportunity for flooding and erosion which could decrease water quality.

5. Conclusion

Several studies have previously addressed the topic of forest treatment's effect on water quantity in Sierra Nevada forests, particularly if an increase or decrease in water yield occurs. However, a novel aspect of our study is that we used a physically-distributed hydrologic model, that was calibrated to a basin during a time of treatment, to quantify the effect of varying area-treatments and CDR-treatments on water yield. Statistical testing showed that a significant change (99% confidence interval) in simulated runoff occurred for every forest treatment scenario tested on the annual scale using the calibrated MIKESHE model. A 25% increase in average annual water yield was observed when the entire basin was treated with a CDR of 40–60%.

When quantifying changes in water yield after CDR verses area treatments, we observed that increasing CDR treatments were more effective at enhancing water yield than increasing treatment area. Like much of the Sierra Nevada, water yield in the Sagehen basin is highly correlated with, and dominated by, precipitation. However, we found that treatments have a compounding effect on water budget partitioning over the years and the calibrated MIKESHE illustrated how each component of the watershed system responds to these longer-term effects. Antecedent basin storage conditions in Sagehen likely contribute to water yield; more work focusing on groundwater conditions (specifically stream interactions between the basin's fens and their effect on post-treatment water yield) would improve interpretation of basin water partitioning.

The current work highlights the need to further explore the effects that groundwater, climate, revegetation, and other variables may have on forest treatment's impact on water yield. Findings from this study are limited by the lack of subsurface data available for model calibration. Further, the characterization of forest treatment impact on water yield could be enhanced by addressing the effects of forest treatments on the subbasin scale. Despite these limitations, this is one of the first studies to systematically evaluate hydrologic tradeoffs between treatment area and CDR in an alpine, snow-dominated basin. As forest managers implement forest treatments with the goal of achieving the co-benefit of enhanced water yield, consideration should be given to 1) the degree to which treatments are implemented by either area or CDR, 2) future climate variability including extended periods of drought, and 3) basin storage (groundwater) conditions and capacity, and how this might buffer any disturbance to the basin.

CRediT authorship contribution statement

Bob Prucha: Validation, Methodology. **Alicia M. Kinoshita**: Funding acquisition, Conceptualization. **Jake Kurzweil:** Conceptualization. **Katie Schneider:** Writing – review & editing, Validation, Methodology, Investigation. **Katy Smith:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Terri Hogue:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Katy Smith reports financial support was provided by California State Board of Forest & Fire Protection Effectiveness Monitoring Committee (EMC)

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101762.

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