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Hydrologic Response of a Montane Meadow from Conifer Removal and Upslope Forest Thinning

Christopher Surfleet [1,*], Noel Fie [1] and John Jasbinsek [2]

[1] Natural Resources Management and Environmental Science Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA; noelcfie@gmail.com
[2] Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA; jjasbins@calpoly.edu
* Correspondence: csurflee@calpoly.edu; Tel.: +1-805-756-2743

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Abstract: This study evaluates the hydrologic response of restoration of a montane meadow by removal of encroached *Pinus contorta* and thinning of the adjacent forest. It is now a follow-up with four years of post-restoration data, on a previous analysis of a hydrologic response of the same meadow one year following restoration. A hydrologic change was evaluated through a statistical comparison of soil moisture and depth to groundwater between the restored Marian Meadow and a Control Meadow. Meadow water budgets and durations of water table depths during the growing season were evaluated. The four years following restoration of Marian Meadow had an increase in volumetric soil moisture during the wet season, but decreased soil moisture during the dry season. An average decrease in depth to groundwater of 0.15 m was found, which is consistent with the first-year post-restoration. The water budget confirms the first-year results that the hydrologic change following removal of encroached conifers was primarily due to a reduction of vegetation interception capture. There was no measurable difference in depth to groundwater or soil moisture following the upslope forest thinning likely due to the low level of forest removal with 2.8 m^2/hectare reduction of the forest basal area. The cost of restoration to water gained was $0.69 USD/1000 L ($2.62 USD/1000 gal.).

Keywords: conifer encroachment; meadow restoration; meadow hydrology; electrical resistivity; water yield; meadow evapotranspiration

1. Introduction

Montane meadows provide an important ecosystem and economic services and are considered areas with high conservation value. Meadows provide a critical habitat for many species of plants and animals [1–3]. Meadows also provide important water storage for flood protection and water quality [4]. Montane meadows throughout North America and Europe have reduced in size and number due to conifer encroachment [5–7]. Conifer encroachment is an invasion of conifers into a meadow ecosystem, which promotes xeric conditions, caused by changes in climate, cessation of grazing, and long-term fire exclusions [8]. Conifer encroachment is a natural successional process with accelerated declines in the montane meadow habitat. Conifer removal efforts are recognized as essential to successful meadow conservation efforts [9]. A review of other studies of conifer encroachment of montane meadows is provided in Surfleet et al. [10]. Of these studies, few individuals attempt to quantify the hydrologic change from conifer removal within or adjacent to meadows. It is crucial to quantify the hydrologic response associated with conifer removal in encroached meadows to understand the efficacy of restoration strategies.

This article examines the hydrologic response of Marian Meadow before and four years after restoration by removal of encroached *Pinus contorta* (lodgepole Pine). This article is a follow-up to the analysis of the meadow one year following restoration by removal of encroached conifers published in Water [10]. We include three additional years of post-restoration results and further evaluate if forest thinning adjacent to the meadow influenced meadow hydrologic conditions.

2. Materials and Methods

A before-after-control-intervention (BACI) study design was used [10–13] to evaluate the hydrologic response of meadow restoration to remove encroached conifers and upslope forest thinning. Linear regression was used to develop pre-restoration and post-restoration relationships between Marian Meadow, the intervention, or treated site, and a Control Meadow (Figure 1). Statistical comparisons of the intercepts and slopes of the pre-regression and post-regression relationships were used to attempt to detect a change in the hydrologic response. Changes to intercepts or slopes of the relationships can reflect a change to the magnitude and/or timing of hydrologic responses to restoration. A simple water budget approach using soil moisture, depth to groundwater, and climate data was used to attempt to validate the statistical analysis and identify processes that influenced the hydrologic response [10,14]. Number of days of specific shallow depths to groundwater during the growing season was used to indicate efficacy of the restoration treatment [15].

Soil moisture, shallow groundwater depth, and climate data was collected at Marian Meadow and a Control Meadow from September 2013 to September 2019 (Figure 1). A pre-restoration “before” time period was almost two years in length. Removal of encroached conifers within Marian Meadow study area occurred in July 2015. The upslope harvest around the meadow occurred from the summer of 2016 through the fall of 2017. A more detailed description of the study meadows and measurements are available in Surfleet et al. [10]. In this article, we only summarize the methods already described [10], which adds detail when new approaches were utilized.

2.1. Study Areas

The two study meadows were located approximately 16 km from Chester, California, USA on private forestland owned by Collins Pine Company (Table 1, Figure 1). Marian Meadow is approximately 18.2 hectares in the area at an elevation of 1370 m. The watershed area contributing to Marian Meadow is 1785 ha. Marian Meadow was encroached primarily by *Pinus contorta* (lodgepole pine) with a basal area of 25.04 m^2/hectare prior to restoration. The restoration of Marian Meadow involved removing all lodgepole pine from the meadow during summer 2015. The forest surrounding Marian Meadow was composed of mixed conifer species. The mixed conifer species include *Pinus ponderosa*, *Pinus jefferyi*, *Pinus monticola*, *Pinus contorta*, *Psuedotsuga mensiezii*, *Calecedrus decurrens*, and *Quercus velutina*. The basal area of the forest surrounding Marian Meadow was 33.1 m^2/hectare. Following the forest thinning, the basal area was 30.3 m^2/hectare with a 2.8 m^2/hectare or 9% reduction in stand density adjacent to Marian Meadow. The area of the forest thinning within the Marian Meadow watershed was 584 ha and 33% of the watershed area. The Control Meadow was 8.1 hectares in area and an elevation of 1460 m, which is a restored meadow. Encroached conifers were removed in 2010. Although recently restored, herbaceous meadow vegetation had filled in the three years prior to our study (Table 1, Figure 1).

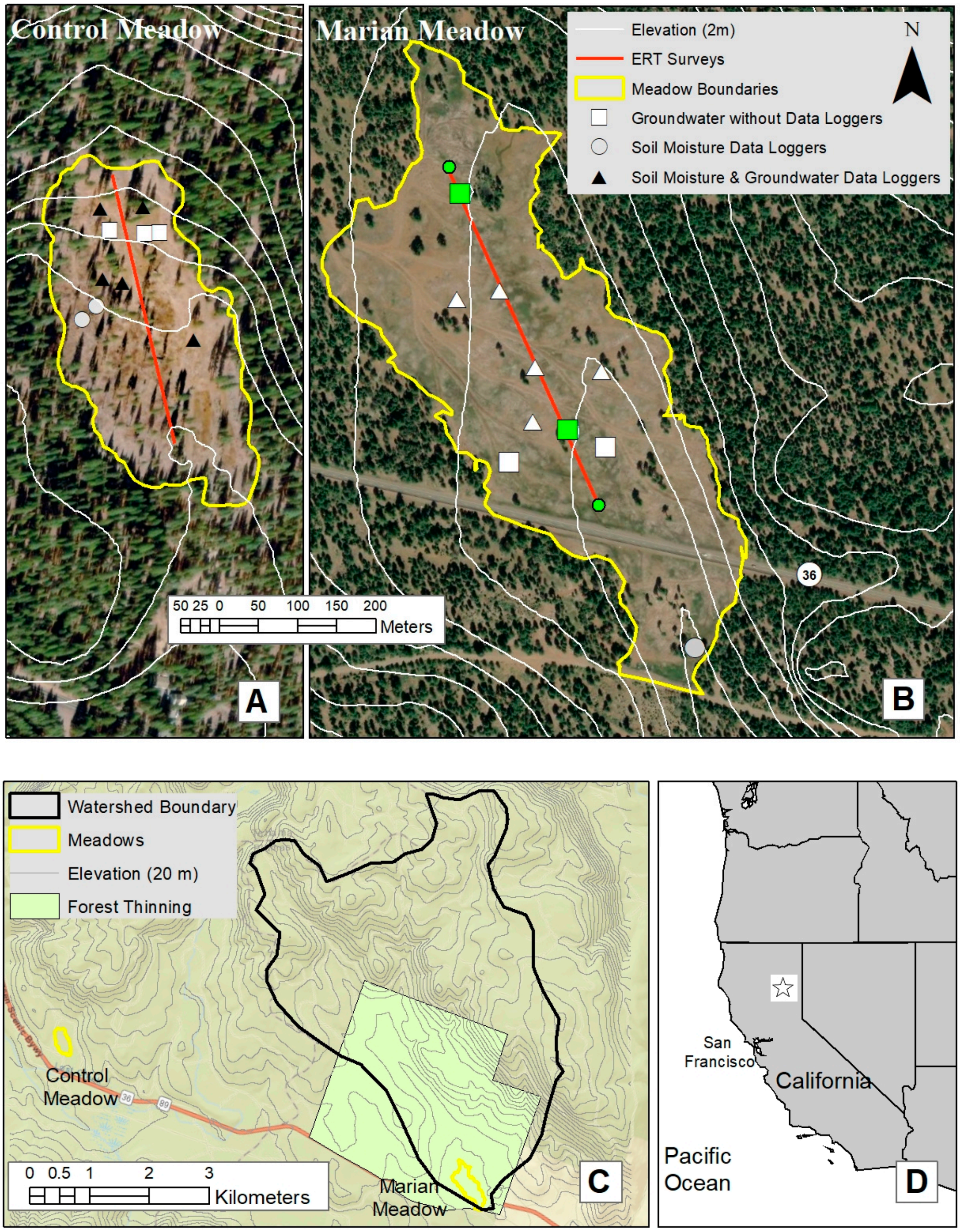

Figure 1. Marian Meadow and Control Meadow study areas. Soil moisture, groundwater depth, and electrical resistivity tomography (ERT) measurements shown. (**A**) Control Meadow. (**B**) Marian Meadow. (**C**) Marian Meadow watershed and area of forest thinning. (**D**) Study sites in relation to California, USA. Satellite imagery and base maps from the Earth System Research Institute (ESRI). Figure adapted from Surfleet et al. [10].

Table 1. Attributes of Marian Meadow and Control Meadow (adapted from Surfleet et al. [10]).

Meadow Attributes	Marian Meadow	Control Meadow
Coordinates (decimal degrees, latitude, and longitude)	40.2636 N 121.3157 W	40.2639 N 121.3945 W
Area of meadow (ha)	18.2	8.1
Area of contributing watershed (ha)	1785	-
Elevation (m)	1370	1460
Surface soil texture (%sand-%silt-%clay)	Clay (32-26-42)	Clay Loam (47-16-37)
Soil porosity at 30 cm depth	47%	42%
Bulk density at 30 cm depth	1.40 g/cm^3	1.53 g/cm^3
Hydraulic conductivity (2 m)	60 m/day	35 m/day
Depth to a partially confining layer	12–30 m	15–>69 m

The average annual precipitation recorded at Chester was 860 mm [16]. Precipitation is a mix of rain and snow. The average annual air temperature of nearby Chester, California (elevation 1372 m) from 1948 to 2005 was 8.7 °C.

The meadows are located in a transitional zone between the Cascade and Sierra Nevada Mountains, USA. Soils have primarily volcanic parent material [17]. The top horizon at Marian Meadow has a clay texture (Table 1). The Control Meadow consists of a clay loam from poorly consolidated alluvial materials with high sand content [18,19]. Soil bulk density and porosity were determined from samples taken at 30 cm. Hydraulic conductivity was determined at 2 m using the Kozeny-Carmen equation [20] based on a particle size distribution analysis [21] (Table 1). Both meadows are classified as dry meadows [22,23].

Electrical resistivity tomography (ERT) surveys were performed across the length of both meadows (Figure 1) to determine the depth to confining layers. ERT was also used in evaluating depth to groundwater when groundwater was below the depth of shallow wells, which is described later. The ERT surveys to determine depth to a confining layer were performed with a SuperSting-R8 electrical resistivity meter operated with Schlumberger Array geometry (Advanced Geosciences Incorporated, Austin, TX, USA), inverted with EarthImager-2D software (Advanced Geosciences Incorporated, Austin, TX, USA), and contoured in Matlab R2016a (MathWorks, Natick, MA, USA). The ERT profile across both meadows employed 112 electrodes at a spacing of three meters in the Control Meadow and four meters in Marian Meadow (Figure 1). Near-surface soil along both profiles was very dry at the survey time (July 2018), but the inverted resistivity models match the field data well with root-mean-square (RMS) errors of 8.3% and 6.3% in the Control Meadow and Marian Meadow, respectively.

The depth of the confining layers differs in the two meadows. The confining layer in Marian Meadow is laterally continuous across the profile (Figure 2) and is interpreted to be composed of moderately fractured extrusive igneous rock with resistivity values >300 $\Omega \cdot$ m. Confining layer depth is 12 m on the SE end of the profile and steadily deepens to approximately 30 m on the NW end of the profile. High resistivity features seen in the first few meters below the profile indicate dry soil conditions. The darkest blue contours (<25 $\Omega \cdot$ m) are interpreted as regions with enhanced clay content derived from weathering of the volcanic rocks of the region. The confining layer resistivity decreases to the NW, which indicates that the confining layer may become more fractured in this direction.

In the Control Meadow, a partially confining layer is detected at a depth of approximately 15 m at the NW end of the profile but disappears to the SE (Figure 2). The confining layer on the NW side of the profile is characterized by resistivity values of >300 $\Omega \cdot$ m, interpreted to be composed of moderately fractured extrusive igneous rock. Very high resistivity features are observed near the surface, which indicates extremely dry near-surface soil conditions. Resistivity values of 100 $\Omega \cdot$ m less typically indicate saturated soil or alluvium. However, regions contoured with the darkest blue colors (<30 $\Omega \cdot$ m) are potentially clay deposits related to the weathering of the volcanic rock of the region. The base of the aquifer in the Control Meadow is, therefore, generally greater than the 69-meter imaging depth of the ERT profile, and significantly deeper than in Marian Meadow.

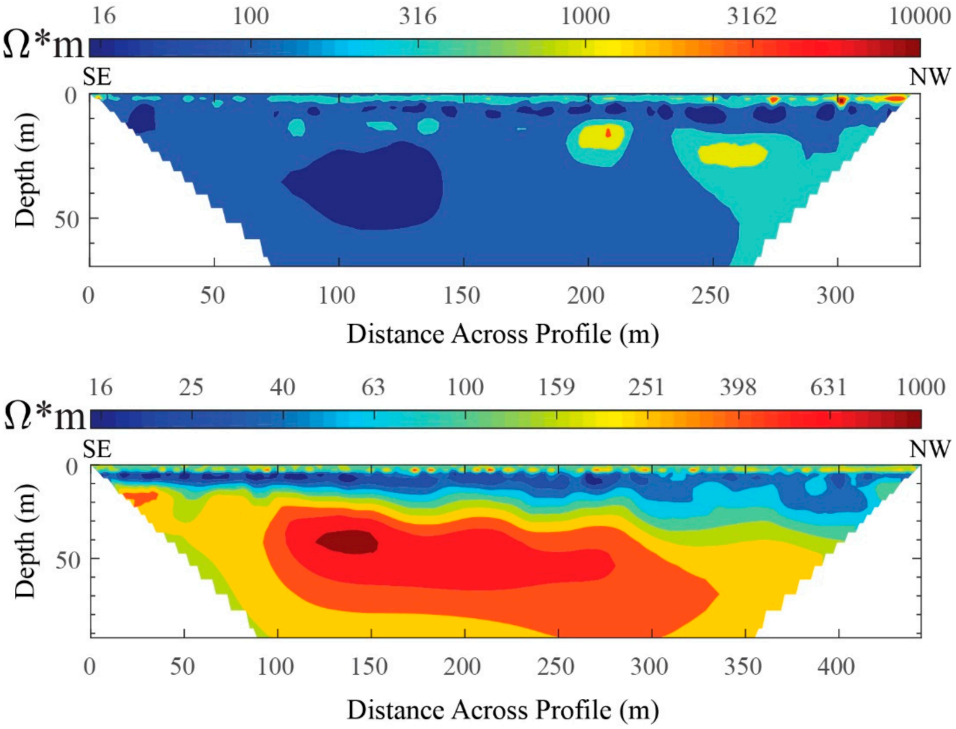

Figure 2. Inverted electrical resistivity models. From left-to-right, both profiles traverse an SE to NW trend (Figure 1A,B). Top: Control Meadow. Bottom: Marian Meadow. Color bars on each panel cover different ranges of resistivity. The Control Meadow image is 333 m long with an image depth of 69 m. The Marian Meadow image is 444 m long with an image depth of 92 m.

2.2. Volumetric Soil Moisture

Soil moisture was measured at 0.3 m (2014–2019 WY) and 0.9 m depths (2015–2019 WY) using Odyssey soil moisture sensors (Dataflow Systems Pty Limited, Christchurch, New Zealand) and time domain reflectometry (TDR) soil moisture sensors (Onset Computer Corp., Bourne, MA, USA). Initially, Odyssey soil moisture sensors were used. Over time, Onset TDR soil moisture sensors were added to increase the distribution of measurements. Both instruments were calibrated prior to use. Ten soil moisture sensors per meadow made measurements at two-hour intervals (Figure 1). Gravimetric to volumetric soil moisture conversion used the core method [24].

2.3. Water Table Depth

Water level loggers (Odyssey Dataflow Systems Pty., Christchurch, New Zealand) were installed within 1.5 m wells. There were seven shallow groundwater wells on Marian Meadow, and five shallow groundwater wells on the Control Meadow (Figure 1). Water level was recorded at 2-h intervals. In August 2018, two 3-m wells were installed at Marian and Control Meadows instrumented with Onset U20L water level recorders. Electrical resistivity tomography (ERT) surveys were used approximately once per year to define the groundwater level when below the depth of the 1.5-m wells. These electrical resistivity data were collected using an automated Wenner Array with a Syscal Kid Switch 24 electrical resistivity meter (IRIS Instruments, Orleans, France). Data inversion was performed with RES2DINV software version 3.71 (Geotomo Software, Penang, Malaysia). Inverted data were exported for contouring and plotting in Matlab R2016a (MathWorks, Natick, MA, USA). Additionally, the number of days the water table depths were within 0.3 m and 0.7 m of the ground surface were compared to published durations for obligate wetland and facultative wetland plant species [15].

2.4. Statistical Analysis for Change Detection

A least squares regression model using analysis of covariance [10,25] was used to detect changes in the slopes and intercepts of the pre-restoration and post-restoration relationships in volumetric soil moisture content and depth to groundwater (m below ground) following restoration. Weekly average soil moistures and depth to groundwater values were compiled for each meadow. A three-week interval between weekly average measurements was required to avoid serial auto-correlation [12]. The pre-restoration period included 13 September 2013 through 30 September 2015. The post-restoration period assessed in this analysis was between 1 October 2014 and 1 September 2019. Data was separated by the water year (WY) based on a start of October the year prior to, ending in September of the WY.

2.5. Meadows' Water Budgets

An annual water budget was created for Marian and Control meadows using methods developed by Rahgozar et al. [14]. Greater detail for procedures for each water budget value is available [10]. The general form of the water budget was shown in Equation (1).

$$P \mathrm{+/-\ Error} = \mathrm{Q_{SEOF}} + \mathrm{ET} \mathrm{+/-} \Delta \mathrm{S} \quad (1)$$

where P is precipitation (mm) from the Chester rain gauge. $\mathrm{Q_{SEOF}}$ was saturated with excess overland flow or surface ponding (mm) assumed to be P when the groundwater was fully saturated. ET was the sum of evapotranspiration from the soil ($\mathrm{ET_S}$) and evaporation from interception capture ($\mathrm{I_C}$) (mm). $\mathrm{I_C}$ was estimated by selecting isolated precipitation events with intensity less than the hydraulic conductivity of the surface soil layers, which occurs after medium to dry antecedent conditions. The intercept of the best fit line on the precipitation to infiltration relationship yields the estimate of the interception capture. Interception capture (Ic) was assumed to represent either evaporation or sublimation of incoming precipitation [10].

$\mathrm{ET_S}$ was determined by the difference in the diurnal fluctuations of soil moisture. ΔS (mm), which is the change in storage of water, was the sum of infiltration to groundwater ($\mathrm{I_{WT}}$) and soil moisture ($\mathrm{I_S}$) minus $\mathrm{ET_S}$ (Equation (2)). Error is defined as the sum of the water balance components subtracted from the annual precipitation. If the water balance was precise, the error would be zero.

$$\Delta \mathrm{S} = (\mathrm{I_{WT}} + \mathrm{I_S}) - \mathrm{ET_S} \quad (2)$$

3. Results

3.1. Hydrologic Change Detection for Encroached Conifer Removal and Upslope Forest Thinning

3.1.1. Soil Moisture

The hydrograph of weekly average soil moisture for 2014–2019 WY for Control and Marian Meadows is shown (Figure 3). There was a statistically significant relationship between the week-averaged Control Meadow soil moisture and Marian Meadow soil moisture pre-restoration, as shown in analysis of the first-year post-restoration results [10] (Table 2). The analysis of covariance of the intercepts of linear relationships for the four post-restoration water years were not statistically significant from zero, p value = 0.93. However, the pre-restoration intercept was statistically significant for its linear relationship. The resulting pre-restoration regression equation had an intercept of 12.21 percent soil moisture (p-value < 0.001) while the post-restoration regression equations had intercepts of zero. This demonstrates a difference in the linear intercept between the pre-restoration and post-restoration relationships. The slopes of the four post-restoration years were statistically different compared to pre-restoration; p-value < 0.001 (Tables 2 and 3, Figure 4). This difference in slopes, but not the intercepts for the post-restoration years, suggest both positive and negative differences in soil moisture depending on the magnitude of the soil moisture. At lower soil moistures, post-restoration Marian Meadow soil moisture percentages decreased while, at higher soil moisture percentages, Marian Meadow soil moisture increased when compared to the Control Meadow (Figure 4). There was not a statistically significant difference between the post-restoration soil moisture (2016 WY) and the post-forest thinning (2018–2019 WY) soil moisture in Marian Meadow when compared to the Control Meadow, *p*-value = 0.93.

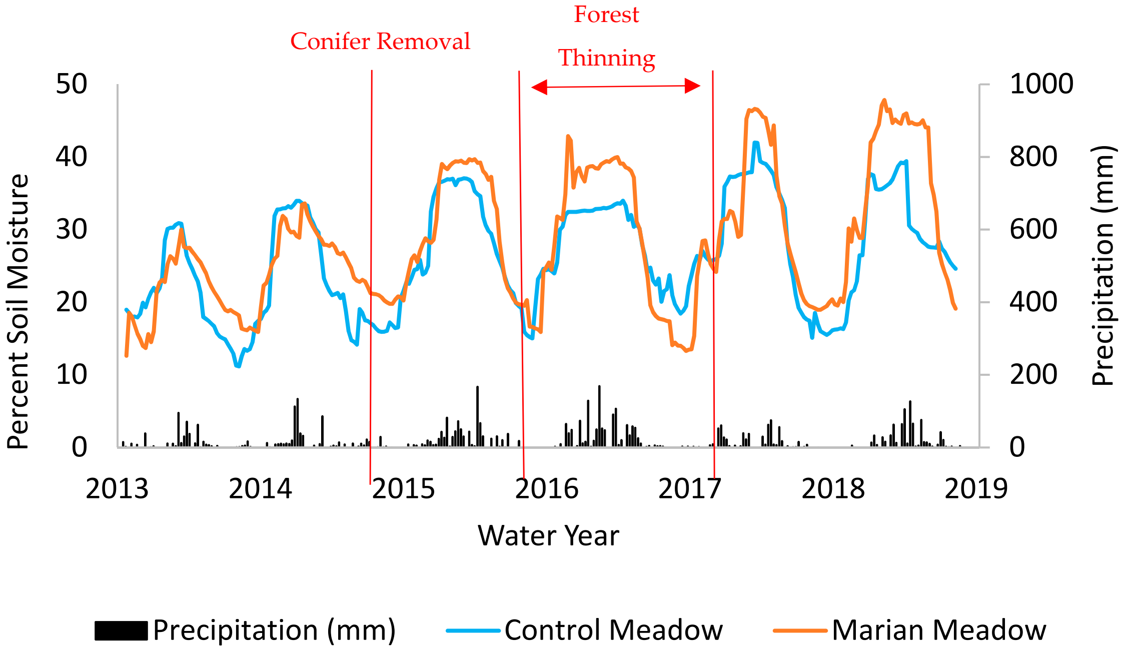

Figure 3. Week-averaged volumetric soil moisture (%) and precipitation (mm) for Control Meadow and Marian Meadow, 2013–2019.

Table 2. Regression coefficients and statistics for soil moisture models.

Term	Estimate	Std Error	*P*-Value
Pre-restoration intercept	12.21	2.12	<0.001
Pre-restoration slope	0.63	0.09	<0.001
Year 1 post-restoration slope	1.09	0.39	0.007
Year 2 post-restoration slope	1.67	0.71	0.02
Year 3 post-restoration slope	1.04	0.40	0.01
Year 4 post-restoration slope	1.19	0.52	0.02

Table 3. Regression equations for soil moisture percent between Marian Meadow and Control Meadow for pre-restoration (2014–2015 water year (WY)) and each year after restoration (2016–2019 WY).

Pre-Restoration	Marian Meadow Soil Moisture (%) = 12.39 + 0.63 × Control Meadow Soil Moisture (%)
First year post-restoration	Marian Meadow soil moisture (%) = 1.09 × Control Meadow soil moisture (%)
Second year post-restoration	Marian Meadow soil moisture (%) = 1.67 × Control Meadow soil moisture (%)
Third year post-restoration	Marian Meadow soil moisture (%) = 1.04 × Control Meadow soil moisture (%)
Fourth year post-restoration	Marian Meadow soil moisture (%) = 1.19 × Control Meadow soil moisture (%)

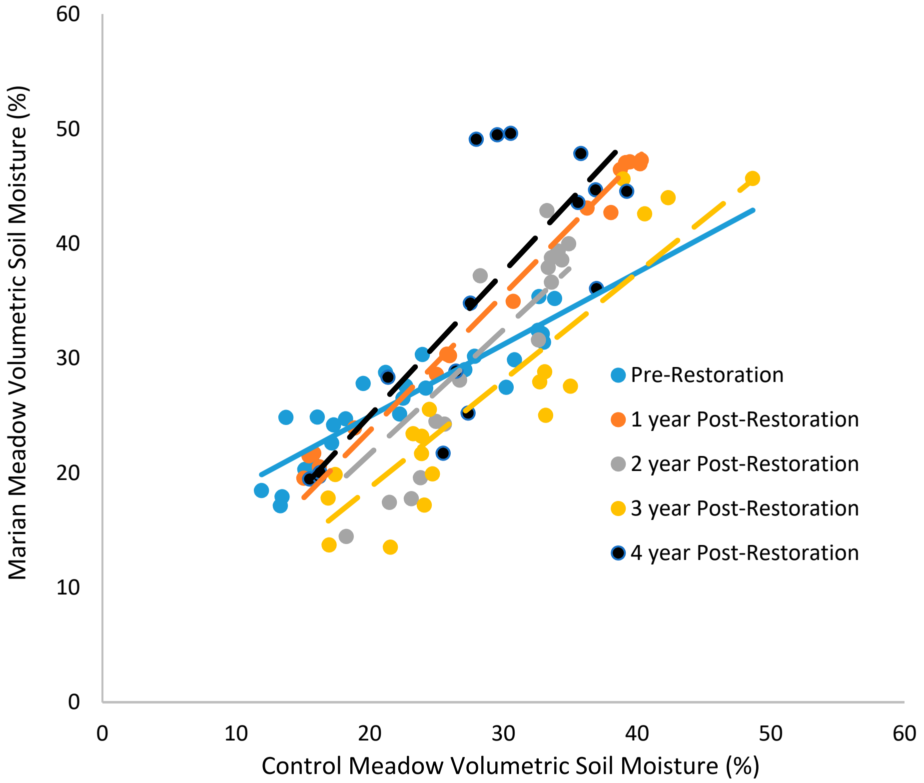

Figure 4. Pre-restoration and post-restoration scatter plots and regression lines between Marian Meadow and Control Meadow soil moisture (%). Solid line indicates pre-restoration relationship while the dashed lines indicate post-restoration relationships.

3.1.2. Water Table Depth

The analysis of covariance of the slopes for the pre-restoration and post-restoration week-averaged depth to groundwater regression lines were not statistically significant with a p-value = 0.93. The regression line slopes were significantly different from zero with a p-value < 0.001 (Table 4). The intercepts of the four post-restoration years were statistically different compared to pre-restoration, p-value < 0.001, with the exception of the third year post-restoration (Table 4). The difference in intercepts, but not slope, suggest that changes in depth to groundwater for the post-restoration years were consistent for the range of depths measured (Tables 4 and 5, Figures 5 and 6). There was not a statistically significant difference between the post-restoration (2016 WY) depth to groundwater and the post-forest thinning (2018–2019 WY) in Marian Meadow compared to the Control Meadow (p-value = 0.20).

Table 4. Regression coefficients and statistics for depth to groundwater regression models for pre-restoration (2014–2015 WY) and each year after restoration (2016–2019 WY).

Term	Estimate	Std Error	*p*-Value
Slope	0.713	0.032	<0.001
Pre-restoration intercept	0.26	0.023	<0.001
Year 1 post-restoration intercept	0.06	0.033	0.03
Year 2 post-restoration intercept	0.03	0.026	<0.001
Year 3 post-restoration intercept	0.18	0.029	0.13
Year 4 post-restoration intercept	0.14	0.032	<0.001

Table 5. Regression equations for depth to groundwater between Marian Meadow and Control Meadow for pre-restoration (2014–2015 WY) and each year after restoration (2016–2019 WY).

Pre-Restoration	Marian Meadow (m) = 0.26 + 0.713 × Control Meadow (m)
First year post-restoration	Marian Meadow (m) = 0.06 + 0.713 × Control Meadow (m)
Second year post-restoration	Marian Meadow (m) = 0.03 + 0.713 × Control Meadow (m)
Third year post-restoration	Marian Meadow (m) = 0.18 + 0.713 × Control Meadow (m)
Fourth year post-restoration	Marian Meadow (m) = 0.14 + 0.713 × Control Meadow (m)

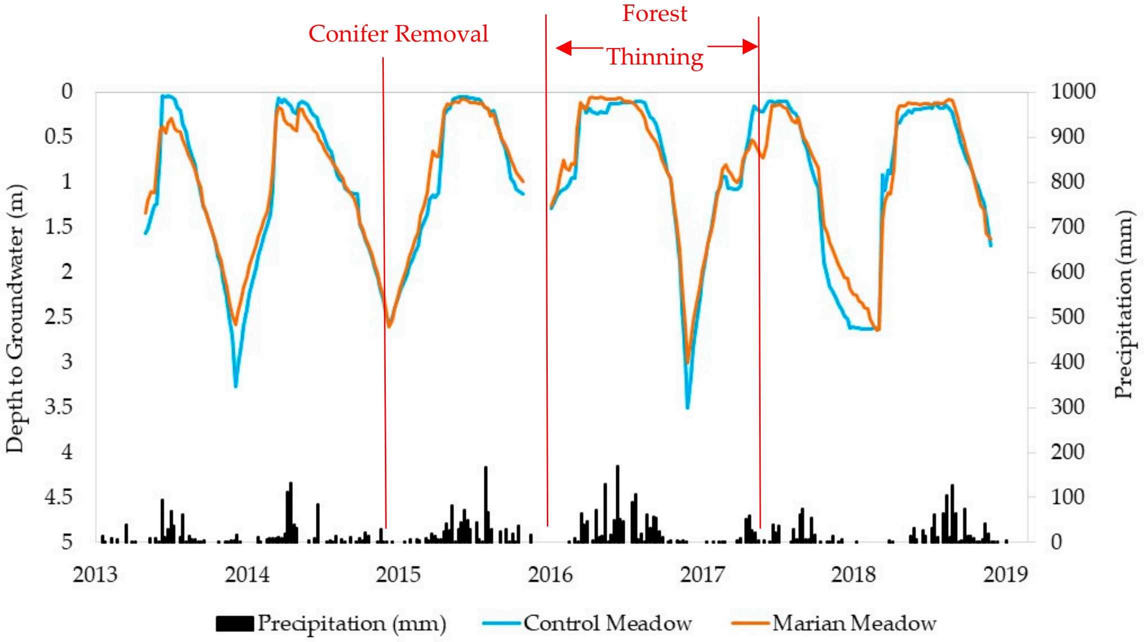

Figure 5. Average weekly depth to groundwater (m) and precipitation (mm) for the Control Meadow and Marian Meadow, 2013–2019. Break in 2016 time series indicate groundwater depths below shallow well depths including a year without ERT imaging for interpretation. In 2018, deeper wells were added.

Figure 7 shows an electrical resistivity profile in Marian Meadow before and after meadow restoration, collected one year apart. The estimated groundwater level (approximately 2.5 m) is nearly unchanged in the two surveys. Furthermore, the repeated survey indicates relatively uniform depth to groundwater along the linear profiles. This validated that the point measurements from wells were representative of the depth to groundwater across the space. Above the water table, a qualitative interpretation of vadose zone soil moisture can be made. Prior to restoration (Figure 7A), electrical resistivity values are generally greater than 450 Ω · m and locally as high as 650 Ω · m. After restoration (Figure 7B), electrical resistivity values are less than 450 Ω · m with some regions showing a decrease in electrical resistivity by a factor of three. Only one location shows a region where electrical resistivity increased. Qualitatively, then, the vadose zone has responded uniformly to meadow restoration with lowered electrical resistivity values, which can be interpreted as an increase in soil moisture. In our ongoing work of a hydrological response to meadow restoration, the relationship between electrical resistivity and soil moisture in the vadose zone is being studied to form local quantitative relationships.

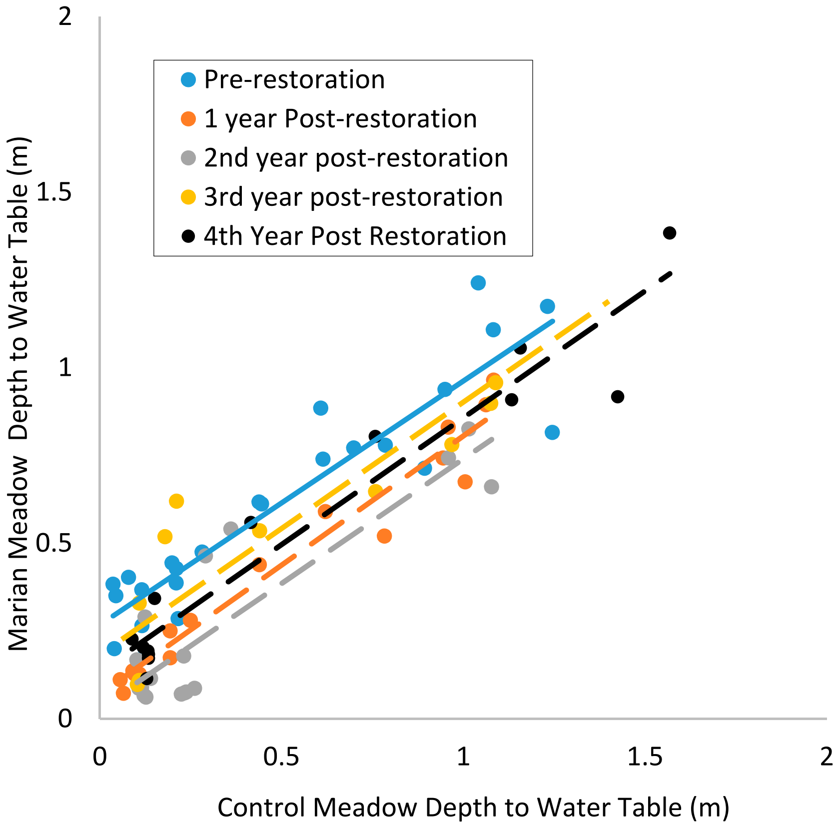

Figure 6. Pre-restoration and post-restoration scatter plots and regression lines between Marian Meadow and Control Meadow depth to groundwater (m). Solid line indicates a pre-restoration relationship while the dashed lines indicate post-restoration relationships.

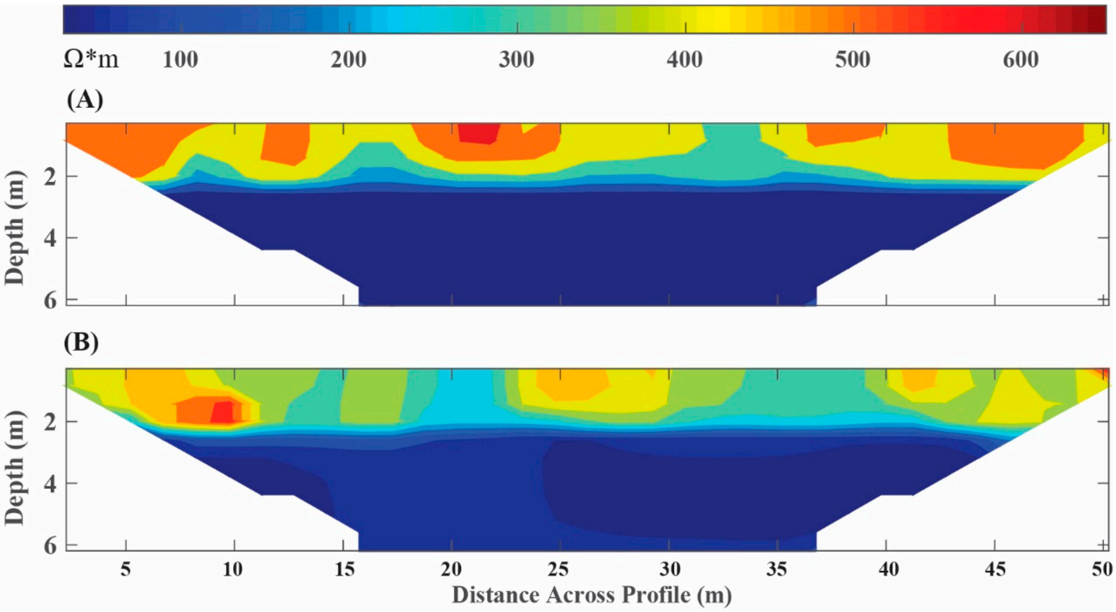

Figure 7. Inverted electrical resistivity profile before and after harvesting in Marian Meadow. The same profile and color bar of electrical resistivity values is represented in both panels. (**A**) Data collected on 7 September 2014. (**B**) Data collected on 9 September 2015. RMS inversion error: (A) 1.45% and (B) 1.43%.

3.2. Water Table Durations at Rooting Depths

In wetland environments, it is typical that depth to groundwater is the primary factor controlling the distribution of herbaceous vegetation communities [15,26]. Plant community types are generally distributed along a hydrologic gradient from xeric to mesic. The average growing-season water-table depth is indicative of the plant community type and, therefore, meadow classification. The number of days the water level is at or above, in average, is 0.7 m (2.3 ft), which represents the number of days the meadow is within the root zone typical of facultative and facultative upland plant species. The number of days the groundwater depth is at or below, on average, is 0.3 m (1 ft), which represents the number of days the meadow is within the root zone typical of facultative wetland plant communities (Table 6).

Table 6. Annual precipitation, precipitation during the growing season (1 April through 31 August), and number of days during the growing season with depth to groundwater <0.3 m and <0.7 m for 2014–2019 WY.

Water Year	**Growing Season**					
	2014	**2015**	**2016**	**2017**	**2018**	**2019**
Precipitation (mm/year)	489	636	931	1234	584	1003
Precipitation during May–August (mm)	45	67	79	21	30	79
Marian Meadow Days < 0.7 m	46	7	85	61	62	75
Marian Meadow Days < 0.3 m	4	0	50	22	16	36
Control Meadow Days < 0.7 m	53	24	71	67	53	81
Control Meadow Days < 0.3 m	25	0	50	43	28	57

In the pre-restoration years of 2014–2015, the Control Meadow had a higher number of days than Marian Meadow at depths <0.3 and <0.7 m. The growing season days post-restoration (2016–2019) with water table depths < 0.7 m and <0.3 m was higher or similar for Marian Meadow compared to the Control Meadow and compared to pre-restoration (2014–2015). The number of days of depth to groundwater <0.3 and <0.7 m is increased in the post-restoration period for Marian Meadow when the late season precipitation is the highest (May–August).

3.3. Annual Water Budget

Annual water budget components for the Control Meadow with meadow vegetation (2014–2019), Marian Meadow with encroached conifers (2014–2015), encroached conifers removed (2016–2019), and Marian Meadow with forest thinning adjacent (2017–2019) are summarized (Table 7).

Annual precipitation (P) varied throughout the study. The annual precipitation was generally higher in the post-restoration (2016–2019) period where only 2018 had lower annual precipitation than a pre-restoration year. The years with higher precipitation had greater saturated excess overland flow (Q_{SEOF}) due to longer periods of saturated soils. Generally, Marian Meadow had higher overland flow than the Control Meadow in the post-restoration years. Other components of the water budget such as evapotranspiration, infiltration, and budget error did not directly relate to higher or lower precipitation.

ET ranged from 335 to 428 mm/year for the Control Meadow with the highest amount of evapotranspiration in 2017 WY from higher precipitation (Table 7). ET was 457 mm/year and 482 mm/year in Marian Meadow during the pre-restoration period of 2014 and 2015 WY, respectively. ET was slightly lower in Marian Meadow for the post-restoration period 2016–2019 WY, 399–425 mm/year. The soil evapotranspiration (ET_S) estimates for Marian and Control Meadows were relatively similar over the study at 234–318 mm/year. The interception capture (I_C) estimates dropped by almost half for Marian Meadow following conifer removal. No clear differences in ET or Q_{SEOF} can be distinguished in the water budget during and following forest thinning (2017–2019) compared to only conifer removal (2016) in the Marian Meadow.

Table 7. Water budget for pre-restoration 2014–2015 water years (WY) and water years 2016–2019 after restoration by encroached conifer removal and upslope forest thinning.

Meadow	WY	P (mm)	Q_{SEOF} (mm)	I_S (mm)	I_{WT} (mm)	ET_S (mm)	Ic (mm)	ET (mm)	Error (mm)
Marian	2014	489	0	280	22	285	172	457	10
Control	2014	489	75	255	79	286	74	360	−25
Marian	2015	636	107	267	40	268	214	482	7
Control	2015	636	102	267	103	258	87	345	87
Marian	2016 *	931	433	308	90	318	107	425	−17
Control	2016 *	931	374	333	42	288	107	395	119
Marian	2017 **	1234	876	263	33	276	124	401	−76
Control	2017 **	1234	616	180	57	303	124	428	134
Marian	2018 ***	584	90	170	49	314	101	415	29
Control	2018 ***	584	58	309	32	234	101	335	158
Marian	2019 ***	1003	572	257	94	299	100	399	53
Control	2019 ***	1003	575	254	81	255	100	355	−7

* 2016 first year post-restoration by conifer removal alone. ** 2017–2019 post-restoration by conifer removal and during forest thinning. *** 2018–2019 post-restoration by conifer removal following forest thinning.

4. Discussion

4.1. Effect of Encroached Conifer Removal and Forest Thinning on Meadow Hydrology

The statistical analysis of soil moisture showed Marian Meadow soil moisture consistently lower than the pre-restoration relationship with the Control Meadow during periods with relatively low soil moisture post-restoration. Marian Meadow had higher soil moisture relative to the Control Meadow post-restoration when soil moisture levels were the highest. The difference in slopes of the post-regression models demonstrate the change from lower soil moisture to higher soil moisture for Marian meadow, which varied by year (Figure 4).

The decreased soil moisture levels in Marian Meadow post-restoration were conducted during periods of extended dry weather between June and November each year. In the article on the first-year post-restoration [10], the decrease was thought to be caused by a reduction of vegetation cover creating higher soil temperatures and increasing soil water evaporation. Additionally, the restoration work created considerable ground disturbance, speculated to increase soil evaporation losses [10]. However, the lower soil moisture during the dry season in Marian Meadow has been consistent for the four years since restoration, even after increased grass and forb regeneration in the meadow (Figures 3 and 4). The grass and forb community either dies or goes dormant during the dry season, which is indicative of a dry meadow at both Marian and Control Meadows. Marian Meadow ground cover still lacks substantial litter for soil cover during plant dormancy or die off, which suggests low-to-moderate cover to soil evaporation in the summer dry season.

The four years post-restoration, there was an average decrease of 0.15 m (range 0.08–0.23 m) between the measured and predicted annual water table depths from the depth to groundwater regression relationships. The water budget value of I_{WT} also showed a change. The change was predicted to be 0.06 m at an average of four years post-restoration (Table 7). This was consistent with the decrease in depth to groundwater from the first-year study [10]. The lower predicted decrease in depth to groundwater from the water budget approach reflects the uncertainty in the budget estimates. The 2018 WY (year 3 post-restoration) depth to groundwater was not significantly different from pre-restoration. This was a low precipitation year with several instrument failures leading to uncertainty in values used in the statistics.

There was no statistical difference in depth to groundwater following the upslope forest thinning. The harvest basal area of the forest surrounding Marian Meadow was 33.1 m^2/hectare. Following the forest thinning in 2018-2019, the surrounding forest basal area was 30.3 m^2/hectare. The area included 2.8 m^2/hectare or a 9% reduction in stand density adjacent to the meadow. However, the forest thinning only affected 33% of the contributing watershed area. The low level of forest thinning and contributing area treated might explain the lack of response in meadow groundwater levels. A recent modelling study of fuels treatment in the Sierra Nevada found a 3% increase in water yield in the mid-regions of the Sierra Nevada associated with an 8% reduction in vegetation [27]. However, modelling studies do not encounter the variability of field measurements. High variability in measured hydrologic values makes small changes difficult to detect. Furthermore, the majority of the increases in water yield occurred during the winter or spring snowmelt when saturated soil creates greater overland flow [28]. The surface runoff in the water budget estimates (Table 7) increased in all post-restoration years except for year 3, which had below-average annual precipitation. This indicates increased water yield from the encroached conifer removal. However, there was not an additional increase in surface runoff estimated in years following the upslope forest harvest.

4.2. Water Budget Changes due to Conifer Removal

The water budget for Marian Meadow showed a decrease in ET in the four years post-restoration from decreased evaporation due to interception capture (I_C) (Table 7). I_C was estimated to be 172 and 214 mm/year in the two pre-restoration years, respectively. The four post-restoration years ranged from 100–124 mm/year. This loss of interception capture created a decrease in ET in Marian Meadow post-restoration. The soil evapotranspiration (ET_S) estimates for Marian and Control Meadows were relatively similar over the study with Marian Meadow and Control Meadow ranging from 268–318 and 234–303 mm/year. There were slight differences in ET_S between the meadows. However, this is likely an artifact of error in the ET_S estimates. The Control Meadow could not close the water budget without a significant error as high as 158 mm (27% of precipitation) in 2018 WY. The soil moisture instruments provided reasonable diurnal fluctuations and values to predict ET_S. However, the manufacturer error was listed as +/−3% [29] that could compound over many measurements. Additionally, depth to groundwater could drop as deep as 3 m, when only 0.3–0.9 m of the soil mantle had soil moisture measurements. Errors aside, no noticeable change occurred in the ET_S estimates between pre-restoration and post-restoration for the meadows. During the four years conducting the post-restoration study, we attributed the reduction of interception capture as the primary process forcing a decrease in depth to groundwater and small soil moisture increases following conifer removal.

4.3. Depth to Water Table Promoting Meadow Vegetation

Both Marian and Control Meadows experienced periods of groundwater depths during the growing season deeper than 1 meter, which is indicative of a dry meadow as classified by Weixelman et al. [23]. Following restoration, Marian Meadow had growing season water table depths similar to meadows dominated by *Poa pratensis and Bromus japonicas,* which are facultative and facultative upland species common in dry meadows [10,15]. Obligate and facultative wetland species have been shown to prefer depth to groundwater less than or equal to 0.7 m for approximately 65 days, and within 0.3 m from the surface for 42–47 days [15]. In this study, the post-restoration depth to groundwater was below these thresholds for 2016 and 2019 WY (Table 6). The high number of days with shallow groundwater depths in these two post-restoration years appear to be related to higher precipitation in late spring and early summer for Marian Meadow. The majority of snowmelt and surface runoff (Q_{SEOF}) occurs through April in response to saturated soil conditions. Greater precipitation after this time appears to maintain the wetter soil conditions into the growing season for Marian Meadow. The climate at Marian Meadow is unlikely to produce conditions conducive for wetland obligate species. The increase in days with groundwater close to the surface indicates hydrologic conditions post-restoration conducive to promoting facultative meadow vegetation.

4.4. Restoration Cost per Water Increase

There is little documentation of the cost benefit of meadow restoration from removal of encroached conifer. Most of the cost benefit for meadow restoration has been documented by pond and plug methods, where a degraded stream channel in a meadow is plugged to increase streambed elevation resulting in groundwater storage increases [7]. Cost information for 18 meadow restoration projects using pond and plug was compiled for the Sierra Nevada [30] and reported in cost per 1000 liters and 1000 gallons of water (Table 8).

Table 8. Cost in US dollars for Plug and Pond Method meadow restoration per 1000 liter (1000 gallons). Adapted from American Rivers, 2012 [30].

25 Percentile Cost/75 Percentile Increase in Storage	$1.32/1000 L ($5/1000 gal.)
Median cost/median increase in storage	$2.64/1000 L ($10/1000 gal.)
75 percentile cost/25 percentile increase in storage	$5.55/1000 L ($21/1000 gal.)

Using the residuals of the pre-restoration regression relationship for the four years post-restoration, the increase in groundwater storage in Marian Meadow is 113,710 m^3 (92.193 ac ft). The direct cost of conifer removal was $78,750 United States dollars (USD). This equates to $0.69 USD/1000 L or $2.62/1000 gal. This suggests the cost per increased water for Marian Meadow encroached conifer removal was at the low range of cost per water gained by Plug and Pond Methods. However, the cost of gaining permits and planning of the restoration was not included since the restoration was part of a larger timber harvest plan. Additionally, the landowner has invested a few days each year in removing lodgepole pine seedlings to maintain the restored meadow. Therefore, the cost of the increased groundwater storage is likely higher than our estimated $0.69 USD/1000 L. These additional costs should be considered in future restoration planning. Yet, even if the cost was double our estimate due to permitting, planning, and maintenance, this restoration effort was still at the low range of cost than the Plug and Pond Method.

5. Conclusions

Statistical analysis indicates that, during the four years following restoration from removal of encroached conifer on Marian Meadow, the slope and intercept of the regression relationship between soil moisture for Marian Meadow and the Control Meadow were statistically different. The change in slope of the post-restoration relationship indicated lower soil moisture during the dry period and higher soil moisture in the wet period of the year. An average decrease in depth to groundwater of 0.15 m for the four years post-restoration was statistically significant with the exception of year 3, which was a low precipitation year. There was no influence of the upslope harvest on the groundwater and soil moisture at Marian Meadow. We attribute this to the low level of thinning, 9% reduction of the basal area, adjacent to Marian Meadow.

The water budget for Marian and Control Meadows indicated the reduction of interception capture was the primary process forcing a decrease in depth to groundwater and increases in soil moisture during the wet season following restoration. The increase in groundwater storage was estimated to be 11.371 ha m (92.193 ac ft) for the four years post-restoration. This equated to a cost of $0.69 USD/1000 L ($2.62 USD/1000 gal.) shown to be at the low end of the cost range for meadow restoration by Plug and Pond Methods. There was an increase in growing season days with depth to groundwater of <0.3 m and <0.7 m, which are indicators of wetland vegetation, following restoration. The increase in days with groundwater close to the surface indicates hydrologic conditions post-restoration conducive to promoting, at a minimum, dry meadow conditions.

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