HYDROLOGIC RESPONSE FROM CONIFER REMOVAL AND UPLOPE HARVEST
FROM AN ENCROACHED MONTANE MEADOW

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by
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ABSTRACT

Hydrologic Response from Conifer Removal and Upslope Harvest on a Montane Meadow

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Meadows are crucial components to larger river watersheds because of their unique hydrologic and ecological functions. Due to climate change, over grazing, and fire suppression, conifer encroachment into meadows has accelerated. In some western regions, nearly half of all meadow habitat has been lost due to conifer encroachment. Restoration of these hydrologic systems requires tree removal. Many studies exist that address the issue of conifer encroachment in montane meadows, however, few studies focus on the role that conifer removal plays on the encroaching meadow. Furthermore, few studies exist that document the hydrologic change from conifer removal and further restoration steps, if any, to take after the removal. The overall research goal is to understand the efficacy of removal of encroached conifers from an encroached meadow (Marian Meadow) for successful meadow restoration. The objectives of this study are to determine (i) quantify the meadow hydrology following removal of encroached conifers, (ii) determine if forest tree removal adjacent to the meadow influences the meadow's hydrology, and (iii) test three common revegetation techniques for a formerly encroached montane meadow.

Marian Meadow is in Plumas County, CA at an elevation of 4,900 feet. This 45-acre meadow enhancement project is part of a 2,046-acre timber harvest plan implemented by the Collins Pine Company. Soil moisture sensors at one foot below the ground and water table depth sensors at four feet below ground were installed in Marian Meadow and a control meadow in September 2013, with additional soil moisture sensors at three-foot depth installed August 2015. The removal of encroaching conifers from Marian Meadow occurred in June 2015. Electrical Resistivity Tomography (ERT) was used to determine maximum water table depths and climatic variables were measured from a weather station as inputs for the water budget. A groundwater recession curve equation was used to model water table depths between water table depth sensor measurements and ERT measurements. A general linear model was used to determine any statistically significant difference in soil moisture and water table depths prior to and after conifer removal. Revegetation plots were installed at the start of the 2017 growing season to determine the establishment rate for three different techniques (BARE, WOOD, and EXISTING) and three different species of meadow plant. Technique BARE, which removes approximately 10 cm of top soil and disperses seed was statistically significant, yielding the highest population count. Another growing season data collection and control plot is required to draw further conclusions and recommendations.

The water balance indicated that the majority of Marian Meadow and the Control Meadow's water storage can be attributed to precipitation and not upland sources. This hydrologic characteristic is common in dry meadows. The statistical analysis indicated that measured water table depths increased on average by 0.62 feet following conifer removal. The first year following restoration and the second year following restoration yielded statistically significantly different water levels than pre-restoration water levels.

The third year following restoration is inconclusive until the end of the 2018 WY data set is available. On average, soil moisture increased by 6.43% following conifer removal and was statistically significantly different in all three post restoration years when compared to pre-restoration volumetric soil moisture content. Additionally, growing season (April through September) water table depths indicated that meadow vegetation communities could be supported in Marian Meadow following conifer removal. The removal of conifers from an encroached meadow appears to promote soil moisture and water table depth conditions indicative of a meadow and meadow plant community types.

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Chapter 1. Project Overview

1.1 Project Overview

This document includes four chapters: Project Overview, Introduction, and Literature Review (1), Conifer Removal and Upslope Harvest on Encroached Montane Meadow Methodology, Results, and Discussion (2), Meadow Plant Revegetation Research Methodology, Results, and Discussion (3), and a combined conclusion for the thesis (4).

1.1.1 Background Information and Problem Statement

Conifer encroachment is an invasion of conifers into a meadow ecosystem, promoting xeric conditions, caused by changes in climate, cessation of grazing, and long-term fire exclusions (Halpern & Swanson, 2009). Conifer encroachment has been occurring in the Sierra Nevada Mountain Range for the past 10,000 years (Wood, 1975). However with loss of meadow habitat in the Sierra Nevada acceleration of conifer encroachment is a major cause of meadow degradation in the Western United States (Rice et al., 2000). Conifer removal efforts are recognized as essential to successful meadow conservation efforts especially if done in the early stages of encroachment (Lang & Halpern, 2007). This study examines the hydrologic response of a meadow before and after removal of encroached conifer and thinning of the upslope watershed.

Many studies exist that address the issue of conifer encroachment in montane meadows, however, few studies focus on the role that conifer removal plays on the encroaching meadow. Furthermore, few studies exist that document the hydrologic change from conifer removal both within and adjacent to the meadow.

1.1.2 Statement of Overall Research Goal

The overall research goal is to understand the efficacy of removal of encroached conifers from meadows for successful meadow restoration

1.1.3 Research Objectives

- Quantify the meadow hydrology following removal of encroached conifers.
- Determine if forest tree removal adjacent to the meadow influences the meadow's hydrology.
- Test three different revegetation technique for a formerly encroached montane meadow by (a) analyzing the establishment rate of three different revegetation techniques and (b) analyzing the establishment rate of three different seed species on a formerly encroached montane meadow (detailed in Chapter 3).

1.1.4 Importance of the Project

Meadows are crucial components to larger river watersheds because of their unique hydrologic and ecological function (Loheide and Gorlick, 2006). The meadows in the Cascade Range, specifically, are important because they act as sinks by storing water during the spring and releasing flows during late summer thus adding to the larger watershed. A healthy meadow can act as a filter to downstream sediment movement, produce rare forage, and provide water for wildlife and plant species. The extent and integrity of these functions have degraded in the Western United States due to conifer encroachment (Rice et al., 2000). Restoration of these hydrologic systems requires tree removal preferably with post monitoring of intrinsic factors (biotic interactions) related to the hydrologic response. The assessment of the hydrologic response to conifer removal in Marian meadow aids land managers across the Cascade and Sierra Nevada range to understand the influence of conifer removal toward restoring meadow habitat.

1.1.5 General Approach

This research is a collection of field data, statistical analysis, and water budget compilation involving the Marian Meadow and a nearby control meadow. To detect a change in hydrology in the Marian Meadow from removal of encroached conifers and upslope forest harvest, a before after control intervention (BACI) study design was used. Measurements of climate, soil moisture, and groundwater depth were collected on the Marian Meadow and Control Meadow for approximately two years prior to restoration, starting September 2013. Electrical resistivity tomography was used periodically to improve the spatial interpretation of sub-surface water elevations. The Marian Meadow had conifers removed July 2015. Changes in hydrology were measured and documented for one year following the conifer removal (August 2015 – September 2016), and for an additional two water years (2017-2018) following a harvest of the forest surrounding the Marian Meadow (approximately 2,046 acres). Change detection was investigated through statistical comparison of soil moisture and water table depths, comparison of the before and after restoration water budget, and durations of water table depths.

1.1.6 Scope

Time:

- Data collection (groundwater depth, soil moisture data, and precipitation collections) of pre- and post-tree removal on Marian meadow to took place over 5 years (September 2013-April 2018).

Space/Location:

- Data collection limited to the entire study area (Marian meadow, 46 acres in the Northeastern portion of Cascade Range) and the nearby Control Meadow (50 acres) location in the eastern portion of the Southern Cascades bioregion.

Population:

- Limited to meadow study area habitat and population of encroached *Pinus contorta* (Lodgepole pine) tree species.

Variables:

- Limited to the dependent variables of groundwater depth (in feet) and soil moisture data (g/cm^3), and precipitation (in).
- Dependent variables containing atmospheric data are limited to PG&E weather stations located near Prattville, California, United States Forest Service precipitation station in Chester, California, and Control Meadow weather station.
- An evaluation of different regeneration treatments will also be measured by plant species types existing on the meadow area. The plant species types are limited to the random sample plot of the study area meadow.
- This study will not be evaluating conifer species characteristics or soil seed bank from either pre or post-conifer removal on the Marian or Control Meadow.

Equipment:

- The equipment is limited by funding which supported electric resistivity tomography, soil moisture probes, groundwater wells, water level loggers, and data loggers.

1.2. Review of Literature

1.2.1 Introduction

This literature review focuses on elements related to montane meadows of the Sierra Nevada mountain range including meadow hydrology, meadow water budget, conifer encroachment, vegetation removal, and conifer re-invasion.

1.2.2 Montane Meadows

Mountain meadows, found at elevations higher than 500 meters in mountainous terrain (Weixelman et al., 2011; Viers et al., 2013) make up less than one-tenth of the Sierra Nevada region yet they provide for over half of the vertebrate species, with one-fifth of the region's terrestrial vertebrate species dependence (Ratliff, 1985). A meadow is defined as a groundwater-dependent ecosystem type dominated by herbaceous plant species where woody vegetation may be present, which supports plants that use surface water and or shallow groundwater at some point during the growing season (Stillwater Sciences, 2012; Weixelman et al., 2011). As a result of fire suppression, cattle and sheep grazing, gold and gravel mining, land management, and water diversions for irrigation, the wet meadow ecosystems in the Sierra Nevada Mountain Range are some of the most degraded (Ankenbauer & Loheide II, 2016; Franklin & Fites-Kaufmann, 1996). The direct causes of degradation because of climate change and past land management includes channel widening, stream incision, water table draw-down, and associated drying of soils (Loheide & Booth, 2011; Loheide & Gorelick, 2007; Hammersmark, Dobrowski, Rains, & Mount, 2010, Choate, 1972). Soils of high-elevation meadows have high carbon (C) and nitrogen (N) densities which are important for storing water, retaining potential pollutants, and sustaining stream flows (Cole, Van Wagendonk W.,

McClaran, Moore, & McDougald, 2004; Huntsinger, 2002; Norton et al., 2011; Peterson et al., 2001). Properly functioning headwater streams remove N (Norton et al., 2011) and furthermore, properly functioning montane riparian meadows mitigate N flow from Sierra Nevada catchments impacted by elevated N deposition (Norton et al., 2011; Sickman et al., 2003). Removal of N is important for the protection of downstream waters susceptible to eutrophication (Norton et al., 2011). It is estimated that wetlands remove 20-21% of the total anthropogenic N load in the United States, and 17% worldwide (Jordan, Stoffer, & Nestlerode, 2010; Norton et al., 2011). The loss of C and N from degrading wetlands is a central source of greenhouse gases (Kayranli et al., 2010) as well as reduced N retention, loss of habitat, and decreased water quality (Elmore and Kauffman, 1994).

1.2.3 Meadow Hydrology

There are four primary water sources for montane meadows: snowmelt, overland flow within the basin, surface flow entering via stream and spring networks, and direct precipitation (Lord et al., 2011). These inputs fluctuate depending on the surrounding landscape, slope, geology, and geomorphology of the meadow. The regional groundwater flow significantly influences meadow groundwater flow in the Sierra Nevada and Cascade Mountain Range (Loheide et al., 2009) and in general, mountain ranges and flanking alluvial fans are groundwater recharge areas (Lord et al., 2011). The most significant input for meadows of the Sierra Nevada is snowmelt which not only provides surface water, but also recharges groundwater which eventually provides soil moisture and baseflow during the growing season (Viers et al., 2013). Snowmelt comes from the snowpack which is a reliable source in the Sierra Nevada mountain range that is made up

of snowmelt pulses leading to periods of saturation and infiltration. These pulses help to compile the groundwater table elevation, which is typically less than one meter, and are essential for hydrophilic meadow plants (Loheide and Gorelick, 2007). A high groundwater table results from greater winter snowpack during cool-moist episodes and is governed by infiltration of sustained meltwater discharge from snowpacks (Gross and Coppoletta, 2013; Wood, 1975).

The meadow outputs in the Sierra Nevada Mountain Range include overland runoff and outflow, seepage through vadose zone, and evapotranspiration (ET). ET is described as the evaporation of water from soil, water bodies, snow cover, and transpiration of water through leaf stoma. ET rates are determined by relative humidity, air temperature, net solar radiation, and wind speed (Allen et al., 1998). ET rates are increasingly higher during the summer when rainfall is less. In the United States, approximately 67% of precipitation re-enters the atmosphere through ET (U.S Geological Survey, 1990). ET depends on rooting depth, depth to the water table, and vegetation type and amount. ET rates are influenced by locality including: vegetation distribution, vegetation specific characteristics such as rooting depth and stomatal resistance, soil moisture content, and the distribution of near surface groundwater or water bodies (Van Osobree, 2014). The potential evapotranspiration (PET) of a land surface assumes uniform land cover by vegetation and unlimited soil moisture conditions. Soil moisture and vegetation present on a given site will determine the actual evapotranspiration (AET). ET is measured directly using the eddy covariance method or lysimeter stations, technique used to measure and calculate turbulent fluxes within the atmospheric boundary layer (Burba & Anderson, 2006). Evapotranspiration is often modeled due to

the complexity and expense of directly measuring ET and the lack of available site-specific atmospheric data. Five ET models that have been extensively utilized in forest ecosystems (in order of decreasing complexity) are the Shuttleworth-Wallace, Penman-Monteith, Penman, McNaughton-Black, and Priestley-Taylor (PT) models. Despite its simplicity, a modified PT model has been shown to closely approximate physically measured ET in the Sierra Nevada Mountains and other Mediterranean climates (Van Osobree, 2015; Fisher et al., 2005; Utset et al., 2004).

The vegetation type in a montane meadow is influenced by the seasonal depth to groundwater and surface water availability (Still Water Sciences, 2012). Meadow plant community composition varies with groundwater hydrology and soil moisture (Ratliff, 1985; Weixelman et al., 2011; Still Water Science, 2012). The water balance formula for basic montane meadows is the following:

$$\text{Change in Meadow Groundwater and Soil Moisture} = \text{Precipitation} - \text{Evapotranspiration} - \text{Runoff}$$

Typically, Precipitation, runoff, and evapotranspiration are the dominate factors in the water balance (Bales et al., 2011). The transpiration rates of vascular plants determine which flora may colonize within a given ecosystem. ET is effected by climate factors including relative humidity, air temperature, net solar radiation, and wind speed (Miller et al., 2014).

1.2.4 Snow Water Equivalent (SWE) and Snow Melt

Snow is an important precipitation input, dominating more than half of the terrestrial areas in the Northern Hemisphere; snowmelt provides freshwater for one fifth of the world population and roughly one fourth of the global gross domestic product. In many

areas of the world snow is the primary water resource (Beniston, 2003; McCreight, Small, & Larson, 2014). An important feature of snow is snow water equivalent (SWE), which is the amount of water that results when snow is melted. There are different phases of snowmelt: the accumulation period and the melting period. The accumulation period is general increase of snowpack water equivalent prior to the melt period which includes negative net inputs of energy, and the average snowpack temperature is decreasing. The melting period of a seasonal snowpack begins when the net input of energy to it becomes more or less continually positive, and it can usually be separated into three phases: warming phase, ripening phase, and output phase. The warming phase occurs when the average snowpack temperature increases more or less steadily until the snowpack is isothermal at 0 degrees Celsius. The ripening phase occurs during which melting occurs, but the meltwater is retained in the snowpack. And, the output phase occurs after the snow is ripe and further inputs of energy produce water output (Dingman, 2002).

There are a variety of methods to measure SWE in montane areas including airborne techniques, satellite remote sensing techniques, and land cover models used to distribute and interpolate SWE (Elder, Rosenthal, & Davis, 1998). Snow water equivalent can be calculated using the following equation (Dickinson & Whitley, 1972; Steppuhn, 1976; Sturm et al., 2010):

$$SWE = h_s * \frac{P_b}{P_w} \quad (1)$$

Where:

SWE = snow water equivalent (cm)

h_s = snow depth (m)

P_b = density of snow (1 g cm⁻³)

P_w = density of water (1 g cm^{-3})

As an alternative to direct SWE measurements, measuring the dynamic parameters (h_s) and estimating the conservative parameters (p_b) is the most practical and potentially accurate method of modelling SWE. The accuracy of collecting Global Positioning System (GPS) snow depth measurements in the past has been shown to be similar to field measurements and nearby ultrasonic snow depth measurements (Larson et al., 2009; McCreight et al., 2014). Nievinski and Larson (2014) determined the difference between GPS snow depth retrievals and single snow pole depth observations over multiple years at two sites and manual depth surveys at a third site in a single year and found that there was a high correlation between GPS snow depth and field site measurements (> 0.97). In a study by McCreight and Larson (2014) that accessed and compared the accuracy of GPS-based snow depth, density, and SWE data at 18 GPS sites with manual observations. Modelled snow bulk density, based on GPS snow depth time series, closely matched density measured in a single snow pit at each validation site. Combining GPS-based depth and density yields an accurate estimate of SWE over its observed range, from 0 to 60 cm. Furthermore, these results showed that the near real-time GPS snow products have errors small enough for monitoring water resources in snow-dominated basins (McCreight et al., 2014).

Snowmelt runoff may be determined using various methods. Two common models for measuring snowmelt runoff include the energy balance method and the temperature index method. The energy balance method is a physical approach to modelling the runoff from snowpack. This method considers and quantifies energy flux on the interfaces of atmosphere-snow-soil and is a simplified description of energy exchange at the

atmosphere – snowpack – ground surface interface. The temperature-index method is widely used for modeling snow accumulation and melting. This method comes from the linear dependence of snowmelt on the air temperature. Incoming longwave radiation and sensible heat represent $\frac{3}{4}$ of total energy balance of the snowpack (Hock, 2003; Jenicek et al., 2012). The faults of the model originate from temperature fluctuations near zero (Jenicek and Taufmannova, 2009; Jenicek et al., 2012). The mean daily air temperature indicates no snowmelt; however, the positive air temperature which occurs during day could cause the snowmelt (Hock, 2003; Jenicek et al., 2012). Because of the difficulty of fulfilling data requirements in the energy balance method, the temperature index approach may be used to compute snowmelt runoff.

1.2.5 Snow Density

Snow density typically requires at least temperature and precipitation information as inputs to estimate the bulk density of a snowpack. The bulk density is then used to convert snow depth into SWE. There are a variety of models that predict snow density, with varying ranges of accuracy depending on the age of the snow. Since snow depth is the more important factor in determining SWE, errors in modeled density have a limited effect on SWE errors when depth is observed accurately (McCreight et al., 2014). The density of new snow varies per air temperature and time at which the snow meets the ground. The density of snow ranges from 5% at 14 ° F and about 20% at 32 ° F (NRCS, 2012).

Jonas et al. (2009) fit a simple linear regression model (Equation 2), where density (ρ) is a linear function of depth (h) and the parameters (a, b) which are solved separately both monthly and over three elevation bands. The Jonas model is tuned

monthly (Jonas, Marty, & Magnusson, 2009; Pistocchi, 2016). This model results in errors associated with the spatial variability of snow density at a site and suggest that 10-20% is a typical range for the within-site variability of repeated p_b measurements. The authors also suggest that the model not be used to convert time series of h_s into SWE at daily resolution or higher (Jonas et al., 2009).

Another model that predicts snow density is the Sturm model which uses snow depth, age of snow (DOY) and snow class found from geographical coordinates of the location as input variables (Sturm et al., 2010; Sturm, Holmgren, & Liston, 1995). The Sturm model predicts snow density and is applicable wherever weather stations are available and representative (Equation 2). Snow classes for each location (i.e. meadow) are found by the snow classification scheme (Table 1). The snow class is classified by the seasonal snow cover proposed from Sturm et. al. (1995). There are six snow class types which are defined by physical characteristics of the snow and the snow layers. These classes are also derived by using three different climate variables given by the weather stations at the different location- wind, precipitation, and air temperature, in a binary classification system.

$$p = (p_{\max} - p_0) (1 - \exp(-k_1 h - k_2 DOY)) + p_0 \quad (2)$$

Where:

$p_{\max}$ = maximum bulk density

p_0 = initial density of the individual snow layer

DOY = Counter of the day of the year (set to 1 on January 1st, with October 1st (-92) to 30th of June (+ 181) to account for the winter season extending across two years in the northern hemisphere).

k_1 and k_2 = the densification parameters for depth

Table 1. Snow Class and corresponding default values for different snow types. (from Sturm et al., 1995)

Snow class	$\rho_{\max}$	ρ_0	k_1	k_2
Tundra	0.3630	0.2425	0.0029	0.0049
Maritime	0.5979	0.2578	0.0010	0.0038
Prairie	0.5940	0.2332	0.0016	0.0031
Alpine	0.5975	0.2237	0.0012	0.0038
Taiga	0.2170	0.2170	0.0000	0.0000

However, the snow densities predicted from this model were in most cases underestimated for the tundra snow class (Sturm et al., 2010). And later pointed out, both the Jonas and Sturm models embed the assumption that there is a positive correlation between snow density and depth, which cannot be applied for density estimates at a daily time step (McCreight & Small, 2014b; Pistocchi, 2016).

A study by McCreight & Small (2014b) compare their model known as the South Tyrol model (ST model; Equation 3) with the Jonas and Sturm models. The ST models uses snow depth anomalies, applied at daily steps when density measurements are available for calibration within distances of tens of kilometers from the point of estimation (McCreight & Small, 2014b)

$$\text{ST Model: } p = p_0 + K (DOY + 61) \quad (3)$$

Where:

p = snow density

p_0 = 200 kg/m³

K = 1 kg/m³ per day.

DOY = 150 (end of May)

The results of the McCreight & Small (2014b) study note that both the Jonas and Sturm models underestimate density relative to ST model, suggesting that the region may tend to Maritime snow type characteristics, but that overall the differences among the three models are small. The study suggests that a simpler model should be preferred in the absence of contrary evidence. The study also suggests that when no snow density measurements are available, then the ST model, as well as a model calibrated by Mizukami and Perica (2008), for predominantly Alpine or Maritime type snow in the western US, can represent a reasonable first guess estimate when no specific density data are available (McCreight & Small, 2014b).

1.2.6 Meadow Vegetation

In the state of California a wetland “shall be defined as land where the water table is at, near, or above the land surface long enough to promote the formation of hydric soils or to support the growth of hydrophytes, and shall also include those types of wetlands where vegetation is lacking and soil is poorly developed or absent as a result of frequent and drastic fluctuations of surface water levels, wave action, water flow, turbidity, or high concentrations of salts or other substances in the substrate.” (14 CCR 13577).

In wet meadow systems, the vegetation community type is highly correlated with water-table depth, indicating that local hydrology is the most important factor determining vegetation community type and distribution (Allen-Diaz 1991; Stromberg et al. 1996; Castelli et al. 2000; Darrouzet-Nardi et al. 2006; Dwire et al. 2004; Hammersmark 2008). It is also equally important to note that specific hydrologic conditions may sustain multiple vegetative community types.

Hammersmark (2008) determined that wet-meadow vegetation is constrained by two hydrologic features: (1) the early growing season moisture conditions must be sufficiently wet to cause waterlogged and anaerobic conditions which wet-meadow vegetation can tolerate but is intolerable to upland vegetation communities and (2) sufficient moisture must remain during the late-growing season to support plant growth and reproduction. Hammersmark also found that mean water table depth (WTD) was not as influential in wet-meadow plant species presence as minimum (shallowest) water-table depth and the number of days that the water table was within 30 cm (approximately 1 foot) of the soil surface. The root zone for typical wet meadow plant species ranges from 30 cm to 70.1 cm (1 foot to 2.3 feet). These were the most distinguished variables among the vegetation communities.

Hammersmark examined the relationship between vegetation communities and growing season water-table depths in a hydrologically restored riparian meadow (pond-and-plug). He determined the number of days the WTD was at 0 cm, < 30 cm, and <70 cm for four different community types ranging from most xeric to most mesic and hydric (*Poa pratensis* / *Bromus japonicus*, *Carex nebrascensis* / *Juncus balticus*, *Downingia bacigalupii* / *Psilocaphus brevissimus*, and *Elocharis macrostachya* / *Elocharis acicularis*) (Table 2). The number of days the WTD was < 0 cm represents the number of days a given plot was inundated. The number of growing-season days that the water-table depth was less than 1 foot (30 cm) in the meadow represents the root zone typical of mesic and hydric herbaceous meadow communities. And, the number of days the WTD was less than or equal to 2.3 feet (70.1 cm) from the surface of the meadow indicate the root zone typical for xeric herbaceous meadow communities. The most xeric community

type (*Poa pratensis* / *Bromus japonicus*) had WTD within 2.3 feet (70.1 cm) and 1 foot (30 cm) from the soil surface for 42 days and 22 days, respectively. Conversely, the mesic community type (*Downingia bacigalupii* / *Psilocaphus brevissimus*) had WTD within 2.3 feet (70.1 cm) and 1 foot (30 cm) from the soil surface for approximately 65 days and 42 days.

Table 2. Growing season water table depths (WTD) for community types with varying compositions of wetland species (adopted by Hammersmark et al, 2009)

Community	<i>Eleocharis macrostachya</i> / <i>Eleocharis acicularis</i>	<i>Downingia bacigalupii</i> / <i>Psilocaphus brevissimus</i>	<i>Carex nebrascensis</i> / <i>Juncus balticus</i>	<i>Poa pratensis</i> / <i>Bromus japonicus</i>
WTD Average (ft)	0.61 ± 0.92	1.92 ± 0.65	1.98 ± 0.41	3.92 ± 1.46
WTD Minimum (ft)	-2.17 ±	-1.1 ±	-0.73 ±	0.4 ± 0.79
WTD Maximum (ft)	3.11 ± 0.79	5.06 ± 0.36	4.51 ± 0.83	7.59 ± 2.43
WTD range (ft)	5.28 ± 0.66	6.15 ± 1.31	5.23 ± 1.00	7.19 ± 2.19
Days WTD < 2.3 ft	91.3 ± 20.5	65.4 ± 8.8	65.5 ± 7.5	41.6 ± 18.3
Days WTD < 1.0 ft	65.4 ± 16.1	46.8 ± 18.0	42.4 ± 10.2	22.3 ± 11.4
Days WTD < 0 ft	65.4 ± 16.1	33.7 ± 18.3	24.9 ± 8.4	9.8 ± 7.1

1.2.7 Conifer Encroachment

In the Western Cascade and Coast Ranges of Oregon, conifer encroachment has resulted in as much as 50% meadow loss since the mid-1940's (Dailey, 2007; Takaoka and Swanson, 2008; Celis, Halpern, & Jones, 2017). There is no one single variable that explains the encroachment of conifers into meadows. The hypothesized causes of conifer encroachment include warming climates, grazing, anthropogenic uses, and reduced snow packs depending on the location of the woody plant invasion: upland or lower elevation meadows (Gross and Coppoletta, 2013). Fire influences the structure and composition of woodland ecosystems. Where fire is excluded from woodlands and savannas, substantial changes occur (Grossmann and Mladendoff, 2007, Hiers *et al.* 2007), frequently, increases in woody stem densities and advancement of forest boundaries lead to shading of herbaceous layers (Hoffman *et al.* 2003, Devine *et al.* 2007). Meadow forbs and grasses vary in the rate at which they dieback (Haugo and Halpern, 2007). Wet meadows

generally show less effects of conifer encroachment than dry meadows and less episodic patterns of successional change (Wood, 1975; Gross and Coppoletta, 2013).

Conifer encroachment in the Sierra Nevada is dominated by lodgepole pine (*Pinus contorta*) and in some cases Grand fir (*Abies grandis*) (Griffiths et al., 2005). Approximately 60% of montane meadows in Sequoia Kings Canyon National Park and upwards of 42% of meadows in the Lake Tahoe basin are comprised of saplings and seedlings of *Pinus contorta* (Gross and Coppoletta, 2013). *Pinus contorta* (lodgepole pine), has a wide tolerance for hydrologic conditions and plays a key role in its ability to colonize meadows while other tree species maintain their current position (Burns & Honkala, 1990). Depending on elevation and geomorphic position, *Pinus contorta* may colonize meadows opportunistically during times of drought to avoid plant water stress (Gross & Coppoletta, 2013). Further, fire suppression in forests has resulted in decreased fire frequency, creating an increase in the density of mid-elevation pine forest and subsequent encroachment of *Pinus contorta* into meadows (Vankat, 1977).

Lodgepole pine (*Pinus contorta*) occupies sites on high mountains of the Western States. It occurs in some places where less than 20 percent of the area is gently sloping and at elevations ranging from 4,000-11,500 feet. Lodgepole pine occupies sites where the frost-free season is 80-120 days, but it is a resilient species that can with stand frost at any time of the year. This species can grow with rainfall averages of 20-50 inches of annual precipitation. Lodgepole pine stands receive 50-60 percent of their annual precipitation in the period of December to March. These pine stands typically have low productivity of understory flora limiting the distribution and frequency of habitual wildlife (McNab et al., 2005).

1.2.5 Meadow Restoration and Regeneration

Successful restoration of degraded meadows could be signaled by a higher groundwater table, improvement of water quality in streams, increase in seasonal soil moisture and the return of endemic meadow species. There are many challenges land managers must overcome to restore meadows encroached by conifers. The impact of conifer encroachment on meadows can lead to adverse effects on soils and vegetation and dramatic consequences for species composition, diversity, and other ecosystem services (Haugo and Halpern, 2007). Initial encroachment is sparked by biotic interactions among the root zones of tree species surrounding the meadows to produce greater rate of sapling survival (Rice et al., 2012; Haugo et al., 2013). One obstacle to meadow restoration is the occurrence of biogeochemical alterations to meadow soils following initial encroachment, which leads to re-establishment of conifers in a meadow following vegetation removal (Halpern et al., 2010) (as cited in Van Oosbree, 2015).

Lang (2007) examined the changes in the soil seed bank associated with conifer encroachment of montane meadows in the western Cascade Range of Oregon. Seed bank composition, ground vegetation, and forest-age structure were quantified for 209 samples representing a chrono-sequence of conifer encroachment including: open meadow (characterized by zero to few trees), young forest (high density of stems <75 years old) and older forest (tree ages 95 to >200 years). Soil seed bank samples were collected from each of the 209 samples. The seed bank was comprised of 44 taxa and 2,332 germinants/m², but dominated by native ruderals (16 species comprising 71% of germinants). Greater than 70% of meadow species were absent from the seed bank. There was no difference in species seed bank composition between open meadow and young forest ($A=0.00283$, $p=0.089$) but significant differences between open meadow and old

forest ($A = 0.0472$, $p < 0.0001$). The results showed that there is limited potential for recovery of most meadow species via seed bank, and therefore, a natural re-establishment of these meadow species will require seed dispersal or gradual vegetative spread. Additionally, response to conifer encroachment may reflect differences in species' physiological rather than morphological variability, or species may be responding to changes in resources other than, or in addition to, light (Celis, Halpern, & Jones, 2017). Following conifer removal, forest understory species will be at a disadvantage because of the lack of shade once created by overstory shading. The lack of a soil seed bank is a major limitation to restoration of encroached meadows (Let and Knapp, 2005).

In Tuolumne meadows in Yosemite, where intense grazing occurred from 1860-1891, has undergone conifer invasion and resulted in the loss of meadow vegetation and soil degradation. Intact perennial sods of meadow vegetation are resilient to minor disturbances such as fire and light grazing, as long as the structure of the rhizome network remains intact. Once that network is degraded, the perennial meadow plants may take centuries to reestablish because of erosion and upland plant establishment (Roche *et al.*, 2006). This process may be encouraged by intensive needle ice formations in the bare soils which cause uprooting of slow growing plants. Additionally, the meadow may be locked in an alternative state of vegetation composition, and soil forming processes. Climate change is also producing warmer and longer summers, with drier meadow soils, preventing ideal reestablish conditions. It's possible that the only potential approach to meadow vegetation restoration will include human aided restoration approached, including seeding and planting of native sedge, grass, and rushes, deer exclusion, and possibly experimental removal of small mammals from study plots (Roche *et al.*, 2006).

Meadow restoration performed by removing encroaching vegetation without the subsequent implementation of selective slash or broadcast burning have demonstrated that conifer removal alone is sufficient for short-term restoration of some encroached meadows, especially meadows with a history of infrequent wildfire (Swanson et al., 2007; Halpern et al., 2012). Additionally, the increases in soil nitrogen and exposure of mineral soil from broadcast burning and slash burning may allow ruderal species suitable establishment.

Figure 1: Mean (+1 SE) richness and density of species and germinants by functionality (habitat affinity) among the three stages of encroachment; p values are from ANOVA or Kruskal-Wallis tests. Differing letters above bars indicate significant differences in means (from Lang et al., 2007).

1.2.4 Forest Management and Water Yield

Vegetation removal is one type of restoration technique for conifer-encroached areas in the Sierra Nevada mountain range and is not well studied for meadow ecosystems. The influence of forest management practices on water yield has been well studied. Hibbert (1967) who reviewed results from 39 catchment experiments throughout the world, made the following generalizations:

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable, and, for the most part, unpredictable.

Since Hibbert's review, Bosch and Hewlett have examined 55 additional experiments for a total of 94 experiments and justified general conclusions: no experiments in deliberately reducing cover caused reductions in yield, nor have any deliberate increases in cover caused increases in yield. Furthermore, the review concluded that coniferous forest, deciduous hardwood, brush, and grass cover (in that order) have a decreasing influence on water yield of the source areas in which these covers are manipulated. Many studies since then have been documented that show both an increase in streamflow following removal of trees (Bosch and Hewlett, 1982; Stednick, 1996; Brown et al., 2005; Flerchinger et al., 2016) and inversely, a decrease in streamflow following tree die-off (Guardiola-Claramonte et al., 2011; Biederman et al., 2015; Flerchinger et al., 2016). Reasons attributed to a decrease in streamflow include an increase in understory cover, an increase in solar radiation reaching the understory, and an increase in sublimation and ET (Biederman et al., 2014, 2014b; Harpold et al., 2014; Flerchinger et al., 2016).

The hydrologic processes most influenced by land use change are evapotranspiration (ET), recharge, and runoff (Batelaan et al., 2003). Generally, the hydrologic responses of vegetation change are most extreme directly after management activities and then the system returns to baseline conditions in subsequent years. These extreme changes in hydrology are due to decreases in ET, interception, greater accumulation of snow in open areas, and changes in timing of snowmelt (Troendle et al., 2001; Watson et al., 2001; Hubbart et al., 2007; Ryu et al., 2009) (as cited by Sanford, 2016). One study analyzed a paired watershed from 1982 to 1992 in Colorado and concluded that the snowpack was 9% greater and the water yield increased 17% in forest harvest openings compared to unharvested areas (Troendle et al., 2001) (as cited by Sanford, 2016).

Sierra Nevada is threatened to meet water demands due to land management practices, climate change, drought, and a growing population. To address this issue the Nature Conservancy analyzed potential water yield impacts from forest thinning operations in the Sierra Nevada from over 150 studies. From 2002 to 2012 the USFS thinned approximately 10% of the Feather River watershed in the Sierra Nevada. The estimated increase in water yield because of thinning operations was 2% to 6% (97,000 to 285,000 acre feet). Thinning operations during the same time period in the Feather River, American River, Yuba River, Battle Creek, Butte Creek, Deer Creek, Mill Creek, Mokelumne River, Truckee River, Cosumnes River, and Bear Creek watersheds resulted in an estimated increase water yield of 165,395 to 505,141 acre feet (Podolak et al., 2015). The results of the literature review suggest that if the current scale of forest

restoration is increased three-fold, there could be up to a 6 percent increase in the mean annual streamflow for individual watersheds (Podolak et al., 2015).

Chapter 2. Conifer Removal and Upslope Harvest on an Encroached Montane Meadow

2.1 Methodology

2.1.1 Study Area

2.1.1.1 Location of Marian Meadow

The study area, Marian Meadow and the Control Meadow, are located within the Upper Feather River Watershed (UFRW) in Plumas County, California (Figure 2). Marian Meadow is directly adjacent to Highway 36 approximately 10 miles west of Lake Almanor and encompasses approximately 45 acres (0.182 km²). The Control Meadow is located approximately 4 miles west of the Marian Meadow, north of highway 36 in the adjacent Tehama County, California (Figure 3) and encompasses approximately 20.3 acres (0.082 km²). Both meadows are tributary to the Sacramento River and are surrounded by mixed conifer pine forest.

2.1.1.2 Southern Cascade Bioregion

The Cascade range extends from British Columbia, Canada, south to northern California where it meets the Sierra Nevada (Skinner, 2014). This area is an undulating, glaciated, volcanic plateau punctuated by isolated buttes and cones. The elevation along this region varies from 4,000 to 8,000 ft (1220 to 2500 m), and is intermediate between subalpine zone and Southern Cascades. Soils in the Southern Cascade Range are generally andisols and spodosols however, the soil series varies depending on the area within the Southern Cascade Bioregion (McNab et al., 2005).

This area is mostly comprised of cryic soils supporting mixed coniferous forests including mountain hemlock (*Tsuga mertensiana*), lodgepole pine (*Pinus contorta ssp. murrayana*), and Pacific silver fir (*Abies amabilis*) (Thorson et al., 2003). The understory

in this area typically includes woodrush (*Carex luzulina*), Prince's pine (*Chimaphila umbellata*), lupine (*Lupinus sp.*), and white veined shinleaf (*Purola picta*). The open meadows at the higher elevation of this range support Shasta buckwheat (*Erigonum pyrolifolium*), knotweed (*Polygonum sawatchense*), and sedge species (*Carex sp.*) including the subspecies Bolander's sedge (*Carex bolanderi*), golden fruited sedge (*Carex aurea*), ample leaved sedge (*Carex amplifolia*), and blister sedge (*Carex vesicaria*)(Database, 2014). The Southern Cascade Range is colder compared to other areas of the Cascade Range and consist of longer summer droughts and more intermittent streams rather than ephemeral streams that comprise the Cascade Crest Montane Forest (Thorson et al., 2003).

Figure 2: The study area, Marian Meadow, located in Plumas County, California, along the Southern Cascade Range.

Figure 3: The Control Meadow, located north of Highway 36 in Plumas County, California.

2.1.1.3 Climate of Southern Cascade Bioregion

The climate of the Southern Cascade Bioregion is Mediterranean with wet, cool winters and dry, warm summer. The nearest city to Marian Meadow is Chester, California. The average annual precipitation is 29.77 inches and the average annual snowfall is 17.06 inches. Precipitation in this area generally occurs from October to May. The temperature in the summer months range from 59.64 °F to 66.29 °F and the temperatures in the winter months range from 31.39 °F to 35.25 °F (Table 3) (U.S. Climate Data, 2016)).

Table 3. Average temperature (°F) and snowfall for each month ranging from 2007 to 2016 in Chester, California (U.S. Climate Data, 2017).

Average Monthly Climate for Chester, CA from historical data ranging from 2007 to 2016 (U.S. Climate Center, 2017)			
Month	Temperature (°F)	Precipitation (in)	Snowfall (in)
January	31.9	4.143	4.35
February	35.245	4.267	0.794
March	39.11	5.185	1.981
April	43.62	1.942	0.275
May	51.295	1.452	0
June	59.64	0.754	0
July	66.29	0.422	0
August	65.42	0.12	0
September	60.095	0.229	0
October	48.99	2.425	0.5
November	38.52	3.12	5.238
December	31.385	5.712	3.918

2.1.1.4 Fire Climate and History of Southern Cascade Bioregion

This region is susceptible to the critical fire weather conditions of high winds and low humidity. There are three types of fire weather conditions that occur during the dry period: (1) Pacific High-Post Frontal (Post-Frontal), (2) Pacific High-Pre Frontal, and (3)

Subtropical High Aloft. Frequent fires used to occur in the Southern Cascade Region because of the combination of Mediterranean climate and commonality of lightning ignitions, and the widespread use of fire by native people. Fire suppression began in 1887 due to a combination of logging of fire resistant trees and a climactic warming trend (Morford, 1984). Fire suppression significantly alters natural disturbance regimes, which alter the hydrologic and vegetative qualities of a watershed. Rather than a full range of seral stage trees, a highly fragmented landscape that consists of late-seral stage trees have developed. In addition to the biological changes, the absence of periodic natural disturbances has also resulted in declines in rangeland integrity and increases in exotic species invasions (Hogan & Fund, 2015).

2.1.2 Restoration and Upslope Harvest

Marian meadow had encroached conifers removed from the meadow during late spring and completed by July 2015. An average of 143 ft²/acre basal area of primarily lodgepole pine was removed from the Marian Meadow. From fall 2016 until Winter 2017 a forest harvest of the watershed above Marian Meadow occurred. A basal area of 132 ft²/acre remained for the 2017-2018 water year. For understanding the sequence of events associated with the Marian Meadow refer to figure 4 below

Figure 4: Timeline of events associated with study of Marian Meadow restoration (adopted from Van Oosbree, 2015).

2.1.2.1 Soil Type

The existing soil type on the Marian Meadow is mapped as Holland-Skalan families association (0 to 35 percent slopes). This soil is considered well drained with a medium runoff class and an average depth to water table of 80 inches with a moderate available water storage. A typical profile of this soil series consists of a cobbly sandy loam surface to a depth of 14 inches, very cobbly loam to a depth of 60 inches, and weathered bedrock to a depth of 79 inches (Soil Survey Staff, 2017). The bulk density of soil at a 1.0 ft (0.3 m) depth was $1.40 \pm 0.13 \frac{\text{g}}{\text{cm}^3}$, yielding a porosity of 47.0% and the bulk density of soil at a 2.00 ft (0.61 m) depth was determined to be $1.48 \pm 0.12 \frac{\text{g}}{\text{cm}^3}$, yielding a porosity of 44.3% (VanOosbree, 2015).

The existing soil type on the Control Meadow is mapped as 80% Elam very gravelly loamy sand (map unit EmB) (0 to 8 percent slopes) and 20% Cohasset stony loam (map unit CgD) (10 to 30 percent slopes) (Soil Survey Staff, 2017). EmB soil is considered somewhat excessively drained with a negligible runoff class and an average

depth to water table of more than 80 inches with a very low average water storage. A typical profile of this soil series consists of a very gravelly loamy sand surface layer to a depth of five inches, a very gravelly sandy loam layer to a depth of 40 inches, cemented layer to a depth of 45 inches, and a very gravelly sandy loam to a depth of 60 inches.

CgD soil is considered well-drained soil with a high runoff class and a depth to water table more than 80 inches with a very low average water storage. A typical profile of this soil series consists of a stony loam surface layer to a depth of 15 inches, a cobbly loam layer to a depth of 40 inches, and an unweathered bedrock to depth of 44 inches (Soil Survey Staff, 2017). The bulk density of soil at a depth of 1.0 ft (0.3) on the CM was $1.53 \pm 0.13 \frac{\text{g}}{\text{cm}^3}$, yielding a porosity of 42.0 % and the bulk density of soil at a depth of 2.00 ft (0.61 m) was $1.59 \frac{\text{g}}{\text{cm}^3}$, yielding a porosity of 39.9%. (Van Oosbree, 2015).

2.1.2.2 Vegetation Type

Marian Meadow, prior to the conifer removal, was surveyed by Lassen National Forest employees (2014) and was comprised of a variety of trees, shrubs, forbs, and graminoids such as lodgepole pine (*Pinus contorta* ssp. *murrayana*), mountain whitethorn (*Ceanothus cordulatus*), nebraska sedge (*Carex nebrascensis*), and pinewoods horkelia (*Horkelia fusca*) (Table 4). The surrounding habitat type is dominated by lodgepole pine stands (CNPS: *Pinus contorta* ssp. *murrayana* Alliance) with scattered mixed conifers including Douglas fir (*Pseudotsuga menziesii*), Jeffrey pine (*Pinus jeffreyi*), white fir (*Abies concolor*), and some sugar pine (*Pinus lambertiana*) and western white pine (*Pinus monticola*) species. Since the conifer removal in 2015, the Marian meadow is mostly dominated by a variety of graminoids and forbs, with occasional scattered tree and shrub seedlings.

Table 4. Marian Meadow plant species list adapted from Collins Almanor Forest Plant Survey form by surveyors: K. Bovee, L. Thomasma, J. Blaufuss, A. Juska, E. O’Kelly, G. Gerbatz.

Collins Almanor Forest Plant Survey		
Trees	Forbs	<i>Perideridia</i> sp.
<i>Pinus contorta</i> ssp. <i>murrayana</i>	<i>Achillea millefolium</i>	<i>Polygonum douglasii</i>
<i>Abies concolor</i>	<i>Acmispon americanus</i>	<i>Polygonum polygaloides</i>
<i>Pinus jeffreyi</i>	<i>Allium campanulatum</i>	<i>Potamogeton natans</i>
Shrubs	<i>Antennaria luzuloides</i>	<i>Potentilla gracilis</i>
<i>Arctostaphylos patula</i>	<i>Apocynum androsaemifolium</i>	<i>Poteridium annuum</i>
<i>Ceanothus cordulatus</i>	<i>Bistorta bistortoides</i>	<i>Ranunculus aquatilis</i>
<i>Frangula rubra</i>	<i>Calochortus</i> sp.	<i>Rorippa curvisiliqua</i>
<i>Symphoricarpos mollis</i>	<i>Calyptridium umbellatum</i>	<i>Rumex acetocella</i>
Graminoids	<i>Cirsium scariosum</i>	<i>Sidalcea glaucescens</i>
<i>Agrostis scabra</i>	<i>Clarkia</i> sp.	<i>Sidalcea oregana</i>
<i>Alopecurus geniculatus</i>	<i>Claytonia rubra</i>	<i>Silene nuda</i>
<i>Bromus carinatus</i>	<i>Cryptantha</i> sp.	<i>Symphyotrichum spathulatum</i>
<i>Bromus tectorum</i>	<i>Danthonia unispicata</i>	<i>Taraxacum officinale</i>
<i>Carex athrostachya</i>	<i>Dichelostemma capitatum</i>	<i>Taraxia</i> sp.
<i>Carex nebrascensis</i>	<i>Drymocallis</i> sp.	<i>Tragopogon dubius</i>
<i>Carex rossii</i>	<i>Erigeron lassenianus</i> var. <i>lassenianus</i>	<i>Trifolium breweri</i>
<i>Carex subfusca</i>	<i>Eriogonum nudum</i>	<i>Trifolium longipes</i> ssp. <i>hansenii</i>
<i>Carex vesicaria</i>	<i>Fragaria virginiana</i>	<i>Viola purpurea</i>
<i>Danthonia unispicata</i>	<i>Galium trifidum</i>	
<i>Deschampsia cespitosa</i>	<i>Gayophytum diffusum</i>	
<i>Deschampsia elongata</i>	<i>Gratiola ebracteata</i>	
<i>Eleocharis macrostachya</i>	<i>Horkelia fusca</i>	
<i>Elymus elymoides</i>	<i>Leptosiphon ciliatus</i>	
<i>Elymus glaucus</i>	<i>Leptosiphon harknessii</i>	
<i>Festuca</i> sp. (annual)	<i>Lomatium</i> sp.	
<i>Juncus nevadensis</i>	<i>Madia</i> sp.	
<i>Juncus tenuis</i>	<i>Navarettia intertexta</i>	
<i>Poa pratensis</i>	<i>Nothocalais troximoides</i>	
<i>Poa secunda</i>	<i>Osmorhiza berteroi</i>	
<i>Stipa occidentalis</i> var. <i>californica</i>	<i>Penstemon rydbergii</i>	

2.1.3 Meadow Soil Moisture and Groundwater Measurements

This section of methods details field site visits, instrument location and installation, and calculations used to measure soil moisture and groundwater data on the Marian and Control meadows.

2.1.3.1 Instrument Deployment

2.1.3.1.1 Soil Moisture Sensors

A total of 5 soil moisture sensors were installed north of CA State Highway 36 on September 2013 for the Marian Meadow, and June 13, 2014, for the Control Meadow (Figure 5 and Table 5). The instruments were randomly assigned using a spatially balanced sample (adapted from Stevens and Olsen, 2004). A 1,250-foot line (381 m) bisecting Marian Meadow was created and then 10 points were placed in equal intervals along the line. Four of the ten points were randomly assigned (points 3,4,6, and 9). A line from each of these 4 points was drawn perpendicularly from the bisection line stretching from the western edge to the eastern edge of the MM. Along these lines, points were established every 25 feet, four points along each line, thus creating the instrument location. This process was repeated for the Control Meadow (Van Oosbree, 2015; Sanford, 2016). Figure 7 and Figure 8 show instrument placement locations.

The initial soil moisture sensors installed in Marian and Control Meadows were manufactured by Odyssey Dataflow Systems Limited. The soil moisture sensors determine the soil moisture values by measuring dielectric permittivity of the soil to known soil moisture values, relating through calibration. The sensors were installed at a depth of 1.0 foot, and the data loggers were placed in PVC piping for additional waterproof protection. Some additional 3 soil moisture sensors were installed at depths of 3.0 feet in August 2015 in Marian and Control Meadows to determine the soil moisture content below 1.0 foot. These were EC5 soil moisture sensors, pre-calibrated prior to deployment, manufactured by Decagon Devices and were attached to micro station data loggers manufactured by Onset Computer Corporation.

Throughout the study, some soil moisture sensors failed due to a variety of reasons, including exposure to elements and wildlife. The failed sensors were either replaced or eliminated. A timeline of the soil moisture sensors is displayed in Figure 5 and described in Table 5.

Figure 5. Soil moisture sensor deployment timeline (see Figure 3.3.2 and Figure 3.3.3 for GPS locations of instruments). The yellow and orange timelines represent Marian Meadow and Control Meadow respectively.

2.1.3.1.2 Water Table Depth Sensors

Water level loggers were installed on the Marian Meadow and Control Meadow within shallow groundwater wells during September 10-13, 2013 (Figure 7 and 8). The

bottom 1.0 ft. (0.3 m) of the well casing was perforated to allow water to enter the PVC well casing. Plastic screen covered the holes to prevent soil particles from entering the well. Each groundwater well was capped to prevent precipitation from entering the well (Van Oosbree, 2015). A timeline of the water level instruments is displayed in Figure 6 and described in Table 5.

Figure 6. Water level sensor deployment timeline (see Figure 3.3.3 and Figure 3.3.4 for GPS locations of instruments).

Table 5: GPS location and type of instruments by site on Marian Meadow and Control meadow.

Site	Instrument	Longitude	Latitude	Date Installed	Manufacturer
Marian Meadow	1-1 SM	?		Sept 2013	HOBO Onset
	1-1 SM 3'			June 2015	HOBO Onset
	3-1 SM	40.26233	-121.31506	Sept 2013	Odyssey
	3-1 WL	40.26233	-121.31506	Sept 2013	Odyssey
	3-2 Blank	40.26241	-121.31477	Sept 2013	
	4-1 SM	40.26281	-121.31493	Sept 2013	HOBO Onset

	4-1 WL	40.26281	-121.31493	Sept 2013	Odyssey
	3-4 SM	40.26281	-121.31385	Sept 2013	Odyssey
	3-4 WL	40.26281	-121.31385	Sept 2013	Odyssey
	4-4 Blank	40.26305	-121.31469	Sept 2013	
	4-2 SM	40.26292	-121.31486	Sept 2013	HOBO Onset
	6-1 Blank	40.26291	-121.31654	Sept 2013	
	6-2 Blank	40.26332	-121.31525	Sept 2013	
	6-3 SM	40.26339	-121.31516	Sept 2013	HOBO Onset
	6-3 WL	40.26339	-121.31516	Sept 2013	HOBO Onset
	6-4 SM	40.26358	-121.31425	Sept 2013	HOBO Onset
	6-4 WL	40.26358	-121.31425	Sept 2013	Odyssey
	9-2 WL	40.26379	-121.31651	Sept 2013	Odyssey
	9-2 SM	40.26379	-121.31651	Apr 2014	HOBO Onset
	9-2 SM 3'	40.26379	-121.31651	Aug 2015	HOBO Onset
	9-3 WL	40.26403	-121.31599	Sept 2013	Odyssey
	9-3 SM 3'	40.26395	-121.31589	Aug 2015	HOBO Onset
	9-3 SM	40.26395	-121.31589	Aug 2014	Odyssey
	9-4 Blank	40.26387	-121.31593	Sept 2013	
Control Meadow	C1-2 SM	40.26465	-121.39500	Sept 2013	Odyssey
	C1-2 WL	40.26472	-121.39509	Sept 2013	Odyssey
	C1-3 SM	40.26480	-121.39447	Sept 2013	Odyssey
	C1-3 WL	40.26490	-121.39452	Sept 2013	Odyssey
	C2-2 Blank	40.26453	-121.39486	Sept 2013	
	C2-3 Blank	40.26463	-121.39438	Sept 2013	
	C2-4 SM	40.26469	-121.39418	June 2014	Odyssey
	C3-1 SM	40.26402	-121.39473	June 2014	HOBO Onset
	C3-1-1 SM 3'	40.26402	-121.39473	Aug 2015	HOBO Onset
	C3-1-2 SM 3'	40.26402	-121.39473	Aug 2015	HOBO Onset
	C3-1 WL	40.26402	-121.39473	Nov 2014	Odyssey
	C3-2 SM	40.26408	-121.39446	June 2014	HOBO Onset
	C3-2-2 SM 3'	40.26408	-121.39446	Aug 2015	HOBO Onset
	C3-2 WL	40.26405	-121.39445	Oct 2014	Odyssey
	C3-3 SM			Sept 2013	HOBO Onset
	C4-1 SM	40.26352	-121.39481	Aug 2015	HOBO Onset
	C4-3 SM	40.26373	-121.39323	Apr 2015	HOBO Onset
	C4-3 WL	40.26373	-121.39331	Oct 2014	Odyssey

Figure 7. Locations of instruments on the Control Meadow. See Table 3.2 for coordinates and instrument descriptions for each site.

Figure 8. Locations of instruments on Marian Meadow. See Table 3.2 for coordinates and instrument descriptions for each site.

2.1.3.2 Soil Moisture Calculation

The Odyssey soil moisture sensors were calibrated using a two-point calibration to convert raw values to gravimetric wetness by Van Oosbree (2015). A manufacture-provided raw value corresponding to 0% soil moisture was used as the calibration point. Soil samples of 100-200 grams of soil were taken on the site after the soil moisture sensors were deployed. These samples, taken directly adjacent to the sensor, were placed in a Ziploc bag and transported to the lab. In the lab, the soil samples were weighed and then oven dried for 24 hours at a temperature of 105°C. The gravimetric wetness of each sample was calculated (Equation 3 and 4). The calibration point was calculated using the gravimetric wetness and the raw value measured at the time of the sample collection. Equation 3 was then used to convert raw values to gravimetric wetness. Gravimetric wetness was then converted to volumetric soil moisture content (Equation 4; Sanford, 2016). The gravimetric soil moisture content to volumetric soil moisture content was applied to every two-hour soil moisture reading throughout the day. The average weekly volumetric soil moisture content was calculated for Marian Meadow and CM. The Onset soil moisture sensors, deployed after the initial Odyssey soil moisture sensors, came pre-calibrated and automatically provide volumetric soil moisture content (Sanford, 2016).

$$\theta_g = \frac{W}{D} \quad (3)$$

Where:

θ_g = gravimetric wetness of soil $\left(\frac{g}{g}\right)$

W = mass of water in soil (g)

D = mass of oven dry soil (g)

Mass of water in soil was calculated using the following equation:

$$W = F - D \quad (4)$$

Where:

W = mass of water in soil (g)

F = mass of soil sample (g)

D = mass of oven dry soil (g)

The soil moisture sensor raw values were then converted to gravimetric wetness values with the following equation:

$$\Theta_{g(sensor)} = \frac{V_{r(sensor)} - off}{(V_{rs} - off) \times \Theta_{g(sample)}} \quad (5)$$

Where:

$\Theta_{g(sensor)}$ = gravimetric wetness $\left(\frac{g}{g}\right)$

$V_{r(sensor)}$ = raw sensor value measured every two hours

off = offset value (factory determined raw value at 0% at moisture content)

V_{rs} = raw value at time of field sample collection

$\Theta_{g(sample)}$ = gravimetric wetness of field sample $\left(\frac{g}{g}\right)$

The following equation was used to convert gravimetric wetness to volumetric water content:

$$\Theta_v = \Theta_g * \frac{P_b}{P_w} \quad (6)$$

Where:

Θ_v = volumetric water content $\left(\frac{g}{cm^3}\right)$

Θ_g = gravimetric wetness $\left(\frac{g}{g}\right)$

P_b = soil bulk density $\left(\frac{g}{cm^3}\right)$

P_w = water density $\left(\frac{g}{cm^3}\right)$

In previous analyses the average bulk density of soil in Marian Meadow was calculated to be $1.48 \frac{g}{cm^3}$ and the average bulk density of soil in Control Meadow was calculated to be $1.59 \frac{g}{cm^3}$ (Sanford, 2016; Van Osobree, 2015). Soil moisture sensors logged gravimetric data in two-hour intervals and was downloaded and converted to volumetric soil moisture content. The average weekly volumetric soil moisture content was then calculated for Marian and Control meadows.

2.1.3.3 Water Level Calculation

The water level loggers installed in this study were calibrated by Van Oosbree (2015) after manually sounding the wells and comparing those values to their corresponding raw values. The average weekly water level content was calculated for the Marian and Control Meadows (feet below ground). The following equation was used for instrument calibration:

$$V_c = \frac{(V_u - O)}{\Delta} \quad (7)$$

Where:

Δ = Slope of the calibration curve

$$\Delta = \frac{(V - V_0)}{(X - X_0)} \quad (8)$$

V_c = Calibrated Value (mm)

V_u = Raw value

V = Raw value at 1500 mm

V_o = Raw value at sounding depth

X = 1500 mm - instrument height above ground (mm)

X_o = sounding depth

2.1.4 Electrical Resistivity Tomography Measurements

Water level sensors logged data in two-hour intervals and appeared as a calibrated value that was converted to depth below ground (ft.). During dry months when the water table was below the groundwater level sensors, electrical resistivity tomography (ERT) was conducted to determine the water table depth. Using measured groundwater depth values and recession curve estimated values, total average weekly groundwater depth was calculated for each meadow.

A recession curve equation (equation 9), which accounts for precipitation, was used for the modeling (e.g. Surfleet and Skaugset, 2013). During summer when the groundwater depth was receding, the last average weekly sensor measurement was fit to ERT-derived depths measured during summer. The recession coefficient was chosen so that the last weekly modeled depth was similar to that of the ERT derived depth. During periods of recession, the recession coefficient is greater than one. During periods of groundwater recovery, the ERT-derived summer groundwater depth was fit to the first average weekly sensor measurement. During periods of groundwater recovery, the recession coefficient is less than one. This modeling technique was applied to each water table depth weekly average (Van Oosbree, 2015; Sanford, 2016).

$$G_{di} = (k * G_{di-1}) - P \quad (9)$$

Where:

G_{di} = water table depth (ft)

k = Recession coefficient

G_{di-1} = water table depth (ft) previous week

P = precipitation (ft)

The electrical resistivity tomography (ERT) is a geophysical technique for imaging sub-surface structures from electrical resistivity measurements made at the ground surface, or by electrodes in one or more boreholes (Hemeda, 2013). Periodic ERT transects were conducted to determine groundwater depths below the range of the groundwater sensors. A SYSCAL Kid Switch resistivity meter manufactured by IRIS Instruments was used to conduct the surveys. A Wenner PRF switch array using 24 electrodes was used for all resistivity measurements. PROSYSII (as cited by Van Oosbree, 2015) software was used to transfer raw data to a computer and RES2DINV (Geotomo Software, 2011) software was used to invert the field data. The produced two-dimensional cross-sections depict resistivity values along the length of the transect versus depth. The Wenner array allows for a maximum depth of approximately 20% of the transect length. The first ERT surveys conducted on Marian Meadow and Control Meadow took place on 9/10/2013 and 5/6/2014, respectively. ERT surveys were not conducted during the summer of 2016 due to lack of suitable conditions. On July 18th, 2017, an ERT survey was conducted in both the Marian Meadow and Control Meadow. See Appendix for a description of these initial surveys as well as subsequent surveys. In

the Marian Meadow, the water table was interpreted as the region above 110-120 $\Omega\cdot\text{m}$. In the Control Meadow, the water table was interpreted as the region where resistivity was below 100-180 $\Omega\cdot\text{m}$ (as cited by Van Osobree, 2015).

The most consistent pattern of ERT surveys involved a 5-meter spacing longitudinally down the center of each meadow. These surveys provided imaging depths of approximately 20 meters. ERT surveys with 1.5-meter spacing were conducted perpendicular to these center lines at two locations. These surveys provided imaging depths of approximately 7 meters. Various other survey lines with varying lengths and node spacing's were conducted (Appendix C; as cited by Van Oosbree, 2014 and Sanford, 2016).

2.2 Water Budget

To quantify the different hydrologic changes from the removal of encroached conifers we calculated different components of a water budget using precipitation, soil moisture, and groundwater water table changes for the Control Meadow and Marian Meadow following methods adapted from Rahgozar et al. (2012). These methods were used for analysis of the first year post-restoration by Surfleet et al. (2018). The water budget components were represented by WY. For the duration of this chapter, time periods referred to as pre-restoration, 2014 WY-2015 WY, first year post-restoration 2016 WY, second year post restoration 2017 WY, third year post-restoration and first year following upslope forest harvest 2018WY, and post-restoration 2016 WY -2018 WY include time periods displayed in the Table 6. The third-year post restoration time period ends in April 2018, and is still awaiting summer data.

Table 6: Significant time periods throughout the research collection on the Marian and Control Meadow

<u>Time Periods</u>	<u>Dates included</u>
2014 WY	October 1, 2013 – September 30, 2014
2015 WY	October 1, 2014 – September 30, 2015
2016 WY	October 1, 2015 – September 30, 2016
2017 WY	October 1, 2016 – September 30, 2017
2018 WY	October 1, 2017 – April 21, 2018
Pre-restoration	September, 2013 – June 2015
Entire Monitoring Period	September 2013 – April 2018

The general form of the water budget is (Equation 10):

$$P = Q_{SEOF} + ET \pm \Delta S \quad (10)$$

Where P precipitation (mm) from the Chester rain gauge, Q_{SEOF} is saturated excess overland flow (mm), ΔS is change in water stored in the soil or groundwater (m), and ET is the sum of evapotranspiration from the soil and evaporation from interception capture (mm).

2.2.1 Snow Density

The Sturm model is used to calculate snow density (P_b) which uses snow depth (h_s), age of snow (DOY) and snow class found from geographical coordinates of the location as input variables (Sturm et al., 2010, 1995). The Sturm model predicts snow density and is applicable wherever weather stations are available and representative (Equation 11). Snow depth was measured from a Judd Ultrasonic snow depth sensor installed onto the weather station adjacent to the Control Meadow on August 15th, 2016. Prior to this time, snow depth and snow density data were not collected or incorporated into the Water Budget. The snow depth sensor was calibrated incorrectly initially and had to be recalibrated on June 17th, 2016.

$$P_b = (p_{\max} - p_0) (1 - \exp(-k_1 h - k_2 \text{DOY})) + p_0 \quad (11)$$

Where:

$p_{\max}$ = maximum bulk density

p_0 = initial density of the individual snow layer

DOY = Counter of the day of the year (set to 1 on January 1st, with October 1st (-92) to 30th of June (+ 181) to account for the winter season extending across two years in the northern hemisphere).

k_1 and k_2 = the densification parameters for depth

Snow classes for each location (i.e. meadow) are found by the snow classification scheme (Table 7). The snow class is classified by the seasonal snow cover proposed from Sturm et. al. (1995). There are five snow class types which are defined by physical characteristics of the snow and the snow layers. These classes are also derived by using

three different climatic variables given by the weather stations at the different location-wind, precipitation, and air temperature, in a binary classification system.

Table 7. Snow Class and corresponding default values for different snow types used in snow density model. Adopted from (Sturm et al., 1995)

Snow class	$p_{\max}$	p_0	k_1	k_2
Tundra	0.3636	0.2425	0.0029	0.0049
Maritime	0.5979	0.2578	0.0010	0.0038
Prairie	0.5940	0.2332	0.0016	0.0031
Alpine	0.5975	0.2237	0.0012	0.0038
Taiga	0.2170	0.2170	0.0000	0.0000

2.2.2 Snow Melt Runoff

Because of the difficulty of fulfilling data requirements using the energy budget method, the temperature-index approach was used to compute snowmelt-runoff. This approach estimates snowmelt, Δw , for a daily period as a linear function of average air temperature (Equation 12).

$$\Delta w = M \times (T_a - T_m) \quad (12)$$

Where:

M = melt coefficient

T_a = daily mean temperature (°C)

T_m = threshold temperature beyond which melt is assumed to occur (°C)

The variable M is a melt coefficient and varies with latitude, elevation, slope inclination, and aspect, forest cover, and time of year and ideally should be empirically estimated for a given watershed. Kuusisto (1980) recommended relating M to density, which generally increases during the melt season (Dingman, 2002; Kuusisto, 1986) (Equation 13).

$$M = 19.6 * \frac{p_s}{p_w} - 0.7 \quad (13)$$

Where:

p_s = density of snow (g/cm³)

p_w = density of water $\left(\frac{\text{g}}{\text{cm}^3}\right)$

2.2.3 Saturated Excess Overland Flow (Q_{SEOF})

The capillary fringe of the meadow was determined to be 0.1 m based on well elevations and observation of overland flow or ponding on the ground surface. Saturated excess overland flow (Q_{SEOF}) was assumed to occur when the depth to water table was <0.1 m. Precipitation during that time period was assumed to be Q_{SEOF} . A water depth recorder manufactured by Odyssey Dataflow Systems Pty. Limited installed at a culvert at the downstream end of Marian Meadow to detect overland flow leaving the meadow was used to validate and adjust time periods when Q_{SEOF} occurred. We assume Q_{SEOF} is water that either flows out of the meadows or evaporated when ponded on the meadows' ground surface.

2.2.4 Infiltration (I) and Change in Storage (ΔS)

The infiltration of precipitation (Equation 14) into the soil and aquifer was represented by the sum of increases in soil moisture (I_s) over the year and the change in water table elevation (I_{wt}) above a datum.

$$I = I_s + I_{\text{wt}} \quad (14)$$

Infiltration in the unsaturated soil (I_s) was evaluated for all soil moisture sensors at 2-hour intervals (time duration between measurements). When an increase in soil

moisture occurred in a 2-hour interval the change in volumetric soil moisture was converted to a depth (mm) based on the unsaturated depth of soil (difference in surface elevation and water table elevation) (adapted from Rahgozar et al. 2012). The soil moisture sensors installed at 0.3 m and 0.9 m depth were assumed to be representative of soil <0.6 and >0.6 m depth respectively. The I_s values were summed for each soil moisture sensor and depth then averaged by WY.

The infiltration to the soil (I_s) does not account for the water that passes through to the saturated soil or water table. Infiltration to the saturated soil or water table (I_{wt}) was calculated from the difference in average annual water table elevation above a datum (12 m partially confining layer in Marian Meadow) of the downstream most groundwater well from the most upstream groundwater well. We assume that the upstream groundwater well is indicative of groundwater levels coming into the meadow and increases in the water table downstream represent infiltration from precipitation.

Storage of water in the sub-surface was the sum of groundwater and soil moisture minus ET_s . This was represented by the difference in infiltration (I) and soil evapotranspiration (ET_s)(Equation 15).

$$\Delta S = (I_s + I_{WT}) - ET_s \quad (15)$$

Evapotranspiration is the sum of soil evapotranspiration and evaporation from interception capture of vegetation. Evapotranspiration from the soil (ET_s) was evaluated for all soil moisture sensors at 2-hour intervals. When a decrease in soil moisture

occurred in a 2-hour interval the change in volumetric soil moisture was converted to a depth (m) based on the unsaturated depth of soil (difference in surface elevation and water table elevation) (Surfleet et al., 2018; adapted from Rahgozar et al. 2012). ET_s for each water year (WY) were the averaged totals for all soil moisture sensors in each meadow. In a given time step (2 hours), depending on the algebraic sum of terms on the right-hand side of (1), either soil infiltration or soil evapotranspiration is assumed to be occurring. An inherent assumption made here is that, since small time intervals (2 hour) were used for the analysis, either evapotranspiration or infiltration took place in a given time step (Rahgozar et al., 2012).

Interception capture (I_c) is the initial abstraction from a rainfall event. If there is no runoff accompanying a given rainfall event, then, theoretically, it can be estimated by subtracting the observed rainfall from the observed infiltration (Rahgozar et al. 2012). Interception capture was estimated by selecting isolated precipitation events with intensity less than the hydraulic conductivity of the surface soil layers, occurring after medium to dry antecedent conditions (in deeper water table conditions). The intercept of the best fit line on the precipitation to infiltration relationship yields the estimate of the interception capture. Interception capture (I_c) was assumed to represent either evaporation or sublimation of incoming precipitation. We further assume that the proportion of precipitation calculated for interception capture in dry to medium antecedent conditions applies to wet antecedent conditions.

2.2.5 Evapotranspiration Validation

Daily evapotranspiration values were calculated using the Priestley-Taylor method. On August 8th 2015, an Onset Computer Corporation weather station, equipped with a tipping bucket rain gauge, temperature sensor, relative humidity sensor, anemometer, wind direction sensor, incoming and outgoing shortwave solar radiation sensors, was installed adjacent to the control meadow. On August 15, 2016, a Judd Snow Depth sensor was added to the weather station to measure snow depth. Temperature and solar radiation data measured with this weather station were incorporated into the Priestly-Taylor analyses. The precipitation data measured by the weather station was incorporated in the Priestley Taylor analyses on July 1, 2013. Measurements from all instruments on the climate station were recorded at two-hour intervals.

For the time periods prior to weather station installation, the data was extended with standard least-squared regression equations using solar radiation and temperature data from Chester and Buntingville, California (Sanford, 2014). These sensors are maintained by US Forest Service and the California Irrigation Management Information System (CIMIS) respectively. The parameter estimates below were used to extend average, minimum, and maximum temperature data measured in the Control Meadow from 09/13/2013 to 08/15/2015 (Sanford, 2015; Table 8). There was a statistically significant difference between the average daily net solar radiation values of Control Meadow weather station and Buntingville ($p\text{-val} < 0.0001$; Sanford, 2015). The parameter estimates below were used to extend the average daily net solar radiation data measured in the Control Meadow from 9/13/2013 to 8/15/2015 (Table 9).

Table 8: Parameter estimates used to correct Chester, CA daily average, minimum, and maximum temperatures (Sanford, 2015).

Daily Average Temperature Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-0.96	0.13	-7.22	<.001
Chester	0.93	0.01	86.92	<.001
Daily Minimum Temperature				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-1.12	0.16	-6.98	<.001
Chester	0.85	0.03	29.31	<.001
Daily Maximum Temperature				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-1.78	0.24	-7.3	<.001
Chester	1.03	0.01	93.58	<.001

Table 9. Parameter estimates used to correct Control Meadow temperature from 9/13/2013-5/15/2015 (Sanford, 2016)

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-2.61	0.38	-6.85	<.001
Chester	0.77	0.2	35.5	<.001

Albedo was calculated using Control Meadow weather station data from August 8th to April 21, 2018. A Priestley-Taylor (PT) coefficient was fit to Control Meadow and Marian Meadow evapotranspiration calculations produced by the water budget iteration of the Priestley-Taylor model for each WY and each meadow.

$$AET = \frac{\Delta_{svpc}(R_n - Gf)}{\Delta_{svpc} + \gamma} * \alpha \quad (16)$$

Where:

$$R_n = \text{Net solar radiation, } \left(\frac{\text{mJ}}{(\text{day})\text{m}^2}\right), R_{ns} - R_{nl} \quad (17)$$

$$R_{ns} = \text{Net shortwave radiation, } \left(\frac{\text{mJ}}{(\text{day})\text{m}^2}\right), (1 - \alpha) * R_{ns} \quad (18)$$

$$R_{nl} = \text{Net longwave radiation, } \left(\frac{\text{mJ}}{(\text{day})\text{m}^2}\right), f_c * f_h * \sigma * f(T_K) \quad (19)$$

$$f_c = \text{Cloudiness factor, } 1.35 \frac{R_s}{R_a} - 0.35 \quad (20)$$

R_a = extraterrestrial radiation ($\frac{mJ}{(day)m^2}$)

$$(\frac{24 * 60}{\pi}) * G_{sc} * d_r (\omega_s * \sin \varphi * \sin \delta + \cos \varphi * \cos \delta * \sin \omega_s) \quad (21)$$

G_{sc} = solar constant, 0.0820 ($\frac{mJ}{(day)m^2}$)

$$d_r = \text{inverse relative distance Earth - Sun, } 1 + 0.033 \cos \frac{2\pi}{365} * J \quad (22)$$

J = number of day in year (1-365)

$$\omega_s = \text{sunset hour angle (rad), } \arccos (-\tan \varphi * \tan \delta) \quad (23)$$

φ = latitude (rad)

$$\delta = \text{solar decimation (rad), } 0.409 \sin (\frac{2\pi}{365} * J - 1.39) \quad (24)$$

$$f_h = \text{Humidity correction factor, } 0.34 - 0.14 \sqrt{e_a} \quad (25)$$

e_a = vapor pressure (kPa)

$$\sigma = \text{Stefan - Boltzmann constant, } 4.903 * 10^{-9} (\frac{mJ}{(day)m^2}) \quad (26)$$

$$f(T_k) = T_{daily\ average}^4$$

$$\alpha = \text{Albedo, } (\frac{R_{s\ reflected\ average}}{R_{s\ incoming\ average}}) \quad (27)$$

$$G_f = \text{Soil heat flux, } (\frac{mJ}{(day)m^2}) = 0 \text{ for daily calculations} \quad (28)$$

$\Delta svpc$ = Slope of the saturation vapor pressure curve, ($\frac{kPa}{^\circ C}$),

$$\frac{4098 (0.6108 * e^{\frac{17.27 * T}{T + 237.3}})}{(T^2 + 237.3^2)} \quad (29)$$

α = PT coefficient (0.65±0.25)

$$\gamma = \text{Psychrometric constant } (\frac{kPa}{^\circ C}), \frac{C_p * P}{\epsilon * \lambda} \quad (30)$$

Where:

ϵ = ratio molecular weight of water vapor to dry air (0.622)

λ = latent heat of vaporization (mJ/kg)

x =elevation (m)

C_p = specific heat at constant pressure, $0.001013 \left(\frac{\text{mJ}}{\text{kg} \cdot ^\circ\text{C}} \right)$

P = atmospheric pressure (kPa, $P_0 * \left(\frac{L * h}{T_0} \right)^{\frac{g * M}{R * L}}$) (31)

P_0 = Sea level standard atmospheric pressure, 101.325 kPa

T_0 = Sea level standard temperature, 288.15 K

L = temperature lapse rate, $0.0065 \frac{\text{K}}{\text{m}}$

ε =ratio molecular weight of water vapor to dry air (0.622)

λ = latent heat of vaporization (mJ/kg), $2.501 - 0.002361T$ (32)

h = elevation of meadow (m)

g = earth surface gravitational acceleration, $9.80665 \left(\frac{\text{m}}{\text{s}^2} \right)$

M = molar mass of dry air, $0.0289644 \frac{\text{kg}}{\text{mol}}$

R= universal gas constant, $8.31447 \frac{\text{J}}{\text{mol} * \text{K}}$

T = mean daily air temperature in $^\circ\text{C}$

2.3 Statistical Analysis

A General Linear Model was used to test changes in weekly average volumetric soil moisture content. Only measured values, not modeled depth to water table values, were used in the statistical analysis. Weekly average for soil moisture was determine, statistical analysis was done for every third weekly average to avoid serial autocorrelation (Sanford, 2016). A time series variable was used in the soil moisture model to adjust for time and 15 indicator variables were incorporated in the model to adjust for the trend and

seasonality (15 indicators to represent 16 measurements per approximately a one-year period in the data). The water level model included a year variable (taking values 1-5 corresponding to 2014 through 2018), rather than an indexed time variable.

The pre-restoration period included September 13, 2013 through July 31, 2015. The post-restoration period assessed in this analysis included the 2016 WY (October 1, 2015-September 30, 2016) and 2017 WY (October 1, 2016-September 30, 2017), and part of 2018 WY (October 1- April 20, 2018). The model for soil moisture includes the following:

$$\begin{aligned} \text{Marian Meadow Soil Moisture (\%)} &= \text{Time} + \text{Control Meadow Soil Moisture (\%)} \\ &+ \text{Seasons} + \text{Restoration} + \text{Control Meadow Soil Moisture (\%)} * \text{Restoration} \end{aligned}$$

The model for the water level includes:

$$\begin{aligned} \text{Marian Meadow Water Level (ft below ground)} &= \text{Year} + \text{Feb/March/Apr} + \\ &\text{Restoration} + \text{Control Meadow Water Level (ft below ground)} + \text{Control Meadow Water} \\ &\text{Level} * \text{Restoration} \end{aligned}$$

2.4 Results Overview

This results section is separated into two sections: hydrologic results for hydrologic components used as inputs for water budget (2.4.1 – 2.4.8), the water budget (2.5), and the statistical analysis (2.6) of soil moisture (2.6.1) and water level (ft below ground) (2.6.2).

2.4.1 Hydrologic Results for the Meadows

The following subsections describe hydrologic results for the meadows including volumetric soil moisture content (4.1.1), depth to water table using ERT (4.1.2), depth to water table content (4.1.3), total equivalent water stored in unsaturated and saturated soil and groundwater (4.1.4), precipitation, evapotranspiration, and snowmelt (4.1.5). Finally, the overall water balance by water year is presented (4.1.6).

2.4.2 Volumetric Soil Moisture Content (%)

Marian Meadow

Weekly average soil moisture content measured from sensors buried 1.0 foot (30 cm) below the surface ranged from 10.6% to 46% throughout the entire study period (Table 10; Figure 9). The average weekly soil moisture content for water years 2014, 2015, 2016, and 2017 were 21.2%, 27.4%, 33.0%, 32.3%, and 27.8% respectively. (Table 10; Figure 10). On average, March and April had the highest average soil moisture content of 37.2% and 38.5% while September and October had the lowest; 17.7% and 18.06% respectively (Figure 9).

Weekly average soil moisture content measured from sensors buried 3.0 feet (90 cm) below the surface ranged from 15.2% to 51.2% for the entire study period (8/7/2015 – 04/20/2018), with an average volumetric soil moisture content 37.7%. During the same

time period, the average volumetric soil moisture content at 1 foot (30 cm) depth below soil surface was 31.15% (Table 10; Figure 9).

Control Meadow

Weekly average soil moisture content measured from sensors buried 1.0 foot (30 cm) below the surface ranged from 10.91% to 37.9% throughout the entire study period. The average weekly soil moisture content for water years 2014, 2015, 2016, 2017, and 2018 were 19.9%, 22.4%, 27.0%, 29.0%, and 25.8% respectively. Similar to Marian Meadow, March and April had the highest average soil moisture content of 32.4% and 32.1% while September and October had the lowest; 15.9% and 17.81% respectively (Table 10; Figure 9).

Weekly average soil moisture content measured from sensors buried 3.0 feet (90 cm) below the surface ranged from 16.8% to 46.4% for the entire study period (8/7/2015 – 04/20/2018, except for October 2016 through June 2016 because of instrument failures). During the same time period, the average volumetric soil moisture content at 1 foot (30 cm) depth below soil surface was 27.0% (Figure 10).

Table 10: Minimum, maximum, and average volumetric soil Moisture content (%) for Marian and Control Meadows; 2014-2018 water years.

	Marian (%)			Control (%)		
	Min	Avg	Max	Min	Avg	Max
2014 WY	10.68	21.24	32.00	10.83	19.83	30.89
2015 WY	17.24	27.24	37.18	12.80	22.44	33.97
2016 WY	18.92	32.66	47.66	14.58	26.75	39.72
2017 WY	15.52	32.59	45.19	14.13	28.65	35.41
2018 WY	14.76	27.83	45.05	18.38	25.82	32.23
Pre-Restoration	10.58	24.51	36.93	10.91	22.19	34.00
Entire Post Restoration	14.74	30.94	46.03	12.91	26.57	26.57
Entire Monitoring Period	10.58	28.46	46.03	10.91	24.89	37.93

Figure 9: Average monthly volumetric soil moisture content (%) for 1 ft (30 cm) depth, for Marian and Control Meadow 2014-2018 water years.

Figure 10. Weekly Precipitation and Percent Soil Moisture Volume at 1 foot (30 cm) depth and 3 foot (90 cm) depth for Control and Marian Meadows; 2013-2018.

2.4.3 Depth to Water Table - Electrical Resistivity Tomography (ERT)

September 7th, 2014 ERT surveys yielded an approximate depth of 41.0 ft (12.5 m) to a confining material for Marian Meadow's aquifer (Figure 11). This depth was used as a reference datum to calculate the equivalent depth of water stored in the aquifer. No confining layer was observed within 66 feet (20 m), the maximum penetration depth of ERT, in the Control Meadow (Figure 11a). For calculation and comparison, the 41.0ft (12.5 m) depth was used for both meadows. ERT surveys conducted on 9/10/2013, 9/7/2014, and 9/9/2015 yielded depth to ground water values of approximately 9.2 feet (2.8 M), 8.5 feet (2.6 M), and 10.4 (3.2 M) feet respectively for Marian Meadow (Figure 12a, Figure 11c, and Figure 12c). ERT surveys conducted on 9/6/2014 and 9/9/2015 yielded depth to groundwater of approximately 10.7 feet (3.3 M) and 8.5 feet (2.6 M) for Control Meadow (Figure 11a and Figure 13b). The two ERT Surveys conducted on 7/18/2017 in the Control Meadow yielded depths of approximately 3.75 feet (1.1 m) and 4.0 feet (1.2 m) (Figure 14a and Figure 14b). Surveys conducted on 7/18/2017 in Marian Meadow yielded depths of approximately 3.5 feet (1.1 m) (Figure 14c and Figure 14d) (Appendix C, Table 29 and Figures 29 through 33).

Figure 11. ER values in $\Omega^* \text{ m}$ vs. depth (m) and distance (m) used to determine depth to bottom of aquifer. a: Control Meadow, survey #9 (9/6/2014); b. Marian Meadow transect, survey #13 (9/7/2014); c: Lower Marian Creek transect, survey #16 (9/7/2014) (Adopted from Sanford, 2016).

a.

b.

c.

Figure 12. ER values in $\Omega \cdot m$ vs. depth (m) and distance (m) used to determine depth to top of aquifer. a: Marian Meadow, survey #3 (9/10/2013); b: Marian Meadow lower transect, survey #14 (9/7/2014); c: Upper Marian Meadow, survey #28 (9/9/2015). (Adopted from Sanford, 2016).

a.

b.

Figure 13. ER values in $\Omega \cdot m$ vs. depth (m) and distance (m) used to determine depth to top of aquifer. a: Lower Control Meadow, survey #11 (9/6/2014); b. Lower Control Meadow, survey #26 (9/9/2015) (Adopted from Sanford, 2016). (Adopted from Sanford, 2016).

a.

b.

c.

d.

Figure 14. ER values in $\Omega^* \text{ m}$ vs. depth (m) and distance (m) used to determine depth to top of aquifer on 7/18/2017. a: Lower Control Meadow, survey #CM2; b. Control Meadow, survey #CM3; c. Upper Marian Meadow, survey #UMM1; d. Lower Marian Meadow, survey #UMM3

2.4.4 Water Table Depth (ft) in Marian Meadow and Control Meadow

Marian Meadow

Average weekly depth to the water table, including recession curve estimated and measured values, ranged from 0.12 feet (0.04 m) to 8.46 feet (2.58 m). The average weekly water table depth prior to restoration was 3.33 ft (1.02 m) and the entire post-restoration weekly water table depth was 2.71 feet (0.83 m). The average water table depth following restoration increased by 0.62 feet (0.19 m) on average (Figure 15 and Table 11).

The average growing season, May 1 through August 30, water table depth prior to restoration was 4.5 feet (1.37 m). Post restoration the growing season depth to water table was an average of 2.25 feet (0.69 m) (Table 12).

Control Meadow

Average weekly depth to the water table, including recession curve estimated and measured values, ranged from 0.12 feet (0.04 m) to 10.31 feet (3.14 m). The average depth to water table for post restoration was 2.71 ft (0.83 m).

The average growing season depth to water table for the pre-restoration monitoring period was 4.57 feet (1.39 m) and was 2.26 ft (0.69 m) for the post-restoration period (Table 12).

Figure 15. Average weekly depth to groundwater (ft) for Control and Marian Meadows; 2013-2018.

Table 11: Marian and Control Meadow minimum, maximum, and average annual depth to groundwater (ft) for 2014-2018 water years, pre-restoration, one-year post-restoration, 2nd year post restoration, 3rd year post -restoration.

Depth to Groundwater for Marian and Control Meadow						
	Marian			Control		
Water Year	Min	Avg	Max	Min	Avg	Max
2014 WY	0.91	4.85	8.38	0.12	5.32	10.31
2015 WY	0.51	3.79	8.36	0.10	3.40	8.07
2016 WY	0.23	2.68	7.52	0.16	2.74	6.47
2017 WY	0.15	1.89	4.37	0.30	2.22	4.17
2018 WY	0.44	2.55	4.46	0.34	2.23	4.07
Pre-Restoration	0.54	3.33	8.46	0.12	3.35	10.70
Entire Post Restoration	0.16	2.71	8.53	0.16	2.76	8.50
Entire Monitoring Period	0.16	2.90	8.53	0.12	2.95	10.70

Table 12: Marian and Control Meadow depth to groundwater (ft) for 2014-2017 water year growing seasons.

	Marian Meadow Growing Season				Control Meadow Growing Season			
	2014	2015	2016	2017	2014	2015	2016	2017
WTD minimum	1.54	2.57	0.43	0.48	0.87	2.34	0.50	0.31
WTD Average	4.47	4.61	2.27	2.30	4.48	4.65	2.49	2.03
WTD maximum	8.14	7.41	4.14	3.83	8.87	7.55	4.06	3.96
Days WTD < 2.3'	20	0	61	61	26	0	55	67
Days WTD < 1.0'	0	0	27	24	2	0	31	43

2.4.5 Equivalent Water Depth in Soil and Aquifer

2.4.5.1. *Marian Meadow*

Marian Meadow's weekly average equivalent water depth of soil moisture ranged from 0.07 feet (0.02 m) to 1.93 feet (0.59 m). The average equivalent water depth for soil moisture was greatest for the 2016 WY and 2018 WY, resulting in 0.68 feet (0.21 m) and 0.62 feet (0.19 m) depth to water table. Conversely, the lowest equivalent depth for soil moisture occurred in 2014 WY and 2015 WY, resulting in 0.91 feet (0.28 m) and 0.92 feet (0.28 m) depth to water table. The first year after restoration exhibited, on average, the highest equivalent depth for soil moisture of 0.89 feet (0.27 m) (Table 13; Figure 16).

The average weekly equivalent water depth for groundwater ranged from 15.26 feet (4.65 m) to 19.21 feet (5.86 m). The second-year post-restoration exhibited the highest equivalent water depth for groundwater of 18.39 feet (5.61 m) (Table 14; Figure 17).

The total weekly water depth stored in the soil and groundwater ranged from 16.18 feet to 20.05 feet. On average, groundwater was 95.7% of total equivalent water depth stored in unsaturated soil and groundwater combined (Table 15; Figure 18).

2.4.5.2 *Control Meadow*

The Control Meadow's weekly average equivalent water depth for soil moisture ranged from 0.00 feet to 1.67 feet (0 – 0.51 m). The average equivalent water depth for soil moisture was the highest for the 2016 and 2017 WY, resulting in 0.65 feet (0.20 m) and 0.66 feet (0.20 m) respectively (Table 13; Figure 16).

The three-foot (90 cm) soil moisture instruments were installed in August, 2015 and had failed from September 2016 until June 2017 and therefore total equivalent water

stored in the soil was calculated with the one-foot (30 cm) soil moisture data for those time periods.

The weekly equivalent water depth for groundwater ranged from 12.09 feet (3.69 m) to 16.31 feet (4.97 m). The 2017 WY resulted in the highest average weekly equivalent water depth stored in the aquifer, at 15.47 feet (4.72 m) (Table 14; Figure 17).

The total weekly water depth stored in the soil and groundwater ranged from 13.43 feet to 16.93 feet. On average, groundwater was 95.6% of total equivalent water depth stored in unsaturated soil and groundwater combined (Table 15; Figure 18).

Table 13: Average weekly equivalent water depth (ft) for soil moisture.

Time Periods	Marian Meadow			Control Meadow		
	Minimum (ft)	Average (ft)	Peak (ft)	Minimum (ft)	Average (ft)	Peak (ft)
2014 WY Pre-restoration	0.31	0.91	1.58	0.04	0.91	1.67
2015 WY Pre-restoration	0.19	0.92	1.93	0.04	0.69	1.61
2016 WY Post-restoration	0.07	0.68	1.70	0.00	0.65	1.40
2017 WY Post-restoration	0.37	0.73	0.89	0.28	0.66	0.97
2018 WY, Post-restoration and 1 st year following upslope harvest	0.16	0.62	0.93	0.00	0.52	0.94
Entire Monitoring Period	0.07	0.79	1.93	0.00	0.70	1.67

Table 14: Average weekly equivalent water depth (ft) for groundwater

Time Periods	Marian Meadow			Control Meadow		
	Minimum (ft)	Average (ft)	Peak (ft)	Minimum (ft)	Average (ft)	Peak (ft)
2014 WY Pre-restoration	15.26	16.99	18.83	12.09	14.23	16.31
2015 WY Pre-restoration	15.27	17.53	19.03	12.97	14.89	16.31
2016 WY Post-restoration	15.77	18.04	19.17	12.97	15.21	16.30
2017 WY Post-restoration	17.21	18.41	19.21	14.66	15.59	16.23
2018 WY, Post-restoration and 1 st year following upslope harvest	17.15	18.08	19.07	14.72	15.47	16.23
Entire Monitoring Period	15.26	17.78	19.21	12.09	15.04	16.31

Table 15: Average weekly equivalent water depth (ft) for soil moisture and groundwater combined.

Time Periods	Marian Meadow			Control Meadow		
	Minimum (ft)	Average (ft)	Peak (ft)	Minimum (ft)	Average (ft)	Peak (ft)
2014 WY Pre-restoration	16.18	17.90	19.14	13.43	15.14	16.35
2015 WY Pre-restoration	17.20	18.46	19.22	14.27	15.58	16.35
2016 WY Post-restoration	17.47	18.72	19.28	14.58	15.86	16.35
2017 WY Post-restoration	17.58	19.15	20.05	14.95	16.24	16.93
2018 WY, Post-restoration and 1 st year following upslope harvest	17.83	18.70	19.26	15.48	15.98	16.24
Entire Monitoring Period	16.18	18.57	20.05	13.43	15.74	16.93

Figure 16. Weekly equivalent water depth (feet) for soil moisture for Marian and Control Meadows for the study period.

Figure 17. Equivalent depth of water (feet) for groundwater for Marian and Control Meadows for the study period

Figure 18. Equivalent depth of water (feet) for soil moisture and groundwater combined for Marian and Control Meadows for the study period

2.4.6 Precipitation, Evapotranspiration, and Snowmelt

2.4.6.1 Precipitation

During the months of October through March of the 2017 water year, the Marian Meadow and Control Meadow received an average weekly rainfall of 2.2 inches. During the same time frame of the previous 2016 water year the Marian Meadow and Control Meadow received an average weekly rainfall of 1.1 inches (2.8 cm) (Table 16). The most rainfall occurred during December through February of the 2017 water year where the meadows received a weekly average of 2.8 inches (7.1 cm) (Table 17 and Figure 19).

Table 16. Minimum, average, and peak weekly precipitation values (inches) for 2014 – 2018 water years.

Water Year	Min	Average	Max
2014 WY	0.0	0.38	3.59
2015 WY	0.0	0.53	6.0
2016 WY	0.0	0.83	7.7
2017 WY	0.0	1.24	9.9
2018 WY*	0.0	1.01	4.31

* through April 2018.

Table 17. Average precipitation (inches) for each month by water year.

Month	2014 WY	2015 WY	2016 WY	2017 WY	2018 WY
October	0.20	0.40	0.46	2.39	0.17
November	0.24	1.38	1.40	0.87	2.43
December	0.10	2.20	1.18	2.15	0.11
January	0.14	0.08	2.03	2.11	1.35
February	1.99	1.16	0.59	4.19	0.07
March	1.22	0.16	3.19	1.41	1.99
April	0.27	0.30	0.47	1.31	1.37
May	0.13	0.35	0.51	0.31	7.49
June	0.01	0.03	0.19	0.12	
July	0.13	0.35	0.00	0.00	
August	0.21	0.08	0.00	0.03	
September	0.16	0.16	0.17	0.01	
Total	4.8	6.65	10.19	14.9

Figure 19. Weekly average precipitation (inches) throughout the study period.

2.4.7 Evapotranspiration by Priestley- Taylor Method

2.4.7.1 Net Solar Radiation

Albedo and average daily net solar radiation are required inputs for the Priestly-Taylor method for estimating evapotranspiration. Albedo was calculated to be 0.21. Average daily net solar radiation ranged from -2.01 MJ/kg to 18.30 MJ/kg (Sanford, 2016). The average daily net solar radiation for the entire monitoring period was 7.60 MJ/kg. The peak daily average net solar radiation for water years 2014, 2015, 2016, 2017, and 2018 is 16.16 MJ/kg, 16.79 MJ/kg, 16.86 MJ/kg, 18.66 MJ/kg, respectively. The lowest daily average net solar radiation for water years 2014, 2015, 2016, and 2017 is -0.69 MJ/kg, -0.68 MK/kg, and 0.44 MJ/kg, and 0.38 MJ/kg respectively (Figure 20).

Figure 20. Net solar radiation in (MJ/kg) used in Priestly-Taylor Method for Marian and Control Meadows.

2.4.7.2 Fitted Priestley- Taylor (PT) Coefficients for Evapotranspiration Estimates

Annual values of evapotranspiration were obtained by fitting the PT model to ET values estimated using the sum of soil evapotranspiration and evaporation from interception capture of vegetation from the water budget. The PT coefficient that provided the best fit to the annual soil evapotranspiration and evaporation from interception capture of vegetation was determined to be 0.67 for Marian Meadow and 0.50 for the Control Meadow pre-restoration years. The coefficient used in the Priestly Taylor model for the Marian Meadow and Control Meadow during post-restoration, 2016 and 2017 water years, decreased to 0.45 (Table 18). The PT annual evapotranspiration rates were fit to a coefficient ranging from 0.25 to 0.68 (Table 19 and Figure 21).

For the 2018 WY the data was collected from October 1, 2017 to April 21, 2018 and therefore the PT coefficient was adjusted but is waiting on more data.

Table 18. Annual average PT evapotranspiration rates (mm) determined using different coefficients for the Control and Marian Meadow.

	Control Meadow ET (mm)					Marian Meadow ET (mm)				
	2014 WY	2015 WY	2016 WY	2017 WY	2018 WY	2014 WY	2015 WY	2016 WY	2017 WY	2018 WY
0.25	177.38	179.70	178.86	163.21	37.18	177.38	179.70	178.86	163.21	37.18
0.35	248.33	251.57	250.40	228.49	52.05	248.33	251.57	250.40	228.49	52.05
0.40	283.80	287.51	286.17	261.13	59.48	283.80	287.51	286.17	261.13	59.48
0.45	319.28	323.45	321.94	293.78	66.92	319.28	323.45	321.94	293.78	66.92
0.48	337.01	341.42	339.83	310.10	70.64	337.01	341.42	339.83	310.10	70.64
0.50	354.75	359.39	357.71	326.42	74.36	354.75	359.39	357.71	326.42	74.36
0.55	390.23	395.33	393.48	359.06	81.79	390.23	395.33	393.48	359.06	81.79
0.60	425.70	431.27	429.25	391.70	89.23	425.70	431.27	429.25	391.70	89.23
0.63	443.44	449.24	447.14	408.02	92.94	443.44	449.24	447.14	408.02	92.94
0.65	461.18	467.21	465.02	424.34	96.66	461.18	467.21	465.02	424.34	96.66
0.68	478.91	485.18	482.91	440.66	100.38	478.91	485.18	482.91	440.66	100.38

Table 19. Annual PT Evapotranspiration rates with fitted coefficient compared to evapotranspiration calculated using soil evapotranspiration and evaporation from interception capture of vegetation. 2018 WY results are up to April 2018.

Water Year	Control Meadow		Marian Meadow		Control Meadow	Marian Meadow
	PT ET	Alpha Used	PT ET	Alpha Used		
2014 WY	355	0.50	461	0.65	360	457
2015 WY	360	0.50	483	0.68	345	482
2016 WY	394	0.55	430	0.60	430	417
2017 WY	424	0.65	391	0.60	428	401
2018 WY*	100	>0.68	100	>0.68	255	232
Average Pre-Restoration	358	0.50	472	0.67	353	470
Average Post-Restoration	409	0.60	411	0.60	429	409

*2018 WY is incomplete and still waiting on data collection; 2017 WY had numerous instrument failures suggesting some uncertainty in measured ET values.

Figure 21. Evapotranspiration (in) for Marian Meadow and Control Meadow estimated using Priestly-Taylor Method.

2.4.8 Snow Melt Runoff

The total snowmelt runoff, used as a reference for precipitation input, for the 2017 water year was predicted to be 521 mm. The snowmelt runoff which occurs throughout December through June 2017 experiences 206.3 mm of runoff between February 2, 2017 and March 31, 2017, comprising 40% of the total snowmelt runoff (Figure 22). From December 2017 through April 2018, the Marian and Control meadow experience 328 mm of snowmelt. (Figure 22).

Figure 22. Average daily snowmelt runoff (mm) and snow depth (in) for Control Meadow and Marian Meadow for 2017 and 2018 WY .

2.5 Water Budget Derived from Precipitation, Soil Moisture, and Groundwater Measurements.

Annual observed water budget components in the Control Meadow with meadow vegetation (2014-2016) and Marian Meadow pre-restoration (2014-2015) and post restoration (2016-2018) are summarized (Table 20). There was high variability in precipitation throughout the study period. Annual precipitation ranged from a low of 489 mm in 2014 WY to a high of 1234 mm in the 2017 WY. ET for the study period at the Control Meadow ranged from 345-430 mm/yr. ET was 457 mm/yr and 482 mm/yr in Marian Meadow during the pre-restoration period of 2014 WY and 2015 WY respectively. ET was lower in Marian Meadow, 417 mm/yr and 401 mm/yr for 2016 WY and 2017 WY respectively, following removal of encroached conifers. ET_s values were similar in the Control and Marian Meadows all five years (Table 20). This demonstrates the majority of the reduction in ET, following removal of conifers in Marian Meadow, was due to a reduction in interception capture in those years. In the post-restoration years, ET was very similar between the Marian and Control Meadows.

Surface ponding or runoff (Q_{SEOF}) for Marian Meadow and the Control Meadow increased as precipitation increased (Table 20 and 21). In the 2014 WY Marian Meadow had no Q_{SEOF} while the Control Meadow had 75 mm of Q_{SEOF} . The 2014 WY had below average precipitation and Marian Meadow had considerably more interception evaporation than the Control Meadow, 172 mm compared to 74 mm respectively (Table 3). In 2015 WY higher annual precipitation forced similar Q_{SEOF} values. However following restoration the amount of Q_{SEOF} increased for Marian Meadow control to the Control Meadow suggesting increased water availability due to decreased interception

capture. Additionally the Control Meadow generally had higher infiltration amounts, reducing Q_{SEOF} , except for 2017 WY. The 2017 WY had the greatest amount of error in the Control Meadow water budget. The Control Meadow did have several equipment malfunctions in the 2017 WY suggesting some uncertainty in the 2017 WY results.

ΔS had dissimilar responses between Marian Meadow and the Control Meadow in the pre-restoration time period, 2014, 2015 and 2018 WY. The ΔS was similar between the meadows in the post-restoration time period, except for 2018 WY. However the 2018 WY is not yet complete. ΔS goes down in both meadows in the 2017 WY, the year with the highest precipitation amounts. At higher water tables the slope of the water table surface in the meadows decreases due to longer periods of saturation, as represented by the high Q_{SEOF} levels.

There are several years with a high amount of error in the Control Meadow water budget.

It is not clear why this occurred, it is speculated that there was a lower number of instruments in the Control Meadow and a higher level of instrument failures.

Table 20. Water budget of Marian and Control Meadows for pre-restoration 2014-2015 water years (WY) and three years following restoration by encroached conifer removal 2016-2018 WY. 2018 WY results are up to April 2018.

Location	Vegetation	Water Year	P (mm)	Q_{SEOF} (mm)	I_s (mm)	I_{WT} (mm)	ET_s (mm)	Intcpt (mm)	ET (mm)	error (mm)
Marian	encroached lodgepole pine	2014	489	0	280	22	285	172	457	15
	encroached lodgepole pine	2015	636	107	274	40	268	214	482	2
	meadow veg. and bare ground	2016	931	433	332	90	310	107	417	-31
	meadow veg.	2017	1234	876	263	33	276	124	401	0
	meadow veg.	2018	554	90	170	49	143	89	232	0
Control	meadow veg.	2014	489	75	255	79	286	74	360	6
	meadow veg.	2015	636	102	178	103	258	87	345	167
	meadow veg.	2016	931	374	392	48	323	107	430	9

Location	Vegetation	Water Year	P (mm)	Q _{SEOF} (mm)	I _s (mm)	I _{WT} (mm)	ET _s (mm)	Intcpt (mm)	ET (mm)	error (mm)
	meadow veg.	2017	1234	616	249	57	303	124	428	188
	meadow veg.	2018	554	58	258	32	166	89	255	116

Table 21. Water budget percentage of precipitation for Marian and Control Meadows for pre-restoration 2014-2015 water years (WY) and three years following restoration by encroached conifer removal 2016-2018 WY. 2018 WY results are up to April 2018.

Location	Vegetation	Water Year	P (mm)	Q _{SEOF} (%)	ΔS (%)	ET (%)	error (%)
Marian	encroached lodgepole pine	2014	489	0%	3%	94%	3%
	encroached lodgepole pine	2015	636	17%	7%	76%	0%
	meadow veg. and bare ground	2016	931	47%	12%	45%	-3%
	meadow veg.	2017	1234	71%	2%	32%	0%
	meadow veg.	2018	554	16%	14%	42%	0%
Control	meadow veg.	2014	489	15%	10%	74%	1%
	meadow veg.	2015	636	16%	4%	54%	26%
	meadow veg.	2016	931	40%	13%	46%	1%
	meadow veg.	2017	1234	50%	0%	35%	15%
	meadow veg.	2018	554	11%	23%	46%	21%

2.6 Statistical Analysis

2.6.1 Soil Moisture Statistical Analysis

The average Control Meadow and Marian Meadow soil moisture content prior to and following restoration were significantly different from one another (p-value < 0.000) (Table 21). The interaction between Restoration period and the Control Meadow Soil Moisture is significant (p-value < 0.001). The intercept and slope of the regression relationship between Marian and Control Meadows soil moisture content pre-restoration and one-year post restoration were significantly different from one another (p-value = 0.032 and 0.003 respectively) (Figure 23; Table 22). The intercepts and slopes of the regression relationships between Marian and Control Meadows soil moisture content pre-restoration and during the second year and third year post restoration were significantly different from one another (p-values for second year = 0.003 for intercept and 0.002 for slope; p-values for third year = 0.000 for intercept and 0.000 for slope) (Figure 23; Table 23). Based on Tukey's pairwise comparison of the average soil moisture volumetric

content on the Marian meadow between the different restoration years, the 1st year post restoration and the 3rd year post-restoration period were statistically significantly different from one another (Table 24). Additionally, the 2nd year post restoration average soil moisture was statistically significantly different than the 3rd year post restoration average soil moisture content.

The regression equation used to predict the soil moisture content prior to restoration is:

$$\begin{aligned} \text{Marian Meadow Soil Moisture Content (\%)} = & 18.68 + 0.1339 * \text{Time} + 0.396 * \\ & \text{Control Meadow Soil Moisture Content (\%)} - 0.79 * \text{Season2_1} - 0.41 \\ & * \text{Season2_2} - 2.47 * \text{Season2_3} - 1.31 * \text{Season2_4} + + 0.34 * \text{Season2_5} - \\ & 1.55 * \text{Season2_6} - 4.73 * \text{Season2_7} - 6.64 * \text{Season2_8} - 4.89 * \text{Season2_9} \\ & - 5.92 * \text{Season2_10} - 4.87 * \text{Season2_11} - 6.45 * \text{Season2_12} - 5.53 * \\ & \text{Season2_13} - 4.93 * \text{Season2_14} - 0.73 * \text{Season2_15} \end{aligned}$$

The regression equation used to predict Marian Meadow soil moisture content following restoration for the first-year post-restoration (p values for intercept and slope = 0.032 and 0.003 respectively):

$$\begin{aligned} \text{Marian Meadow Soil Moisture Content (\%)} = & 8.44 + 0.1339 * \text{Time} + 0.874 * \\ & \text{Control Meadow Soil Moisture Content (\%)} - 0.79 * \text{Season2_1} - 0.41 \\ & * \text{Season2_2} - 2.47 * \text{Season2_3} - 1.31 * \text{Season2_4} + + 0.34 * \text{Season2_5} - \\ & 1.55 * \text{Season2_6} - 4.73 * \text{Season2_7} - 6.64 * \text{Season2_8} - 4.89 * \text{Season2_9} \\ & - 5.92 * \text{Season2_10} - 4.87 * \text{Season2_11} - 6.45 * \text{Season2_12} - 5.53 * \\ & \text{Season2_13} - 4.93 * \text{Season2_14} - 0.73 * \text{Season2_15} \end{aligned}$$

The regression equation used to predict Marian Meadow soil moisture content following restoration for the second-year post-restoration was statistically significant (p values for intercept and slope = 0.003 and 0.002 respectively):

$$\begin{aligned} \text{Marian Meadow Soil Moisture Content (\%)} = & 5.25 + 0.1339 * \text{Time} + 0.875 * \\ & \text{Control Meadow Soil Moisture Content (\%)} - 0.79 * \text{Season2_1} - 0.41 * \\ & \text{Season2_2} - 2.47 * \text{Season2_3} - 1.31 * \text{Season2_4} + + 0.34 * \text{Season2_5} \\ & - 1.55 * \text{Season2_6} - 4.73 * \text{Season2_7} - 6.64 * \text{Season2_8} - 4.89 * \\ & \text{Season2_9} - 5.92 * \text{Season2_10} - 4.87 * \text{Season2_11} - 6.45 * \\ & \text{Season2_12} - 5.53 * \text{Season2_13} - 4.93 * \text{Season2_14} - 0.73 * \\ & \text{Season2_15} \end{aligned}$$

The regression equation used to predict Marian Meadow soil moisture content following restoration for the third-year post-restoration was statistically significant (p values for intercept and slope = 0.000 and 0.000):

$$\begin{aligned} \text{Marian Meadow Soil Moisture Content (\%)} = & -15.00 + 0.1339 * \text{Time} + 1.395 * \\ & \text{Control Meadow Soil Moisture Content (\%)} - 0.79 * \text{Season2_1} - 0.41 * \\ & \text{Season2_2} - 2.47 * \text{Season2_3} - 1.31 * \text{Season2_4} + + 0.34 * \text{Season2_5} \\ & - 1.55 * \text{Season2_6} - 4.73 * \text{Season2_7} - 6.64 * \text{Season2_8} - 4.89 * \\ & \text{Season2_9} - 5.92 * \text{Season2_10} - 4.87 * \text{Season2_11} - 6.45 * \\ & \text{Season2_12} - 5.53 * \text{Season2_13} - 4.93 * \text{Season2_14} - 0.73 * \\ & \text{Season2_15} \end{aligned}$$

Figure 23. Pre-restoration and post restoration (2015 WY- 2018 WY) soil moisture content scatter plot.

Table 22. Pre-restoration (2014 - 2015 WY) and post restoration years (2016 WY, 2017 WY, and 2018 WY) soil moisture volumetric percentage (%) ANOVA using all soil moisture instruments

Source	df	SS	MS	F	P
Time	1	194.84	25.72	2.75	0.104
Control Meadow Soil Moisture (%)	1	4257.86	86.23	9.22	0.004
Season2_1		0.05	1.36	0.15	0.704
Season2_2		1.04	0.37	0.04	0.843
Season2_3		33.81	12.75	1.36	0.249
Season2_4		13.1	3.59	0.38	0.538
Season2_5		15.12	0.24	0.03	0.873
Season2_6		14.13	4.96	0.53	0.470
Season2_7		0.32	38.02	4.07	0.050
Season2_8		6.46	70.84	7.58	0.008
Season2_9		1.33	35.03	3.75	0.059
Season2_10		1.28	46.60	4.98	0.030
Season2_11		3.51	29.09	3.11	0.084
Season2_12		13.84	64.74	6.92	0.012

Source	df	SS	MS	F	P
Season2_13		8.87	46.30	4.95	0.031
Season2_14		11.67	40.27	4.31	0.044
Season2_15		4.61	1.04	0.11	0.741
Restoration	3	395.53	91.76	9.81	0.000
Control Meadow Soil					
Moisture (%) *	3	262.67	87.56	9.36	0.000
Restoration					
error	46	430.10	9.34		
total	69	5670.1			

Table 23. Pre-restoration (2015 WY) and post restoration years (2016 WY, 2017 WY, and 2018 WY) soil moisture volumetric percentage (%) parameter estimates

Source	Estimate	Std Error	T ratio	Prob > t
Time	0.14	0.08	1.66	0.104
Control Meadow Soil				
Moisture (%)	0.4	0.13	3.04	0.004
Season2_1	-0.8	2.06	-0.38	0.704
Season2_2	-0.41	2.06	-0.2	0.843
Season2_3	-2.47	2.12	-1.17	0.249
Season2_4	-1.31	2.11	-0.62	0.538
Season2_5	0.34	2.10	0.16	0.873
Season2_6	-1.55	2.13	-0.73	0.470
Season2_7	-4.73	2.35	-2.02	0.050
Season2_8	-6.64	2.41	-2.75	0.008
Season2_9	-4.89	2.53	-1.94	0.059
Season2_10	-5.92	2.65	-2.23	0.030
Season2_11	-4.87	2.76	-1.76	0.084
Season2_12	-6.45	2.45	-2.63	0.012
Season2_13	-5.53	2.49	-2.23	0.031
Season2_14	-4.93	2.37	-2.08	0.044
Season2_15	-0.73	2.2	-0.33	0.741
Restoration				
1 st Year Post Restoration	-10.24	4.64	-2.21	0.032
2 nd Year Post Restoration	-13.42	4.23	-3.17	0.003
3 rd Year Post Restoration	-33.67	6.30	-5.34	0.000
Control Meadow Soil				
Moisture (%) * Restoration				
1 st Year Post Restoration	0.48	0.15	3.11	0.003
2 nd Year Post Restoration	0.48	0.14	3.32	0.002

Source	Estimate	Std Error	T ratio	Prob > t
3 rd Year Post Restoration	1.00	0.21	4.72	0.000

Table 24: Tukey Pairwise Comparisons: Mean Annual Soil Moisture comparison between Marian Meadow restoration years. The means that are statistically significantly different from one another do not share a letter in common.

Restoration	N	Mean	Grouping	
Pre-Restoration	25	31.03	A	B
One-Year Post Restoration	13	33.16	A	
2 nd Year Post Restoration	18	30.00	A	
3 rd Year Post Restoration	14	23.21		B

Means that do not share a letter are significantly different

2.6.2 Water Level (ft below ground) Statistical Analysis

The average Control Meadow and Marian Meadow water level (ft below ground) prior to and following restoration are significantly different from one another (p-value < 0.0000) (Table 25). Based on the Durbin-Watson test statistic of 1.32, there appears to be some serial autocorrelation between the variables and therefore the model may be improved (Table 27). The model fits the data well ($R^2=0.89$) and the residual plots indicate no severe violations to model assumptions. A year variable, rather than an indexed time variable, was used in the model and is not statistically significant (p-value=0.959). Rather than a seasonal component, because there is evidence of seasonality, a quasi-seasonal component “February/March/April” variable was used in the model and is marginally statistically significant (p-value = 0.080).

The interaction is not significant in the model and therefore individual variables were assessed (p-value = 0.628) (Table 25). The first-year post-restoration period was significantly different than the pre-restoration period for the Marian Meadow (p-value = 0.014) (Table 25). The second-year post-restoration period was significantly different than the pre-restoration period for the Marian Meadow (p-value = 0.031) (Table 26). The third-year post-restoration period was not statistically significantly different than the pre-restoration period for the Marian Meadow and is still awaiting data collection from April 2018 until the end of the 2018 water year (p-value = 0.315) (Table 26).

With an R^2 of 0.89, the regression equation used to predict water level (ft. below ground) prior to restoration is:

$$\begin{aligned} \text{Marian Meadow Water Level (ft below ground)} &= 1.035 + (0.6620 * \text{Control} \\ &\text{Meadow Water Level (ft below ground)}) - (0.006 * \text{Year}) - (0.206 \\ &* \text{Feb/March/April}) \end{aligned}$$

The regression equation used to predict Marian Meadow water level (ft. below ground) content following restoration for the first-year post-restoration is (p value= 0.014 respectively):

$$\begin{aligned} \text{Marian Meadow Water Level (ft below ground)} &= 0.370 + (0.6947 * \text{Control} \\ &\text{Meadow Water Level (ft below ground)}) - (0.006 * \text{Year}) - (0.206 \\ &* \text{Feb/March/April}) \end{aligned}$$

The regression equation used to predict Marian Meadow water level (ft below ground) content following restoration for the second-year post-restoration is (p value for slope = 0.001 respectively):

$$\begin{aligned} \text{Marian Meadow Water Level (ft below ground)} &= 0.240 + (0.6707 * \text{Control} \\ &\text{Meadow Water Level (ft below ground)}) - (0.006 * \text{Year}) - (0.206 \\ &* \text{Feb/March/April}) \end{aligned}$$

The regression equation used to predict Marian Meadow water level (ft below ground) content following restoration for the third-year post-restoration is (p value for slope = 0.885 respectively):

$$\begin{aligned} \text{Marian Meadow Water Level (ft below ground)} &= 1.026 + (0.5505 * \text{Control} \\ &\text{Meadow Water Level (ft below ground)}) - (0.006 * \text{Year}) - (0.206 \\ &* \text{Feb/March/April}) \end{aligned}$$

Figure 24. Restoration time periods and Pre-Restoration scatter plot and trendlines between Marian Meadow and Control Meadow depth to water table (feet below ground).

Table 25. Pre-restoration (2015 WY) and post restoration years (2016 WY, 2017 WY, and 2018 WY) water level (ft. below ground). 2018 WY results are up to April 2018.

Source	df	SS	MS	F	P
Regression	9	68.14	7.57	53.64	0.000
Control Meadow Water Level (ft)	1	16.60	16.59	117.58	0.00
Year	1	0.00	0.00	0.00	0.959
Feb/March/Apr	1	0.45	0.45	3.16	0.080
Restoration	3	3.23	1.08	7.62	0.000
Control Meadow Water Level (ft) *	3	0.25	0.08	0.58	0.628
Restoration					
error	59	8.33	0.1412		
total	68	76.47			

Table 26. Pre-restoration (2015 WY) and post restoration years (2016 WY, 2017 WY, and 2018 WY) soil moisture volumetric percentage (%) parameter estimates. 2018 WY results are up to April 2018.

Source	Estimate	Std Error	T ratio	Prob > t
Control Meadow Water Level (ft)	0.66	0.06	10.84	0.000
Year	-0.006	0.124	-0.05	0.959
Control Meadow Water Level (ft)	0.66	0.12	-1.78	0.080
Restoration				
Post Restoration	-0.66	0.26	-2.54	0.014
2 nd Year Post Restoration	-0.80	0.36	-2.21	0.031
3 rd Year Post Restoration	-0.01	0.51	-0.02	0.987
Control Meadow * Restoration (Slope)				
Post Restoration	0.03	0.09	0.36	0.723
2 nd Year Post Restoration	0.00	0.11	0.08	0.937
3 rd Year Post Restoration	-0.11	0.11	-1.01	0.315

Table 27: Durbin-Watson Statistic

Durbin-Watson Statistics	Value
Durbin-Watson Statistic	1.32

Durbin-Watson test statistic takes a value between 0-4; as it approaches 0, there is evidence of positive autocorrelation

2.7 Discussion

2.7.1 Groundwater Depth and Soil Moisture Content

2.7.1.1 *Water Table Depth in Marian and Control Meadow*

Utilizing the pre-restoration groundwater depth regression equation, the predicted Marian Meadow groundwater depth (ft) for post-restoration years 1, 2, and 3 were determined to be 1.97 feet, 1.66 feet, and 2.11 feet respectively. The measured average groundwater depth for post-restoration years 1, 2, and 3 was 1.39, 0.89, and 1.90 feet respectively (Table 28). The difference between the measured and predicted groundwater depth represents a 45% increase in measured values and a gain of 27.9-acre feet of water stored as groundwater during the first year post-restoration. An 87% increase in measured values and a gain of 34.65-acre feet of water stored as groundwater during the second year post-restoration. For the 2018 WY up to the end of April there was an 11% increase in groundwater volume a gain of 9.45-acre feet of water (Table 28).

The difference between predicted and measured groundwater depth values ranged from 0.006 feet to 1.28 feet. The greatest variability in the model appeared to occur when water table levels were increasing (January 2017 through April 2017) and during the second and third post restoration years (Figure 25). Visual inspection of Figure 25 illustrates that some water-level measurements generally mimics moving averages of weekly precipitation, however, the difference in the Marian Meadow water levels and the Control Meadow water levels were statistically significantly different from one another ($p < 0.05$) for pre-restoration and 2017 WY.

Figure 25: Marian Meadow predicted – observed weekly groundwater depths (ft below ground) for pre-restoration and two years post-restoration values. A positive value means the observed groundwater level is closer to the surface (more groundwater).

Table 28. Predicted – observed water level values converted to acre feet gain in Marian Meadow

Average WL	Predicted Water level	Measured WL Averages	Difference	% increase	Acre Feet
Pre-Restoration	1.99	1.99	0.00	0%	
1 Year	1.97	1.36	0.62	45%	27.9
2 Year	1.66	0.89	0.77	87%	34.65
3 Year*	2.11	1.90	0.21	11%	9.45

* not a complete water year; results are up to April 2018.

2.7.2 Growing Season Groundwater Depth

In wetland environments, it is typical that the groundwater depth is the primary factor controlling the distribution of herbaceous vegetation communities (Mitsch and Gossenlink, 2000; Hammersmark, 2009). However, there are other factors that can influence plant productivity including flooding, competition, grazing intensity, nutrient availability, soil properties, fire history, and diseases. Plant community types are largely distributed along a hydrologic gradient, from most xeric to most mesic. The average growing-season water-table depth is indicative of plant community type, and therefore

meadow classification. The number of days on average the water level is at or above 2.3 feet (70 cm) represents the number of days the meadow is within the root zone typical of xeric herbaceous plant species ($WL < 70$ cm or 2.3 feet). The number of days on average the water level is at or above 1.0 foot (30 cm) represents the number of days the meadow is within the root zone typical of mesic and hydric herbaceous plant communities ($WL < 30$ cm).

During the 2014 growing season and prior to restoration, Marian Meadow and Control Meadow experienced average growing season water levels of 4.47 feet (136.25 cm) and 4.48 feet (136.55 cm)(Table 12). Water levels were on average deeper than 3.28 ft (1 meter), and therefore indicative of a dry meadow as classified by Weixelman et al. (2011). During the 2015 growing season, Marian Meadow and Control Meadow experienced average growing season water levels of 4.61 feet (140.51 cm) and 4.65 feet (141.73 cm)(Table 12; Figure 26), indicative of a dry meadow. In assessing the number of days the water level was within 2.3 feet (70 cm) and 1.0 foot (30 cm), another meadow species community type indicator, the Marian Meadow exhibited growing season water levels indicative of a meadow with a high proportion of obligate, facultative wetland, and facultative plant species (Hammersmark *et al*, 2009). The number of days the water level was less 1.0 foot (30 cm) for 2014 and 2015 growing season was 0 and 20 days. The number of days the water level was less than 2.3 feet (70 cm) for the 2014 and 2015 growing season were 0 days for both growing seasons.

During the 2016 growing season and post-restoration, the Marian Meadow and Control Meadow experienced average growing seasons water levels 2.27 feet (69.19 cm) and 2.49 feet (75.90 cm)(Table 12; Figure 26). Water levels (feet below ground) were on

average less than 3.28 feet (1 meter), and within the rooting zone of 2.3 feet which supports common dry meadow plant species (Hammersmark et al., 2010). The number of days the water level was less than 1.0 foot (30 cm) was 27 days and less than 2.3 feet (70 cm) was 61 days for 2016 growing season. During the 2016 growing season, the Marian meadow exhibited water levels supportive of *Carex nebrascensis* / *Juncus balticus* species which are facultative wet (FACW) and Obligate (OBL) species. Following restoration, the water table increased and became more conducive to a mesic community type (Table 12; Figure 27).

During the 2017 WY, second year post restoration, the Marian Meadow and Control Meadow experienced average growing seasons water levels 2.30 feet (70.10 cm) and 2.03 feet (61.87 cm) (Table 12; Figure 26). Groundwater elevations were, on average, less than 3.28 feet (1 meter), and within the rooting zone of 2.3 feet which supports common dry meadow plant species (Hammersmark et al., 2010). The number of days the water level was less than 1.0 foot (30 cm) was 24 days and less than 2.3 feet (70 cm) was 64 days for 2017 growing season (Table 12). During the 2017 growing season, the Marian meadow continued to exhibit water levels similar to the 2016 growing season and supportive of *Carex nebrascensis* / *Juncus balticus* species (Figure 26).

Following restoration, the water table increased and became more conducive to a mesic community type (Table 12). Pre-restoration, the number of days the water level was less than 2.3 feet (70 cm) was approximately 20 days and the number of days the water level was less than 1.0 foot was 0 days, therefore indicative of a dry meadow. During post-restoration, number of days the water level was less than 2.3 feet (70 cm)

was approximately 125 days and the number of days the water level was less than 1.0 foot was 51 days (Table 12)(Figure 27).

Figure 26. Average growing season water level (ft below ground) for Marian Meadow during 2014, 2015, 2016, and 2017 growing season.

Figure 27. Average growing season water level (ft below ground) in Marian Meadow for pre-restoration and post-restoration time periods.

2.7.3: Soil Moisture

The interaction between Restoration periods and Control Soil Moisture is significant ($p\text{-value} < 0.001$) which means after adjusting for time and seasonality in the data, the change in Marian Meadow soil moisture for each percent increase in the Control Meadow Soil Moisture depends on the restoration year period. There was a statistically significant difference in the relationship between Marian Meadow and Control Meadow soil moisture content among pre-restoration and each year post restoration period (Table 22). The Marian Meadow experienced increased volumetric soil moisture when compared to the Control Meadow during the second year after restoration compared with pre-restoration and third year post restoration values. Based on the Tukey comparison, the mean Marian Meadow soil moisture in the pre-restoration period is not significantly different from the mean soil moisture in any of the post-restoration periods. The mean soil moisture is different between the 2nd year and 3rd year post-restoration, which can be attributed to the lack of data collected during the 3rd year post-restoration (stops in April 2018). The slope is statistically significantly different in all three years compared with the pre-restoration period. During winter when the soil moisture is high, the soil moisture in Marian Meadow increased in the post-restoration periods. When soil moisture is low, during summer, the soil moisture decreases in Marian Meadow in the post-restoration years.

On average soil moisture decreased on by 3.03 % during the months of August through October and increased by 3.39 % during the months of November through June during pre-restoration. Following restoration years, there is an average soil moisture decrease of 3.62% from August through October and an average of 16.07% increase in soil moisture from November through June. Assuming the 16.07% increase measured

1.0 foot below the surface was consistent from the surface to the water table, and with an average water table depth of 2.71 ft following restoration, this increase represents an increase of 7.23 acre-feet of water stored in the soil because of removing the conifers.

Periods of high evapotranspiration losses combined with reduced interception losses and greater annual precipitation values can attribute to the increased soil moisture content during the first year following restoration. Inversely, as vegetation growth increases in the meadow post-restoration, the soil moisture decreases slightly from increased interception loss and evapotranspiration. Evidence from previous research shows that in clear cut areas, the soil moisture losses are diminished and replenished sooner (Bethlahmy, 1962). Similarly, the Marian Meadow experienced more rapid fall recharge of soil moisture following the first fall rain events post-restoration.

The difference between observed and predicted Marian Meadow soil moisture values ranged from 0.14 % to 19.64 % volumetric soil moisture (Figure 28). The greatest variability, 19.64% occurs in the 2018 WY since the summer months of 2018 WY have yet to be collected.

2.7.4 Upslope Harvest

Effects from the upslope harvest were difficult to discern for the 2018 WY. There was not an obvious increase in groundwater in the winter of 2018. However, it was a low precipitation year. There is an overall increase in soil moisture following the completion of the conifer removal in June 2015 and during the upslope harvest ending in winter 2017 (Figure 10). Directly following the completion of the upslope harvest, the Marian meadow experiences 29.9 % soil moisture during the months of December 2018 through

March 2018 one foot below ground and an average of approximately 44% soil moisture 3 feet below ground. The winter 2018 received a total of 4.89 inches during the months of December through April yet experiences higher soil moisture at 3 feet below ground than the first-year winter (Winter 2016) following restoration which received 7.46 inches of rain. This could be attributed to an increase in stored soil moisture at three feet depth due to restoration or increased water level. The greatest percent increase in soil moisture occurs during the months of November through June, averaging 27% increase in soil moisture. It is unlikely that the increase in soil moisture is due to the upslope harvest, since the groundwater was not significantly higher. The increased soil moisture may be the result of decreases in soil evaporation losses as the meadow vegetation fills in.

Table 29. Soil Moisture (%) and Water level (ft. below ground) on the Marian Meadow during the winter 2018, directly following upslope harvest completion, compared with preceding winter 2017 data.

	Precip. (in)	Soil moisture (%) at 1' below surface	Soil moisture (%) at 3' below surface	Water level (ft below ground)
December - April 2016	7.46	38.77	42.79	1.32
December - April 2017	11.17	41.29	50.17	0.47
December - April 2018	4.89	29.90	43.88	1.89

Figure 28. Pre-restoration – observed average volumetric soil moisture values (%).

2.7.4.1 Evapotranspiration

The PT coefficient that best fit the annual evapotranspiration rates for Marian Meadow was 0.67 for pre-restoration, the time-period when the meadow had encroached conifers. Data from previous research determined a PT coefficient ranging from 0.65 to 0.68 for moderate vegetation to temperature coniferous forests (Komatsu, 2005; Hamimed et al., 2014; Van Oosbree, 2015) and a coefficient of 0.35 for sparse vegetation or bare soil (Hamimed et al., 2014). Based on the Priestly Taylor model the best fit coefficient for time periods during which the Marian Meadow and Control Meadow was lacking conifers was an alpha of 0.60. The Control Meadow Preistley Taylor coefficient increased from 0.50 to 0.60 between the pre- and post-restoration suggesting possible increases in vegetation density during the study period (Table 18).

The alpha decreased by 0.07 from pre-restoration to post-restoration for Marian Meadow evapotranspiration. This is only a small change in the coefficient. The soil ET calculated in the water budget was relatively similar through the 5 years of study at the Control Meadow and Marian Meadow (Table 20). This similarity between years for soil

ET was observed in a study on transpiration in the Sierra Nevada (Christenson et al., 2008). Christensen et al. (2008) found ET in low lying areas within elevations similar to Marian and Control Meadows, had little inter-annual variability due to topographic controlled high soil moistures.

Chapter 3. Marian Meadow Revegetation Plot Analysis

3.1 Methods

Three revegetation sites were established on the Marian meadow on April 30, 2017 (Site 1, Site 2, and Site 3; Figure 29). Within each site there were a total of three subplots (Figure 30). Subplots included a cluster of three 1 m² grids that represented one of three revegetation techniques: (BARE) seeds manually dispersed over bare soil with top soil and vegetation removed, (WOOD) seeds manually dispersed over bare soil with top soil and vegetation removed and woody debris placed on top, and (EXISTING) seeds manually dispersed over existing soil and existing vegetation conditions. Technique BARE and WOOD include shallow top soil removal (TSR) up to 10 cm (approximately 4 inches) application to remove the unwanted seed banks and accumulated nutrients. Three species were chosen for the revegetation techniques: *Deschampsia cespitosa* (tufted hairgrass) (seed species TH), *Agrostis exarata* (spike bentgrass)(seed species SB), and *Deschampsia elongata* (slender hairgrass)(seed species SH). The species selected are native to the Marian Meadow. Two of the seed types (Seed species SH and SB) were donated by Hedgerow Farms in Winter, California. Hedgerow Farms collected *D. elongata* from Sacramento County along the Consumnes River and *A. exarata* from Tehama County in Kopta Slough. The third seed type, Seed TH, were donated by Lassen National Forest and were collected adjacent to Marian Meadow. Seeds dispersed on the Marian Meadow were collected as close to the site as possible to prevent any influence on the genetic composition of prior and existing meadow plant communities. The wetland plant status for all three seed species is facultative wet (FACW; Table 30)(USDA, 2017).

Table 30: Seed species used in revegetation plots on Marian Meadow

Seed Name for Report	Scientific Name	Common Name	Wetland Plant Status	Sourced
TH	<i>Deschampsia cespitosa</i>	Tufted hairgrass	FACW	Lassen National Forest
SB	<i>Agrostis exarata</i>	Spike bentgrass	FACW	Hedgerow Farms, Winters CA
SH	<i>Deschampsia elongata</i>	Slender hairgrass	FACW	Hedgerow Farms, Winters CA

Three locations with three -1 m² subplots were evaluated. The 1 m² subplots were divided into 12 grids (approximately 18 cm x 18 cm). For every grid there was one species type randomly assigned with twenty seeds of that same species dispersed. Each subplot had one of the three techniques implemented (Figure 30).

3.1.1 Site Locations

The three sites for evaluation on Marian Meadow were established and assigned using a stratification process based on similarities in elevation but variation in hydrologic influence, based on growing season days at different water table depths. Each site was established adjacent to water level instruments and clustered to control for variation in soil type. The locations were established on the same elevation across the Marian Meadow. Elevations of Marian Meadow were determined using a 30-m DEM, provided by The Collins Pines Company. The DEM was converted to a 1-foot contour layer in ArcMap and used to determine three site locations (Figure 29).

The hydrologic influence was analyzed based on two criteria: average groundwater depth (ft below ground)(referred to as WTD) of the growing season (May through August) and number of growing season days with a shallow water table

(Hammersmark, 2009). An average WTD for a growing season that supports hydric plants is 1.98 feet (Hammersmark, 2009). A mesic/hydric vegetation community requires a mean of 65 days with a WTD below 2.3 ft. (0.70 m) and approximately 42 days with a WTD below 1 foot (0.31 m) (Hammersmark et al., 2009).

Site 3 was located adjacent to water level (WL) sensor 3-1 on the Marian Meadow because the average WTD for the 2016 growing season was 1.98 feet below ground (Table 31). This depth has been shown to support hydric meadow plant species (Hammersmark et al., 2009). The second criteria, number of growing season days with a shallow water table supporting a mesic/hydric vegetation community type, was assessed on the Marian Meadow and did not fit any of the water level sensors for the 2016 growing season. Therefore, WL sensor 3-1 was chosen which included the highest amount of days, 56 days total, with a shallow groundwater table below 1.0 foot (0.31m) (Table 33).

After the WL sensor was determined adjacent to Site 3, the WL sensors for Site 1 and Site 2 were determined based on differences with WL Sensor 3-1, and similarities in elevation with Site 3. Site 1 is adjacent to WL sensor 4-1 and Site 2 is adjacent to WL sensor 6-3, which provided variation in hydrology (Figure 29).

Table 31. Average 2016 growing season WTD below soil surface (ft) of selected water level sensors for revegetation plots.

Date	3-1 WL	4-1 WL	6-3 WL
5/6/2016	0.26	0.59	0.93
5/13/2016	0.28	0.84	1.24
5/20/2016	0.25	0.73	2.19
5/27/2016	0.35	1.09	1.52
6/3/2016	0.40	1.41	1.84
6/10/2016	0.48	1.73	2.07
6/17/2016	0.75	1.84	2.22
6/24/2016	1.49	2.09	2.51
7/1/2016	2.35	2.28	2.86
7/8/2016	2.40	2.53	3.29
7/15/2016	2.45	2.75	3.46
7/22/2016	2.51	3.01	3.47
7/29/2016	3.19	3.37	3.50
8/5/2016	3.91	3.87	3.50
8/12/2016	3.91	4.12	3.51
8/19/2016	4.21	4.39	3.51
8/26/2016	4.52	4.68	3.51
Average 2016 Growing Season WTD (ft)	1.98	2.43	2.66

Table 32: Average 2016 Growing Season WTD (ft.) below soil surface of water level instruments on Marian Meadow and Control Meadow.

Date	Marian Meadow WL sensors						
	3-1 WL	3-4 WL	4-1 WL	6-3 WL	6-4 WL	9-2 WL	9-3 WL
5/6/2016	0.26	0.20	0.59	0.93	0.83	1.08	0.09
5/13/2016	0.28	0.51	0.84	1.24	1.23	1.38	0.52
5/20/2016	0.25	0.39	0.73	2.19	1.11	1.39	0.36
5/27/2016	0.35	0.73	1.09	1.52	1.53	1.73	0.88
6/3/2016	0.40	1.08	1.41	1.84	1.93	2.12	1.29
6/10/2016	0.48	1.37	1.73	2.07	2.24	2.53	1.63
6/17/2016	0.75	1.47	1.84	2.22	2.39	2.95	1.91
6/24/2016	1.49	1.65	2.09	2.51	2.64	3.61	2.23
7/1/2016	2.35	1.75	2.28	2.86	2.86	3.84	2.51
7/8/2016	2.40	1.99	2.53	3.29	3.15	4.05	2.88
7/15/2016	2.45	2.16	2.75	3.46	3.48	4.27	3.29
7/22/2016	2.51	2.34	3.01	3.47	3.80	4.51	3.64
7/29/2016	3.19	2.59	3.37	3.50	7.94	4.75	3.89
8/5/2016	3.91	2.80	3.87	3.50	4.23	5.01	4.10
8/12/2016	3.91	3.00	4.12	3.51	4.49	5.29	4.33
8/19/2016	4.21	3.24	4.39	3.51	4.77	5.57	4.56
8/26/2016	4.52	3.51	4.68	3.51	5.07	5.88	4.81
Average 2016 Growing Season WTD (ft)	1.98	1.81	2.43	2.66	3.16	3.53	2.52

Table 33: The number of days that report a shallow groundwater table below 1.0 foot (<0.3 m) or between 1.0 foot and 2.3 feet (0.31 m to 0.70 m) for each WL sensor on the Marian Meadow for the 2016 growing season.

Marian Meadow WL Sensors							
	3-1 WL	3-4 WL	4-1 WL	6-3 WL	6-4 WL	9-2 WL	9-3 WL
Days with WTD < 1.0 ft	56	35	28	11	13	1	31
Days with WTD between 1.0 ft - 2.3 ft	5	50	37	39	35	39	29
Total Days	61	85	65	50	48	40	60

Figure 29: Marian Meadow Revegetation Plot location adjacent to 3-1 WL, 4-1 WL, and 6-3 WL within similar topology and elevation.

Figure 30: Site 1 on the Marian Meadow showing the three -1m² grids with 12 sub-grids apiece.

3.1.2 Vegetation Establishment and Analysis

On August 8, and 9 2017, approximately 3 months after technique and seed dispersal, the number of planted species rooted within each subgrid were recorded. A random effects model (REML) for binary data with square root transformation were used in JMP Pro 12 statistics program software. Revegetation technique types, seed species type, and groundwater elevation, were used as fixed effects, while replicates of the site number, plot number, and subplot number were used as random effects, with plot number nesting in site number, and subplot number nesting in plot.

3.2 Results

3.2.1 Species Type

Species type had significant effects on population seed count. The population of seed species according to species types were significantly different from each other (p-

val<0.0001). Seed species type TH yielded the highest 2017 average growing season established seed count, with a 6.69 average seed count/grid and is statistically significantly different from the other species (p-val < 0.0001, t-ratio=5.53)(Table 34 and Figure 31). A Tukey HSD test conducted determined that all three species were significantly different from one another (p-val<0.05).

Table 34: The least squared means and standard error for each species type used in the revegetation plots, measuring seed count for the 2017 growing season.

Species Type	Least Square Means	Standard Error
TH	6.69	0.03
SB	4.80	0.03
SH	3.42	0.03

Figure 31: Average 2017 growing season seed count for species type TH, SB, and SH.

3.2.2 Technique Type

The variances for the three techniques were statistically significantly different from one another (p-val <0.0001). BARE technique yielded the highest 2017 average growing season established seed count, with a 8.24 average established seed count/grid

and is statistically significant in determining the number of native meadow seed species (p-val = 0.0004, t-ratio=4.15)(Table 35 and Figure 32).

A Post-Hoc Tukey's test showed that Technique BARE and Technique WOOD were significantly different than Technique EXISTING (p-val<0.05); Technique BARE and Technique WOOD were not significantly different from one another (p > 0.05).

Table 35: The least squared means and standard error for each technique type used in the revegetation plots, measuring seed count for the 2017 growing season.

Species Type	Least Square Means	Standard Error
BARE	8.24	0.22
WOOD	5.70	0.22
EXISTING	2.54	0.22

Figure 32: Average 2017 growing season seed count (square root transformed in JMP) for techniques type BARE, WOOD, and EXISTING.

3.2.3 Species Types and Technique Interaction

There were two interactions that were statistically different from the other interactions in determining population: species type TH using technique BARE (p-value

= 0.0087, t-ratio= 2.64) and seed species type SB using technique BARE (p-value=0.0046, t-ratio=-2.85) (Table 36 and Figure 33).

Table 36: The least squared means and standard error for each combination of species type and technique type used in the revegetation plots, measuring seed count for the 2017 growing season.

Combination of Techniques	Least Square Means	Standard Error
*Species TH, BARE	3.504	0.253
Species TH, WOOD	2.734	0.253
Species TH, EXISTING	1.519	0.253
*Species SB, BARE	2.577	0.253
Species SB, WOOD	2.488	0.253
Species SB, EXISTING	1.504	0.253
Species SH, BARE	2.532	0.253
Species SH, WOOD	1.941	0.253
Species SH, EXISTING	1.070	0.253

* Indicates p-value<0.05

Figure 33: Average 2017 growing season seed count (square root transformed in JMP) for species type TH, SB, and SH using technique types BARE, WOOD, EXISTING.

3.2.4: Water Table Depths (WTD)

The water level sensors adjacent to each site measured at two-hour increments which was averaged by week and day for each site (Table 37 and Table 38). The WTD was not a significant predictor of the number of seeds established at the end of the growing season (p-value = 0.49). The number of days with a shallow water table <1 foot (<0.3 m) were not significant predictors of the number of seeds established at the end of the growing season for any species or technique.

Table 37: Average Growing Season Water Table Depth (ft. below ground) from May to August 2017 for each of the three revegetation sites established on the Marian Meadow

Date	Site 1 4-1 WL	Site 2 6-3 WL	Site 3 3-1 WL
5/5/2017	0.49	0.83	1.03
5/12/2017	0.59	0.87	1.16
5/19/2017	0.87	1.13	1.30
5/26/2017	1.21	1.47	1.50
6/2/2017	1.44	1.69	1.72
6/9/2017	1.57	1.79	1.81
6/16/2017	1.74	1.83	1.90
6/23/2017	2.00	2.10	2.09
6/30/2017	2.25	2.43	2.27
7/7/2017	2.46	2.83	2.47
7/14/2017	2.58	3.28	2.73
7/21/2017	2.67	3.49	3.06
7/28/2017	2.98	3.50	3.51
8/4/2017	3.40	3.51	3.72
Avg WTD (ft)	1.87	2.20	2.16

Table 38. Total Days with WTD below 1.0, between 1.0 and 2.3, and between 2.3 and 3.0 feet below ground.

	Site 1 4-1 WL	Site 2 6-3 WL	Site 3 3-1 WL
Days with WTD < 1.0 ft	7	24	20
Days with WTD between 1.0 ft and 2.3 ft	58	41	41
Days with WTD between 2.3-3.0'	19	27	12
Total Days < 1.0' and between 1.0' < 2.3' WTD	65	65	61

3.3 Discussion

Knowledge of establishment rates of three different native species and three different revegetation techniques can be useful in the selection of appropriate revegetation in meadow restoration in the South-Eastern Cascade Mountain Range, specifically on previously encroached montane meadows. Our study shows that the seed population of *D. cespitosa* yields the highest population count after the 2017 growing season in all three sites (p-val <0.05). The distance between the three sites is approximately 50 feet (15 m) (Figure 2), and therefore the genetic differences and soil type differences among the 144 populations may contribute to variation in seed count. Technique BARE was statistically significant, yielding the highest population count. Shallow top soil removal (TSR) up to 15 cm has well known positive effects on species development but is not commonly used in restoration. This application can be an effective mechanism to “reset” a degraded peatland to its initial state of nutrient limitation, base saturation and high availability of light (Emsens et al., 2015). Although sediment removal in restored playas exports accumulated nutrients from surface soils, more C is stored in subsurface depths, allowing them to substantially contribute C sequestration (Dale et al., 2017). Sediment removal practices for depressional wetlands increases services such as water storage volume, biodiversity provisioning, and habitat for wetland biota (Beas et al., 2013; Dale et al., 2017).

The BARE technique is very cost intensive and does not come without risk, the potential for this approach to rehabilitate meadows to a functional state may result in wider benefits (Klimkowska et al., 2010b). Playas in Nebraska that have had top soil removal have shown to have functional attributes more similar to historic conditions (Beas et al., 2013; Daniel et al., 2015, Dale et al., 2017). However, since there is very

limited data on the effects of TSR on previously encroached montane meadows, another growing season data collection of plant population count is suggested.

Chapter 4. Conclusions

4.1 Conclusions Overview

Removing conifers from an encroached montane meadow in the south eastern cascade mountain range can improve the meadow hydrology. The statistical analysis of the soil moisture and observations of groundwater level in the Marian and Control Meadow identified an increase in ground and soil water. The statistical model showed that there was a statistically significant increase in soil moisture between pre-restoration and all three post-restoration years. The statistical groundwater model showed that there was a statistically significant increase in groundwater depth (ft below ground) between pre-restoration and the 1st and 2nd post-restoration years. The 3rd post-restoration year groundwater depth was not significantly different than pre-restoration groundwater depth, however the 3rd year post-restoration was not completed at the time this thesis was prepared. Overall, there was an increase of volumetric soil moisture content of approximately 16.07% during the months of November through June. The third-year post-restoration exhibited higher soil moisture values than the prior two post-restoration years.

The increase in the groundwater depth resulted in a total of gain of 27.9 acre feet of water stored as groundwater during the first-year post-restoration and a gain of 34.65 acre feet of water stored as groundwater during the second year post-restoration.

An increase in days during the growing season with elevated groundwater in Marian Meadow showed that the xeric-supported community type that existed prior to restoration shifted to a mesic supported community, indicative of a wet meadow. The re-

vegetation study design showed that manual restoration exhibited statistically significant results in producing higher seedlings than seed dispersal. Another season of data collection and a control plot would help determine further results. The study design suggests that some type of top soil removal and manually planted seeds would result in higher seedling population and therefore a greater opportunity for meadow plant species to colonize the meadow.

Periodic removal of conifers may be necessary within the Marian Meadow so that the recolonization of meadow plant species and elevated soil moisture conditions can take place. Nonetheless, the combination of the statistical analysis results, the Hammersmark-defined growing season water table depth data, and the water balance provide enough information to conclude that the removal of encroached conifer encouraged hydrologic characteristics that can promote the maintenance of Marian Meadow.

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Appendix A. Electrical Resistivity Tomography Survey Details

Appendix A

A. Electrical Resistivity Tomography survey details and locations

Appendix A. Electrical Resistivity Tomography Survey Details

Table 39: ERT Survey Descriptions (Van Osobree, 2013; Sanford, 2015)

Date	Meadow	Survey #	Survey Line	Lat (°)	Long (°)	Azimuth towards Node 1 (°)	Survey Length (m)	Node Spacing (m)
9/10/2013	Marian	1	Upper bisecting long line	40.26413	-121.31631	65	115	5
9/10/2013	Marian	2	Upper bisecting short line	40.26413	-121.31631	65	34.54	1.5
9/10/2013	Marian	3	Marian transect	40.26416	-121.31636	340	51.75	1.5
9/10/2013	Marian	4	Lower bisecting transect	40.2639	-121.31616	230	51.75	1.5
5/3/2014	Control	5	Ecotone boundary	40.265071	-121.394067	55	56	5
5/3/2014	Marian	6	Marian transect	40.26325	-121.314062	220	175	5
5/3/2014	Marian	7	Upper bisecting line	40.263952	-121.316121	245	56	1.5
9/6/2014	Control	8	Ecotone boundary	40.264983	-121.394165	70	47	2
9/6/2014	Control	9	Center transect	40.264117	-121.394534	335	175	1.5
9/6/2014	Control	10	Upper bisecting line	40.263404	-121.394209	60	34.5	5
9/6/2014	Control	11	Lower bisecting line	40.264091	-121.39442	60	34.5	1.5
9/6/2014	Marian	12	Upper bisecting line	40.263962	-121.316015	272	51.75	1.5
9/6/2014	Marian	13	Marian transect	40.263462	-121.315577	345	115	5
9/6/2014	Marian	14	Lower bisecting line	40.263286	-121.315321	25	51.75	1.5
9/6/2014	Marian	15	Lower Marian Creek bisecting line	40.261006	-121.3117	278	34.5	1.5
9/6/2014	Marian	16	Lower Marian Creek line	40.261443	-121.311618	15	92	4

Appendix A. Electrical Resistivity Tomography Survey Details

Date	Meadow	Survey #	Survey Line	Lat (°)	Long (°)	Azimuth towards Node 1 (°)	Survey Length (m)	Node Spacing (m)
3/27/2015	Control	17	Center transect	40.264117	-121.394534	335	175	5
3/27/2015	Control	18	Lower bisecting line	40.264091	-121.39442	60	34.5	1.5
3/27/2015	Control	19	Upper bisecting line	40.264801	-121.394897	85	46	2
3/27/2015	Marian	20	Upper bisecting line	40.261081	-121.311715	68	51.75	1.5
3/27/2015	Marian	21	Marian transect	40.263462	-121.315577	345	115	5
3/27/2015	Marian	22	Lower bisecting line	40.263286	-121.315321	25	51.75	1.5
3/27/2015	Marian	23	Lower Marian Creek bisecting line	40.261006	-121.3117	278	34.5	1.5
3/27/2015	Marian	24	Lower Marian Creek line	40.261443	-121.311618	15	92	4
9/9/2015	Control	25	Center transect	40.264117	-121.394534	335	175	5
9/9/2015	Control	26	Lower bisecting line	40.263384	-121.394385	84	34.5	1.5
9/9/2015	Control	27	Upper bisecting line	40.264801	-121.394897	85	46	2
9/9/2015	Marian	28	Upper bisecting line	40.263962	-121.316015	272	51.75	1.5
9/9/2015	Marian	29	Marian transect	40.263731	-121.315723	315	115	5
9/9/2015	Marian	30	Lower bisecting line	40.263281	-121.315309	25	34.5	1.5
9/9/2015	Marian	31	Lower Marian Creek line	40.261366	-121.311697	0	92	4
9/9/2015	Marian	32	Lower Marian Creek bisecting line	40.26119	-121.311757	95	34.5	2

Appendix A. Electrical Resistivity Tomography Survey Details

Date	Meadow	Style #	Survey Line	Lat (°)	Long (°)	Azimuth towards Node 1 (°)	Survey Length (m)	Node Spacing (m)
7/18/2017	Control	CM2	Control Transect	40.26354	-121.39421	65	100	1.5
7/18/2017	Control	CM3	Control Transect through trees	40.26476	-121.39493	72	100	2
7/18/2017	Marian	UM3	Lower Marian Transect	40.26329	-121.31536	25	100	1.5
7/18/2017	Marian	UM1	Upper Marian Transect	40.26376	-121.31661	50	100	1.5

Figure 34. September 2013 ERT surveys. No ERT survey was conducted on Control Meadow Sept. 2013 (Van Osobree, 2013; Sanford, 2015)

Appendix A. Electrical Resistivity Tomography Survey Details

Figure 35. May 2014 ERT Surveys

Appendix A. Electrical Resistivity Tomography Survey Details

Figure 36. September 2014 ERT Surveys (Van Osobree, 2014; Sanford, 2015)

Appendix A. Electrical Resistivity Tomography Survey Details

Figure 37. March 2015 ERT Surveys (Sanford, 2016).

Appendix A. Electrical Resistivity Tomography Survey Details

Figure 38. September 2015 ERT Surveys (Sanford, 2016) and 2017 surveys.