# THE WATER TABLE AND SOIL MOISTURE RESPONSE FOLLOWING THE REMOVAL OF CONIFERS FROM AN ENCROACHED MEADOW

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# ABSTRACT

The Water Table and Soil Moisture Response Following the Removal of Conifers from an Encroached Meadow

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Montane meadows play a key role in the physical and biologic processes of coniferous forests in the western United States. However, 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 loss due to conifer encroachment. To combat this issue, encroaching conifers can be removed in an attempt to increase meadow habitat and function. While multiple studies have assessed changes in soil structure and vegetation composition, few studies directly investigate changes in hydrology following meadow conifer removal projects. The goal of this study is to determine if the removal of conifers from an encroached meadow (Marian Meadow) has an effect on soil moisture and groundwater depth such that meadow hydrologic conditions are promoted. This goal will be accomplished by the following objectives: 1) develop a water budget incorporating groundwater depth, soil moisture, and climate measurements to quantify the hydrologic processes prior to and after conifer removal, 2) conduct a statistical analysis of the project meadow's wet season water table depth prior to and after conifer removal, 3) conduct a statistical analysis of the meadow's soil moisture prior to and after conifer removal. Marian Meadow is located 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 and water table depth sensors were installed in Marian Meadow and a control meadow in September 2013. The soil moisture sensors were installed at one and three foot depths. Soil moisture and water table depth measurements used in this study span from September 2013 through June 2016. The removal of encroaching conifers from Marian Meadow occurred in July 2015. Evapotranspiration was estimated using the Priestly Taylor equation. Electrical Resistivity Tomography (ERT) was used to determine maximum water table depths. A groundwater recession curve equation was used to model water table depths between water table depth sensor measurements and ERT measurements. Standard least squared linear regression and ANCOVA was used to determine any statistical significant difference in soil moisture and water table depths prior to and after conifer removal. 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 0.58 feet following conifer removal. Relative to the control meadow, soil moisture in Marian Meadow initially decreased following conifer removal. However, from November 2015 through June 2016 soil moisture increased. On average soil moisture increased by 4% following conifer removal. Also, 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 INTRODUCTION

Montane meadows play a key role in the physical and biologic processes of coniferous forests in the western United States (Roche et al., 2014). However, due to causes such as climate change, over grazing, and fire exclusion, conifer encroachment into meadows has accelerated. In some western regions, nearly half of all meadow habitat has been loss due to conifer encroachment (Miller and Halpern, 1998; Norman and Taylor, 2005). To combat this issue, encroaching conifers can be removed in an attempt to increase meadow habitat and function (Halpern and Swanson, 2009). While multiple studies have assessed changes in soil structure and vegetation composition, few studies directly investigate changes in hydrology following meadow conifer removal projects (Halpern and Swanson, 2009; Halpern et al., 2012; Miller and Halpern, 1998; Norman and Taylor, 2005).

The goal of this study is to determine if the removal of conifers from an encroached meadow (Marian Meadow) has an effect on soil moisture and groundwater depth such that meadow hydrologic conditions are promoted. This goal will be accomplished by the following objectives: 1) develop a water budget incorporating groundwater depth, soil moisture, and climate measurements to quantify the hydrologic processes prior to and after conifer removal, 2) conduct a statistical analysis of the restored meadow's wet season water table depth prior to and after conifer removal, 3) conduct a statistical analysis of the restored meadow's soil moisture prior to and after conifer removal. Marian Meadow is located near the town of Chester, CA, which is situated in the northern Sierra Nevada. This 45-acre meadow enhancement project is part of a 2,046-acre timber harvest plan implemented by the Collins Pine Company.

Hydrologic and climate data analyzed for this study spans from September 2013 through June 2016 and includes data collected from Marian Meadow, the meadow with encroached conifers, and a control meadow. The removal of all encroaching conifers from Marian Meadow occurred in July 2015.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Introduction

In the western United States, meadows are a small but important component of forested ecosystems. They provide critical habitat for many species of plants and animals (Halpern et al., 2012; McIlroy and Allen-Diaz, 2012; Viers et al., 2013) and play an important role in improving water quality, flood protection, and carbon storage (Norton et al., 2013). However, over the last century, meadows have reduced in size and number due to conifer encroachment. In areas where it has been assessed, such as the Cascade region of central Oregon, meadow habitat has decreased by nearly 50%; decreasing from 5.5% of the regions habitat to 2.5% (Takaoka and Swanson, 2008).

Tree ring records indicate that conifer establishment within meadows accelerated during the 1870s and peaked during the first decade of the 20$^{th}$ century (Norman and Taylor, 2005). During this time, changes in forest management policy such as fire suppression and grazing regulations were implemented. These policy shifts, along with changes in climate are believed to be the causes of conifer encroachment (Norman and Taylor, 2005; Roche et al., 2014).

## 2.2. Causes of Conifer Encroachment

### 2.2.1 Fire Suppression

Historically, fires in western United States occurred more frequently and at a lower intensity than today. In a review that synthesized multiple studies from across the Sierra Nevada, it is estimated that the pre-1900 fire return interval for red fir, mixed conifer-fir, mixed conifer-pine, and pine forests types were 26, 12,15, and 11 years, respectively (Skinner and Chang, 1996). These small, low intensity fires, often started by lightning strikes or Native Americans, resulted in a spatially complex pattern of montane meadows that had limited net conifer encroachment (Norman and Taylor, 2003). However, due to fire suppression polices that were implemented in the early 20$^{th}$ century, it is estimated that the fire return intervals of these forest types are now 1,644, 644, 185, and 192 years respectively (McKelvey et al., 1996). In a study that assessed the fire frequency directly adjacent to meadows in northeastern California, it was estimated that the mean fire frequency (fires per 100 years) from 1750 to 1849 was 7.7 fires. From 1850 to 1905, it was determined that the mean fire frequency was 5.1 fires, and from 1906 to 1996 it was determined that the mean fire frequency was 0.3 fires (Norman and Taylor, 2005). The effects of fire suppression on conifer establishment within meadows is believed to be amplified by historical grazing practices, especially during the first wave of accelerated conifer encroachment in the early 20$^{th}$ century.

### 2.2.2 Livestock Grazing

From the mid-19$^{th}$ century to the establishment of grazing allotments by the U.S. Forest Service in 1898, sheep grazing within the National Forests was intensive. These mostly unregulated grazing practices caused substantial environmental degradation such as excessive erosion and a reduction in vegetative cover. Following the establishment of grazing allotments, conifer establishment increased by nearly 300% in areas of the southern cascades and northern Sierra Nevada (Miller and Halpern, 1998; Norman and Taylor, 2005). It is believed that disturbed soil following high intensity livestock grazing and a lack of competing grasses and forbs created conditions more susceptible to conifer establishment. Also, sheep grazing may have reduced fuel continuity between the forest and meadow boundary. This may cause the inability of fire to check conifer establishment within meadows. In a study that assessed conifer encroachment along the forest-meadow ecotone in Lassen National Forest, it was determined that fires abruptly stopped burning into the forest-meadow boundary during the mid-1800s although the fire frequency of the surrounding forest remained relatively high (Norman and Taylor, 2005).

### 2.2.3 Climate

Changes in climate can have a profound effect on conifer expansion. According to Miller and Halpern (1998), conifer expansion into meadows can increase with reduced wintertime precipitation. When precipitation is low, the snowpack melts earlier. This creates a longer conifer growing period providing greater opportunities for tree establishment. Reduced wintertime precipitation compounded with an increase in summertime rainfall can also result in an increase of conifer establishment. Elevated summertime moisture can accelerate seedling establishment by providing a more hospitable environment for seed germination, especially for lodgepole pine (*Pinus contorta*), which is a prolific meadow invader (Taylor, 1995). It has been found that lodgepole pine germination rates increase with higher soil moisture (Petrie et al., 2016). Although there is uncertainty regarding the effects of climate change on annual precipitation in California,  generally, projections indicate a reduction in annual precipitation (Mastrandrea and Luers, 2012). A reduction in precipitation can result in a lowering of the water table, which can cause a reduction in meadow specific plant communities (Hammersmark et al., 2009).

In addition to potential changes in precipitation, climate change is expected to have a profound effect on temperature in the western United States and Sierra Nevada. Over the next century, summer temperatures are expected to increase by 4.1 to 6.5°F and winter temperatures are expected to increase by 2.7 to 3.6°F (Pierce et al., 2013). This increase in temperature is expected to result in a greater percentage of Sierra Nevada annual precipitation to fall as rain and reduce snowpack by 48% to 65% by the year 2099 (Pierce and Cayan, 2013). The reduction in snowpack has already caused shifts in timing of runoff on the Sacramento River. During the first half of the 20th century peak flow on the Sacramento River normally occurred in April. During the second half of the 20th century peak flow shifted a month earlier to March (California Department of Water Resources, 2015). Earlier snowmelt can result in reduced summer base flows and a reduction in growing season water tables (Peterson et al., 2005).

**2.3 Meadow Type**

Landform controls such as surrounding topography, location within the landscape, soil parent material, and depth to bedrock, influence meadow processes such as surface water and groundwater inputs/outputs, meadow vegetation, and meadow type. Meadows that receive the majority of their water from upland groundwater and surface water sources often exhibit elevated water table depths throughout the growing season. As a result, they tend to support a high proportion of obligate, facultative wetland, and facultative plant species. Meadows that receive the majority of their water surplus from precipitation, such as dry meadows, usually have growing season water table depths of less than 1 meter (3.28 feet), and as a result are usually dominated by facultative and facultative upland plant species (Weixelman et al., 2011).

In order for a meadow to form and maintain the water table must be within the rooting zone, especially during the growing season, of meadow plant communities. In a study by Hammersmark et al., 2009 that reviewed growing season water table depths (WTD) among various meadow community types, it was determined that the growing season water table depth for vegetation communities common in dry meadows ranged from 1.30 feet to 4.01 feet. For communities common in wet meadows water table depth ranged from 0.57 feet to 2.05 feet (). The duration of time the water table spends near the surface also influences vegetation community and meadow types. Hammersmark et al., 2009 estimated that meadows dominated by *Eleocharis macrostachya* and *Eleocharis acicularis*, both of which are obligate wetland species common in wet meadows, the water table was within 2.3 feet and 1.0 foot from the surface for 91 days and 65 days, respectively. For meadows dominated by *Poa pratensis* and *Bromus japonicas*, both of which are facultative and facultative wetland plant species common in dry meadows, the water table was within 2.3 feet and 1.0 foot from the surface for 42 days and 22 days, respectively (Table 2.2). 2.3 feet and 1.0 foot are typical rooting depths for plants common in dry and wet meadows.

Table 2.1: Growing season water table ranges for similar meadow vegetation community types. Adapted from (Hammersmark et al., 2010)

| Community Name | Growing Season Water Table Depth Range (ft) |
|---|---|
| *Poa pratensis / Bromus japonicus* | 0.33 - 7.55 |
| *Poa pratensis / Potentilla gracilis* | 0.85 - 2.03 |
| Moist meadow | 0 - 1.64 |
| Dry meadow | 0.66 - 2.79 |
| Mesic meadow (Corral Canyon) | 2.95 - 4.92 |
| Moist bluegrass | 1.15 - 3.94 |
| Dry bluegrass | 2.62 - 4.59 |
| Mesic graminoid | 1.8 - 4.59 |
| **Average** | 1.30 - 4.01 |
| | |
| *Carex nebrascensis / Juncus balticus* | -0.66 - 5.25 |
| *Carex nebrascensis ecological type* | 0 - 0.66 |
| Wet meadow | 0 - 0.98 |
| Wet meadow | 0 - 0.98 |
| *Deschampsia caespitosa / Carex nebrascensis* | 0.21 - 3.08 |
| Moist meadow | 0.66 - 3.28 |
| *Carex nebrascensis* ecological type | 1.64 - 1.64 |
| *Carex nebrascensis* community type | 1.08 - 1.08 |
| *Juncus balticus* community type | 2.17 - 2.17 |
| **Average** | 0.57 - 2.05 |
| | |
| *Downingia bacigalupii / Psilocarphus brevissimus* | -1.14 - 5.05 |
| *Downingia bicornuta* community type | -1.08 |
| *Navarretia* community type | 1.08 |
| **Average** | -1.14 - 5.05 |
| | |
| *Eleocharis macrostachya / Eleocharis acicularis* | -5.29 |
| *Eleocharis macrostachya* community type | 0 |
| **Average** | -2.65 |

Table 2.2: Growing season water table depths (WTD) for community types with varying compositions of wetland species (Hammersmark et al., 2010)

| Community | *Eleocharis macrostachya / Eleocharis acicularis* | *Downingia bacigalupii/ Psilocarphus brevissimus* | *Carex nebrascensis/ Juncus balticus* | *Poa pratensis/ Bromus japonicus* |
|---|---|---|---|---|
| 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 | 49.7 ± 17.2 | 33.7 ± 18.3 | 24.9 ± 8.4 | 9.8 ± 7.1 |

## 2.4 Conifer Removal

Techniques used to restore encroached meadows generally involve the removal of encroaching conifers with prescribed fire, mechanical removal, or a combination of both. These techniques have shown to be effective in quickly reestablish a functioning meadow vegetation community. However, it appears that the presence and disposal method of logging slash can influence the vegetation response following conifer removal. In studies where mechanical removal was followed by the pile burning of residual logging slash, there was subsequent natural reestablishment of meadow plant species. In studies where logging slash was broadcast burned over the entire meadow, there was extensive fire scaring, less responsive vegetation reestablishment, and higher nitrogen availability; which can cause an increase in weedy plant species. Meadow vegetation reestablishment success is also influenced by the presence of remnant meadow plant species and a viable seed bank in the soil. Depending on the extent and duration of encroachment, remnant meadow plant species and a viable seedbank can be depleted, and a manual dispersion of meadow seeds maybe required (Halpern and Swanson, 2009; Halpern et al., 2012). Because some of the causes of conifer encroachment, such as climate change and fire suppression cannot be addressed in restoration plans, and because conifer encroachment is a natural phenomenon, encroachment will continue to following restoration. Therefore, periodic removal projects may be required. In order to reduce the reestablishment rate following restoration, it has been shown that tree removal should be maximized between the meadow and conifer seed sources by removing nearby large trees that are susceptible to seeding. (Halpern and Swanson, 2009; Halpern et al., 2012; Kremer et al., 2014).

### 2.5 Forest Management and Water Yield

A change in fire regime has also affected overall forest structure. Historically, coniferous forests in the western United States exhibited stand conditions that were less dense than what they are today. In areas in the Sierra Nevada, such as portions of the Sierra National Forest, average tree density is now 2.3 to 3.4 times greater than historical conditions and average basal areas is now 44% greater (Meyer and Schroer, 2013). This increase in forest density has resulted in an increase in wildfire severity, individual wildfire size, and total annual burned area (Miller et al., 2009). To reduce the threat of catastrophic wildfire and insect infestation, the USFS intends to thin and/or treat 9 million acres of national forest lands over the next 15 to 20 years (United States Forest Service, 2013).

Vegetation management activities have been shown to effect forest hydrology and water yield. Numerous studies have shown that timber harvests, fuels reduction, and controlled burns can result in an increase of stream peak discharge, water yield, and soil moisture. Generally, these hydrologic responses are most extreme directly after management activities and then the system returns to baseline conditions in subsequent years. The changes in hydrology are attributed to decreases in evapotranspiration, interception, greater accumulation of snow in open areas, and changes in the timing of snowmelt. (Troendle et al., 2001; Watson et al., 2001; Hubbart et al., 2007; Ryu et al., 2009). A paired watershed study that spanned from 1982 to 1992 in Colorado determined that snowpack was on average 9% greater and water yield increased 17% in forest harvest openings compared to unharvested areas (Troendle et al., 2001). In the Rocky Mountain region, a measurable hydrologic response occurs when as little as 15% of the vegetation in a watershed is removed (Stednick, 1996). It is believed that in the Sierra Nevada, a reduction of forest cover by 30% can increase water yields by 9% (Bales et al., 2011).

From 2002 to 2012 the USFS thinned approximately 10% of the Feather River watershed in the Sierra Nevada. The estimated increase in water yield as a result 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. The same study estimated that 6% to 34% of the cost of thinning operations, for a low water yield response, could be offset by the increase of available water to downstream users (hydropower, irrigation, and municipal). For a high water yield response it was estimated that 17% to 101% of the cost could be offset by the increase in available water to downstream users (Podolak et al., 2015).

Podolak et al., 2015 estimated that the total economic benefit of an increase in water yield for downstream users ranged from 254 million to 741 million dollars. For the Feather River watershed alone, the economic benefit ranged from 142 million to 415 million dollars. Scaling the Feather River watershed values down, the economic benefits for downstream water users of a 2,000-acre group selection timber harvest would range from 123,114 to 359,805 dollars. For a 45-acre meadow restoration project, the economic benefit ranges from 2,770 to 8,097 dollars.

**2.6 Economic Benefit of Meadow Restoration**

There are multiple direct and indirect valuation techniques that can be used to estimate the economic benefit of meadows and meadow restoration. Each of these valuation techniques have their inherent advantages and disadvantages, and the selection and use of a valuation method depends on the availability of direct market prices, circumstantial evidence of market prices, and/or the use of surveys that express willingness to pay for the ecosystem service. One of such methods is the replacement cost method. The replacement cost method, which is an indirect method that employs circumstantial evidence, can estimate the value of meadows and meadow restoration by measuring the cost to acquire and restore alternative meadow locations. Using this method, and the estimated total cost of the 45 acre Marian Meadow restoration project ($78,750), the replacement cost of a similar meadow is $1,750/acre. (King and Mazzotta, 2000). The disadvantage of this valuation techniques is that it does not include direct measures of onsite and offsite services. Additional valuation methods can be utilized to quantify onsite and offsite economic services of meadow restoration. These economic services include an increase in productivity for rangelands, improved habitat for meadow-dependent plant and animal species, and improved water quality (Aylward and Merrill, 2012).

Methods used to quantify the economic benefit meadow restoration has on rangeland productivity include the valuation of an increase in forage, the willingness to pay for grazing permits, and quantifying the fees for substitute goods such as hay or alfalfa.  Utilizing these methods, Aylward and Merrill, 2012 estimated the on-site economic benefits to forage and beef production range from $600-$900/acre, $900-$2,500/acre, and $1,100-$4,500/acre for low, medium, and high economic scenarios, respectively. Aylward and Merrill, 2012 also estimated the off-site benefits from sediment reduction ranges from $1/acre, $10/acre, and $19/acre for low, medium, and high economic scenarios, respectively. These economic benefits are a result of a decrease in downstream dredging operations. Improved habitat for meadow-dependent plant and animal species can increase tourism and recreational (i.e. hunter, fishing, hiking, and birdwatching etc.) economic values. However, the on and off-site economic benefits to meadow habitat improvements have yet to be quantified (Aylward and Merrill, 2012).  Future valuation methods used to estimate ecosystem services associated with an increase in habitat and recreation potentially include the willingness to pay and travel costs methods.

# CHAPTER 3 MATERIALS AND METHODS

## 3.1 Study Area

### 3.1.1 Location

Marian Meadow (MM) is located in northwestern Plumas County, California approximately 5 miles southwest of Chester, California. The MM project area is 45 acres and at an elevation of approximately 4,900 feet above sea level. Marian Creek, which flows though MM, is a tributary to the Upper North Fork Feather River. The contributing area of the Marian Creek Watershed above MM is approximately 7.5 square miles (Figure 3.1). The control meadow (CM) is located 4 miles west of MM, and is approximately 20 acres. It is at an elevation of 4,800 feet above sea level and was previously dominated by conifers until restoration in 2012. CM is situated in the Deer Creek watershed (Figure 3.1).

### 3.1.2 Climate

In nearby Chester, CA, average annual precipitation is 31.8 inches and the average annual snowfall is 127.8 inches. The majority of precipitation occurs from October to May.  Average maximum and minimum temperatures are 62.3 °F and 31.3 °F respectively. Temperature ranges from 85.3 °F to 44.8 °F in the summer to 41.8 °F to 19.8 °F in the winter (Table 3.1: Average monthly climate data for Chester, CA (Western Regional Climate Center, 2016))

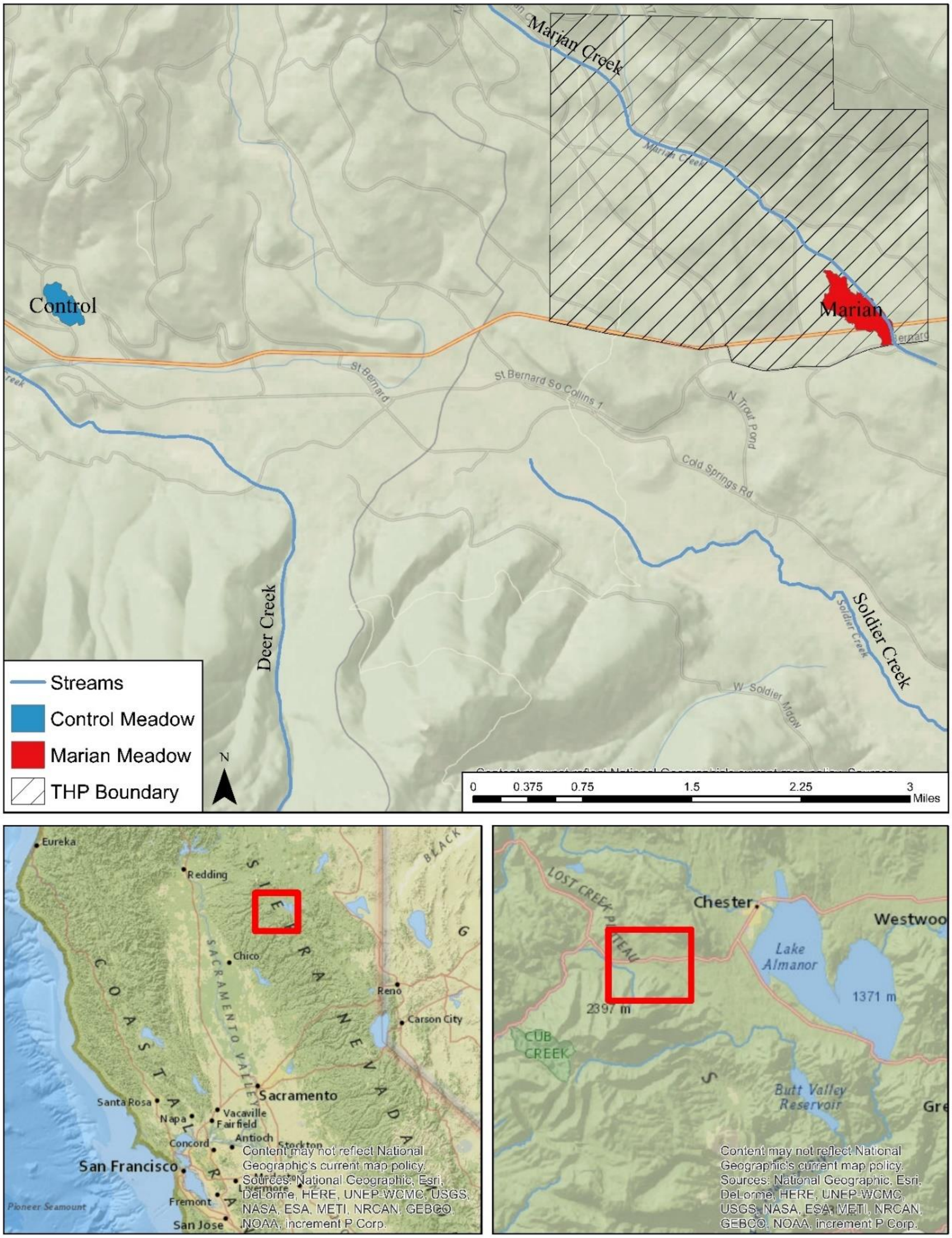



Figure 3.1: Project vicinity map

Table 3.1: Average monthly climate data for Chester, CA (Western Regional Climate Center, 2016)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ave. Max. Temperature (F) | 41.8 | 45.7 | 50.8 | 58.1 | 67.5 | 76.6 | 85.3 | 84.4 | 78.3 | 66.3 | 50.3 | 42.1 | 62.3 |
| Ave. Min. Temperature (F) | 19.8 | 22.3 | 25.2 | 28.4 | 34.5 | 40.7 | 44.8 | 43.3 | 38.1 | 31.5 | 25.8 | 20.7 | 31.3 |
| Ave. Total Precipitation (in.) | 6 | 5.15 | 4.15 | 2.22 | 1.53 | 0.82 | 0.27 | 0.26 | 0.64 | 1.88 | 3.77 | 5.16 | 31.83 |
| Ave. Total Snowfall (in.) | 35.4 | 26.2 | 20.6 | 7.1 | 1.4 | 0.1 | 0 | 0 | 0.1 | 0.8 | 10.5 | 25.7 | 127.8 |
| Ave. Snow Depth (in.) | 17 | 21 | 15 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 5 |

### 3.1.3 Vegetation

The surrounding forest is classified as Sierra Mixed Conifer and is mostly composed of ponderosa pine *(Pinus ponderosa)*, lodgepole pine *(Pinus contorta)*, sugar pine *(Pinus lambertiana)*, white fir *(Abies concolor)*, incense cedar *(Calocedrus decurrens)*, and Douglas-fir *(Pseudotsuga menziessii)* (Marian Creek Timber Harvest Plan, 2013). Over 200 plant species are known to grow in the meadows of the Sierra Nevada. Common meadow plant species include, Nebraska sedge *(Carex nebrascensis)*, Baltic rush *(Juncus balticus)*, Kentucky bluegrass (*Poa pratensis)*, Bacigalupi's downingia *(Downingia bacigalupii)*, and short wollyheads (*Psilocarphus brevissimus var. brevissimus)* (Ratliff, 1985).

### 3.1.4 Soils

The predominant soil mapping unit for MM and its surrounding area is the Holland-Skalan families association (60% Holland soil series, 30% Skalan soil series). It is characterized as being deep to moderately deep and well drained. The Holland soil series is a fine-loamy, mixed, semiactive, mesic, Ultic Haploxeralf. The Skalan soil series is a loamy-skeletal, isotic, mesic Vitrandic Haploxeralf. Both soil series are Alfisols and have weathered basalt as parent materials (Natural Resource Conservation Service, 2016).

Approximately 75% of the control meadow is composed on the Elam soil series. This soil series is composed of alluvium derived from igneous rock, moderately deep, and somewhat excessively drained. The Elam soil series is a loamy-skeletal, mixed, superactive, nonacid, frigid Typic Xerofluvent. The remaining 25% of the meadow is composed of the Cohasset soil series. This soil series is moderately deep and well drained. It is derived from weathered volcanic rock. The Cohasset soil series is a fine-loamy, mixed, superactive, mesic, Ultic Haploxeralf (Natural Resource Conservation Service, 2016).

## 3.2 Study Design

### 3.2.1 Restoration

MM and CM are located on the Collins Pine Company Almanor Forest (CAF) and MM is part of an approximate 2,000-acre group selection timber harvest (Figure 3.1). Prior to restoration, MM had a basal area of 111 $ft^2$/ac (Marian Creek Timber Harvest Plan, 2013). The primary tree type within MM was lodgepole pine *(Pinus contorta)* and ponderosa pine *(Pinus ponderosa)* (Figure 3.2). The meadow restoration phase of the timber harvest was performed during the month of July 2015. This included the mechanical removal of all lodepole pine and the majority of ponderosa pine from the 45-acre project area. Ponderosa pine that was established prior to lodgepole pine encroachment were not removed. The majority of logging slash was removed from the site (Figure 3.3). The remaining upslope portion of the timber harvest began during the summer of 2016 and will continue through 2017.

Figure 3.2: Meadow looking north near Hwy 36 prior to restoration; December 2014

Figure 3.3. Marian Meadow looking north from Hwy 36 after restoration; September 2015

### 3.2.2 Instrument Deployment

Within ArcMap (ESRI, 2015), a 1,250-foot line bisecting MM was created. Along this line, 10 equally spaced points were established, and four of them were randomly selected (points 3, 4, 6, and 9). A line from these four randomly selected points, perpendicular to the bisection line, was extended to the meadow boundary. Along these lines and starting from the western edge of the meadow boundary, points every 25 feet were created. Four points along each line were randomly selected for instrument placement. Fourteen of the 16 points were used for instrumentation. This procedure was repeated for the control meadow (Van Oosbree, 2015). See  Figure 3.6: and Figure 3.7: for instrument placement locations.

In September 2013, 5 soil moisture sensors were deployed into MM and CM. The soil moisture probes were manufactured by Odyssey Dataflow Systems Limited and measure soil moisture by relating through calibration, the measured dielectric permittivity of the soil to known soil moisture values. The soil moisture sensors were installed at a depth of 1.0 foot, and the data loggers were housed in PVC pipe for additional weatherproofing. Throughout the study period, some sensors were temporarily removed due to instrument failure and in July 2015, four additional soil moisture sensors were installed at 1.0 foot depths. The timeline for each soil moisture sensor deployment is described in Figure 3.4. To quantify the soil moisture content below 1.0 foot depths, 5 additional soil moisture probes were installed at a depth of 3.0 feet. The additional soil moisture sensors were manufactured by Decagon Devices. These sensors come pre-calibrated from the manufacture. The data loggers and software were manufactured by Onset Computer Corporation.

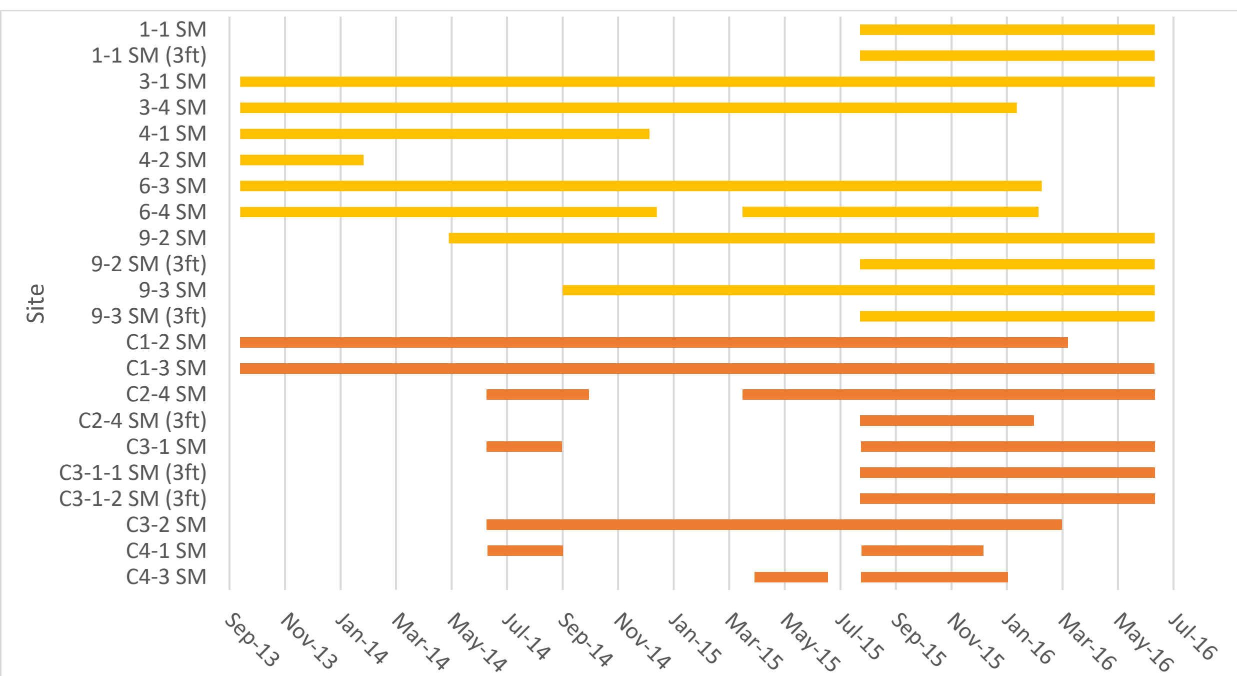


Figure 3.4: Soil moisture sensor deployment timeline (see figures 3.6 and 3.7 for the spatial location of measurement sites)

1.5-meter (4.92 feet) water table depth sensors manufactured by Odyssey Dataflow Systems Limited were deployed into MM and CM in September 2013. Additional water table depth sensors were deployed September, 2014 (Figure 3.5). On average, the water table depth sensors had the ability to measure a maximum depth of 4.0 feet. The maximum depth the sensors can measure depends on wellhead height, which was on average 0.9 feet. 5.0-foot-deep wells were dug using a manually pounded corer or auger. The wells were then outfitted with a 5.0 foot by 1 inch perforated PVC well casing. Connected to the well casing, with a coupler, was a 0.5 foot by 1.5 inch PVC pipe. This served as the water proof housing for the data logger. Nine non instrumented wells were installed in MM and CM. These wells were manually sounded during each site visit. Electrical resistivity tomography (ERT) derived data was utilized to model groundwater depths below the range of the sensors. See Table 3.2 for a description of the instruments deployed at each sites.

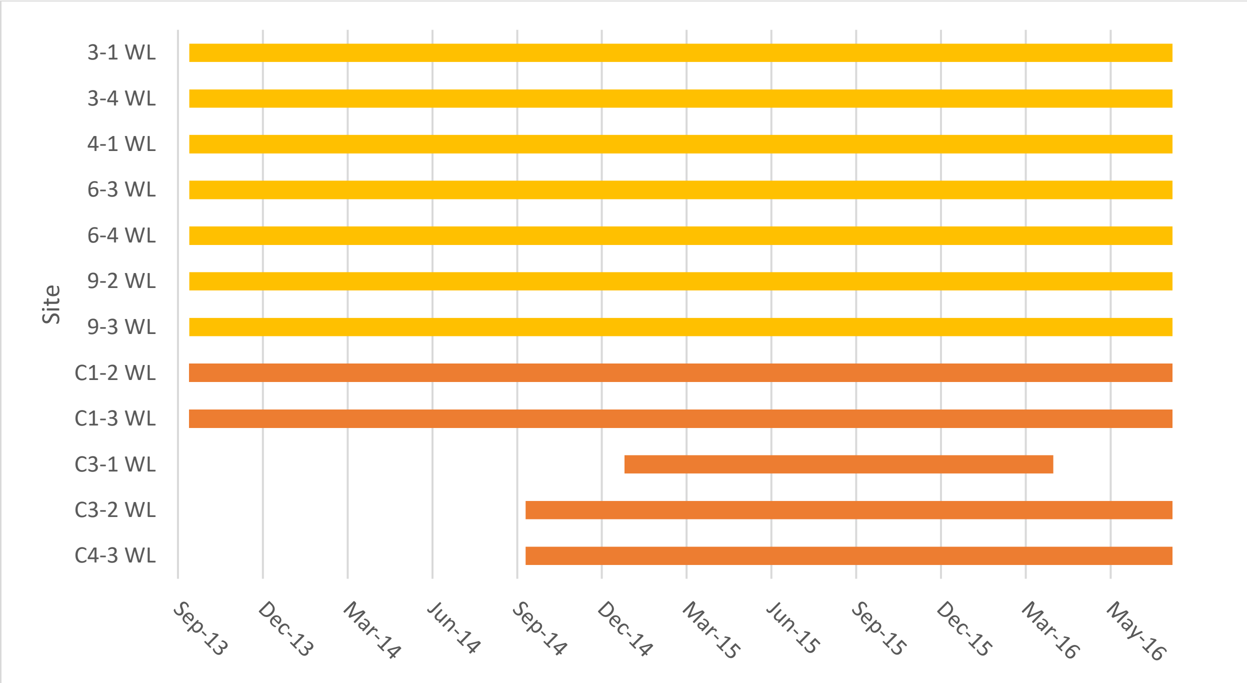



Figure 3.5: Groundwater depth sensor deployment timeline (see Figures 3.6 and 3.7 for spatial location of measurement sites).

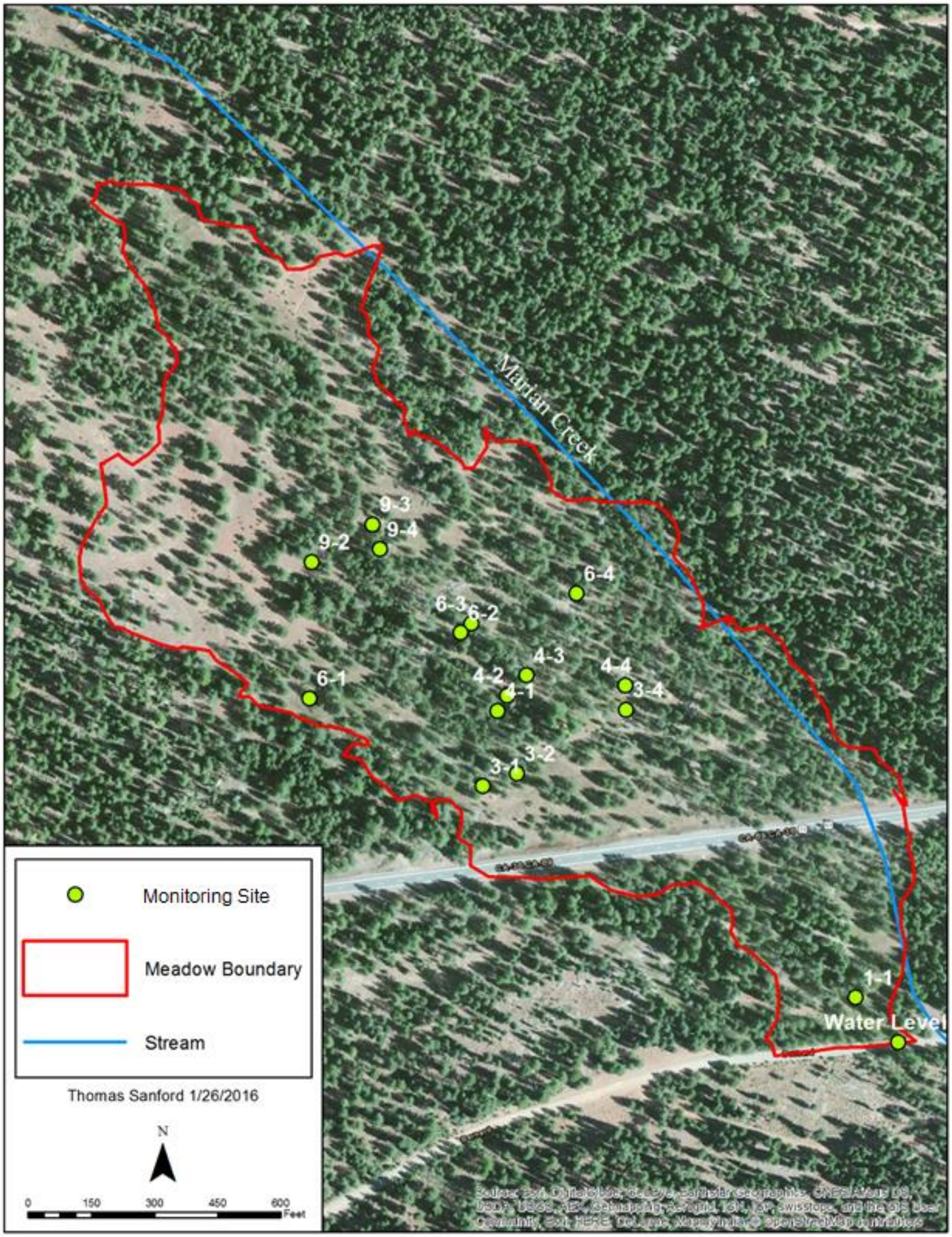



Figure 3.6: Marian Meadow monitoring sites for soil moisture and/or groundwater level.

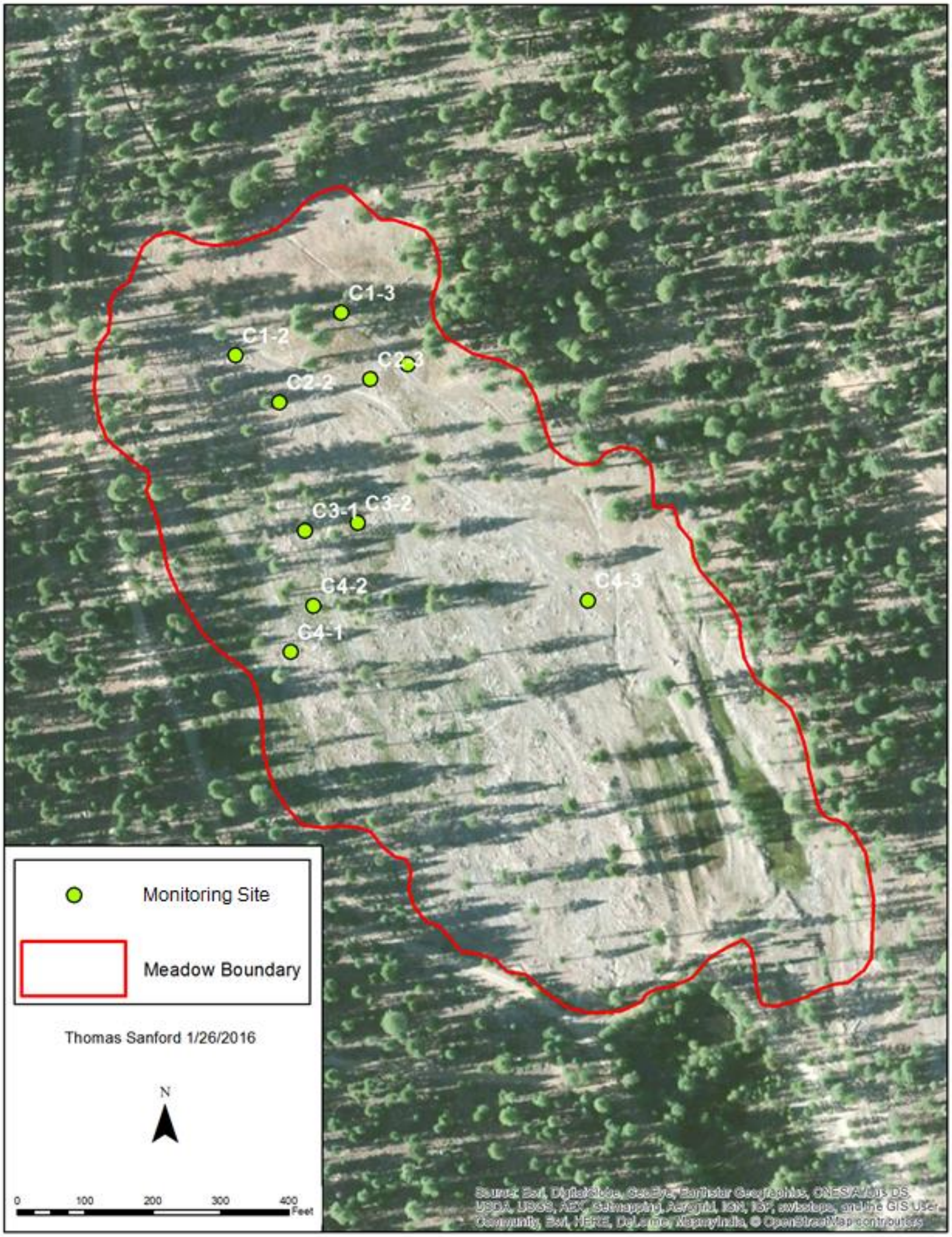


Figure 3.7: Control Meadow soil moisture and groundwater monitoring sites.

Table 3.2: Description of instrumentation deployed at monitoring site

| Site | Soil Moisture | Water Level | Blank Well | Current Soil Moisture Sensors Type and Depth Installed |
|---|---|---|---|---|
| 1-1* | ✓ | | | Onset: 1ft and 3ft |
| 1-Mar | ✓ | ✓ | | Odyssey: 1ft |
| 2-Mar | | | ✓ | |
| 4-Mar | ✓ | ✓ | | Odyssey: 1ft |
| 1-Apr | ✓ | ✓ | | Onset: 1ft |
| 2-Apr | ✓ | | | Odyssey: 1ft |
| 3-Apr | | | ✓ | |
| 4-Apr | | | ✓ | |
| 1-Jun | | | ✓ | |
| 2-Jun | | | ✓ | |
| 3-Jun | ✓ | ✓ | | Odyssey: 1ft |
| 4-Jun | ✓ | ✓ | | Odyssey: 1ft |
| 2-Sep | ✓ | ✓ | | Odyssey: 1ft, Onset: 3ft |
| 3-Sep | ✓ | ✓ | | Odyssey: 1ft, Onset: 3ft |
| 4-Sep | | | ✓ | |
| C1-2 | ✓ | ✓ | | Odyssey: 1ft |
| C1-3 | ✓ | ✓ | | Odyssey: 1ft |
| C2-2 | | | ✓ | |
| C2-3 | | | ✓ | |
| C2-4 | ✓ | | ✓ | Odyssey: 1ft, Onset: 3ft |
| C3-1 | ✓ | ✓ | | Odyssey: 1ft, Onset: 3ft |
| C3-2 | ✓ | ✓ | | Odyssey: 1ft |
| C4-1 | ✓ | | | Onset: 1ft |
| C4-3 | ✓ | ✓ | | Odyssey: 1ft |

*Site added August 2015

### 3.3 Water Budget

To quantify and assess the hydrologic response following meadow restoration, a weekly water budget was constructed using the water balance equation below:

$$P = ET + \Delta S + \Delta G \quad (1)$$

Where:

P= Precipitation (ft)

ET= Evapotranspiration (ft)

$\Delta$S= Change in soil moisture storage (ft)

$\Delta$G= Change in groundwater storage (ft)

While surface water outflow was measured in MM, inflow was not. As a result, surface water flow will not be included in this water balance assessment. Precipitation (rain) data was downloaded from the California Data Exchange Center (CDEC) website from a gage maintained by Pacific Gas and Electric (PG & E) in Prattville, California, which is approximately 10 miles southeast from MM.  Accurate and/or operational snow depth sensors could not be located in the general proximity of MM and CM. Consequently, snowfall data was not included in this analysis. Evapotranspiration was modeled with the Priestly-Taylor method (Priestley and Taylor, 1972).

### 3.3.1 Change in Soil Moisture Storage

#### 3.3.1.1 Soil Moisture Sensor Calibration

The Onset soil moisture sensors came pre calibrated and automatically provide volumetric soil moisture content. Each Odyssey soil moisture sensor was calibrated using a two-point calibration to convert raw values to gravimetric wetness. A manufacturer provided raw value corresponding to 0% soil moisture was used as a calibration point. After the soil moisture sensors were deployed, a 100-200 gram soil sample directly adjacent to each sensor was collected and placed into a Ziploc bag. In the lab, the soil samples were transferred to weighing tins, weighed, and then oven dried for 24 hours at a temperature of 105 °C. The gravimetric wetness of each sample was calculated (equation 2 and 3). This value, along with the raw value measured at the time of the sample collection, was used as another calibration point. Equation 4 was then used to convert raw values to gravimetric wetness. Gravimetric wetness was then converted to volumetric soil moisture content (Equation 5).

$$\Theta_g = \frac{W}{D} \tag{2}$$

Where:

$\Theta_g$ = gravimetric wetness of soil ($\frac{g}{g}$)

W = mass of water in soil (g)

D = mass of oven dry soil (g)

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

$$W = F - D \tag{3}$$

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:

$$\Theta_{g(sensor)} = \frac{V_{r\,(sensor)} - off}{(V_{rs} - off) \times \Theta_{g(sample)}} \tag{4}$$

Where:

$\theta_{g(sensor)}$ = gravimetric wetness ($\frac{\text{g}}{\text{g}}$)

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

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

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

$\theta_{g(sample)}$ = gravimetric wetness of field sample ($\frac{\text{g}}{\text{g}}$)

#### 3.3.1.2 Gravimetric to Volumetric Soil Water Conversion

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

$$\theta_{\text{v}} = \theta_g * \frac{P_b}{P_w} \qquad (5)$$

Where:

$\Theta_{\text{v}}$ = volumetric water content ($\frac{\text{g}}{\text{cm}^3}$)

$\Theta_{\text{g}}$ = gravimetric wetness ($\frac{\text{g}}{\text{g}}$)

$P_{\text{b}}$ = soil bulk density ($\frac{\text{g}}{\text{cm}^3}$)

$P_{\text{w}}$ = water density ($\frac{\text{g}}{\text{cm}^3}$)

In a previous analysis, the average bulk density of soil in MM was determined to be 1.48 $\frac{\text{g}}{\text{cm}^3}$ and the average bulk density of soil in CM was determined to be 1.59 $\frac{\text{g}}{\text{cm}^3}$ (Van Oosbree, 2015). The gravimetric soil moisture content to volumetric soil moisture content conversion was applied to every two-hour soil moisture sensor reading. The average weekly volumetric soil moisture content was then calculated for MM and CM.

### 3.3.1.3 Equivalent Water Depth of Unsaturated Soil

From 9/13/2013 to 8/7/2015 equivalent water depth of unsaturated soil was calculated with only 1.0-foot-deep soil moisture sensors (Equation 6). The three-foot-deep sensors were not yet deployed. The soil moisture content of the entire unsaturated zone, including the capillary fringe, was assumed to be the soil moisture content measured at 1.0 foot depths.

$$S_{Ed} = V_w * G_d \tag{6}$$

Where:

$S_{Ed}$ = equivalent depth of water in soil (ft)

$V_w$ = average weekly volumetric water content ($\frac{g}{cm^3}$)

$G_d$ = depth to water table (ft)

After 8/7/2015, the 3.0-foot soil moisture sensors were incorporated into the unsaturated soil moisture equivalent water depth calculations (Equation 7). The soil moisture content from 0 to 2.0 feet was assumed to be the soil moisture content measured at 1.0 foot depths. The soil moisture content from 2.0 feet to the water table, including the capillary fringe, was assumed to be the soil moisture content measured at 3.0 foot depths.

$$S_{Ed} = (V_{w\,(1\,ft\,sensors)} * 2) + (V_{w\,(3\,ft\,sensors)} * (G_d - 2)) \tag{7}$$

The change in soil moisture storage was determined with the following equation:

$$\Delta S = S^1_{ED} - S^0_{ED} \tag{8}$$

Where:

$S_{ED}^1$= Current soil moisture equivalent water depth (ft)

$S_{ED}^0$= Preceding soil moisture equivalent water depth (ft)

### 3.3.2 Change in Ground Water Storage

#### 3.3.2.1 Groundwater Depth Sensor Calibration

Initially the water level sensors were calibrated following the instructions of the manufacture. However, after manually sounding the wells and comparing those values to the calibrated instrument values, it was determined that the calibration points used were insufficient. The sensors were then recalibrated with manually sounded well values and their corresponding raw values. The following equation was used for instrument calibration:

$$V_c = \frac{(V_u - O)}{\Delta} \quad (9)$$

Where:

$\Delta$= Slope of the calibration curve

$$\Delta = \frac{V - V_o}{X - X_o} \quad (10)$$

$V_c$ = 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

#### 3.3.2.2 Electrical Resistivity Tomography (ERT)

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 (IRIS Instruments, 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 MM and CM took place on 9/10/2013 and 5/6/2014, respectively. See Table 3.3 for a description of these initial surveys as well as subsequent surveys. In MM, the water table was interpreted as the region where resistivity was below 45Ω·m and the base of the aquifer was interpreted as the region above 110-120 Ω·m. In the CM, the water table was interpreted as the region where resistivity was below 100-180 Ω·m (Van Oosbree, 2015).

In general, ERT surveys with 5-meter spacing were conducted in 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. These surveys provided imaging depths of approximately 7 meters. Various other survey lines with varying lengths and node spacing's were conducted (Table 3.3).

Table 3.3: ERT survey descriptions

| 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 |

| 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 |

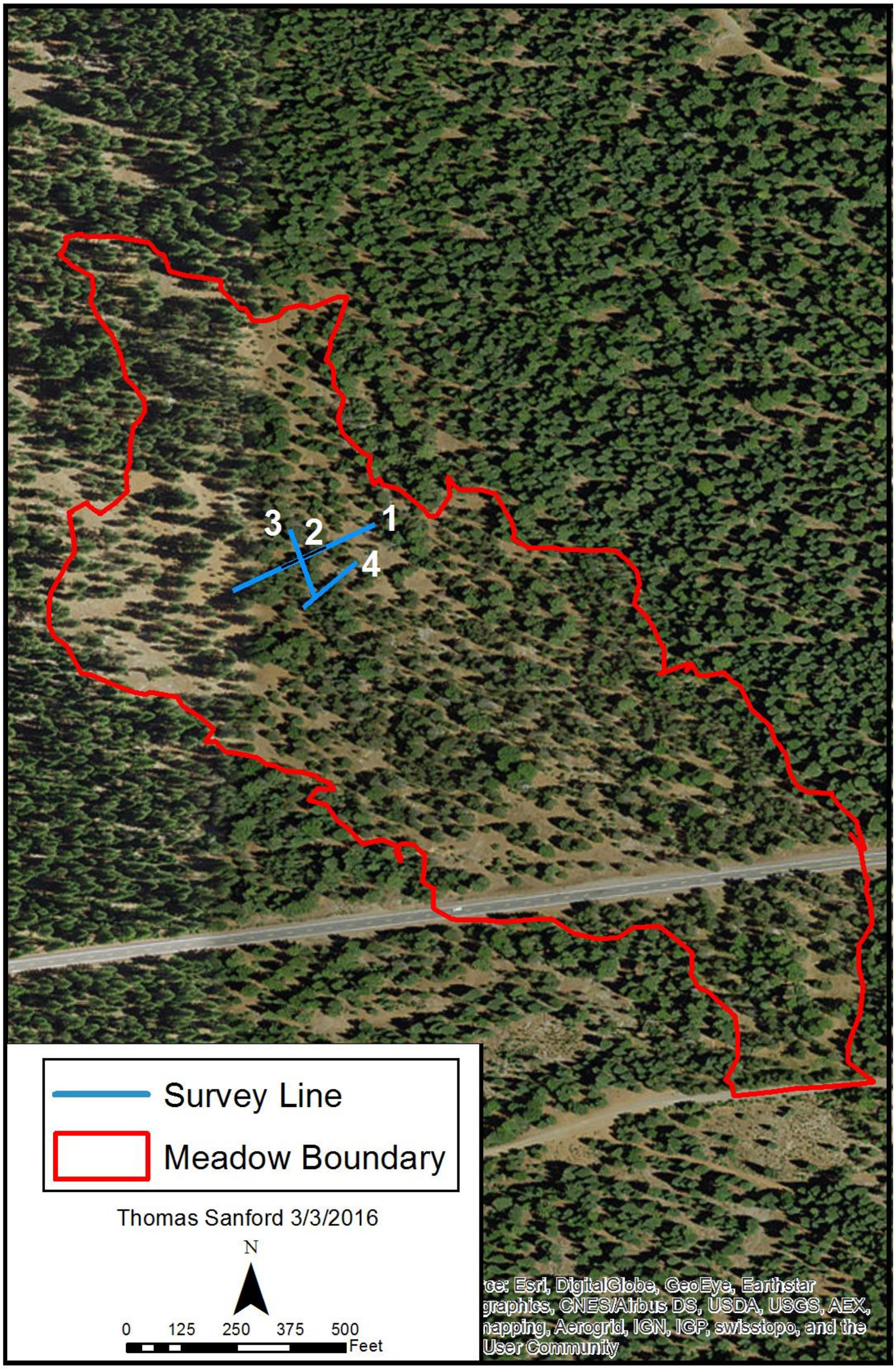



Figure 3.8: September 2013 ERT surveys. No ERT survey was conducted on CM Sept. 2013.

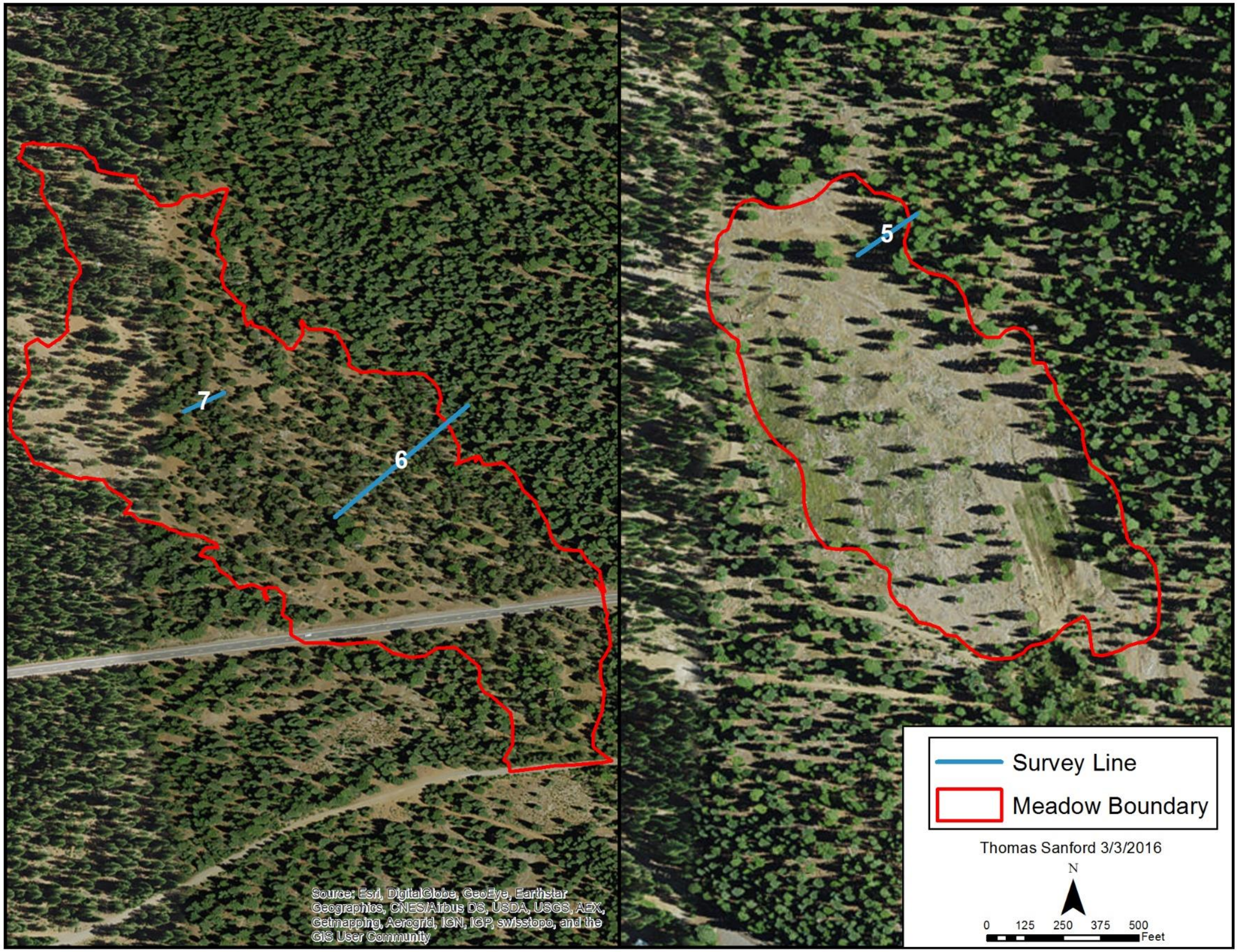



Figure 3.9: May 2014 ERT surveys

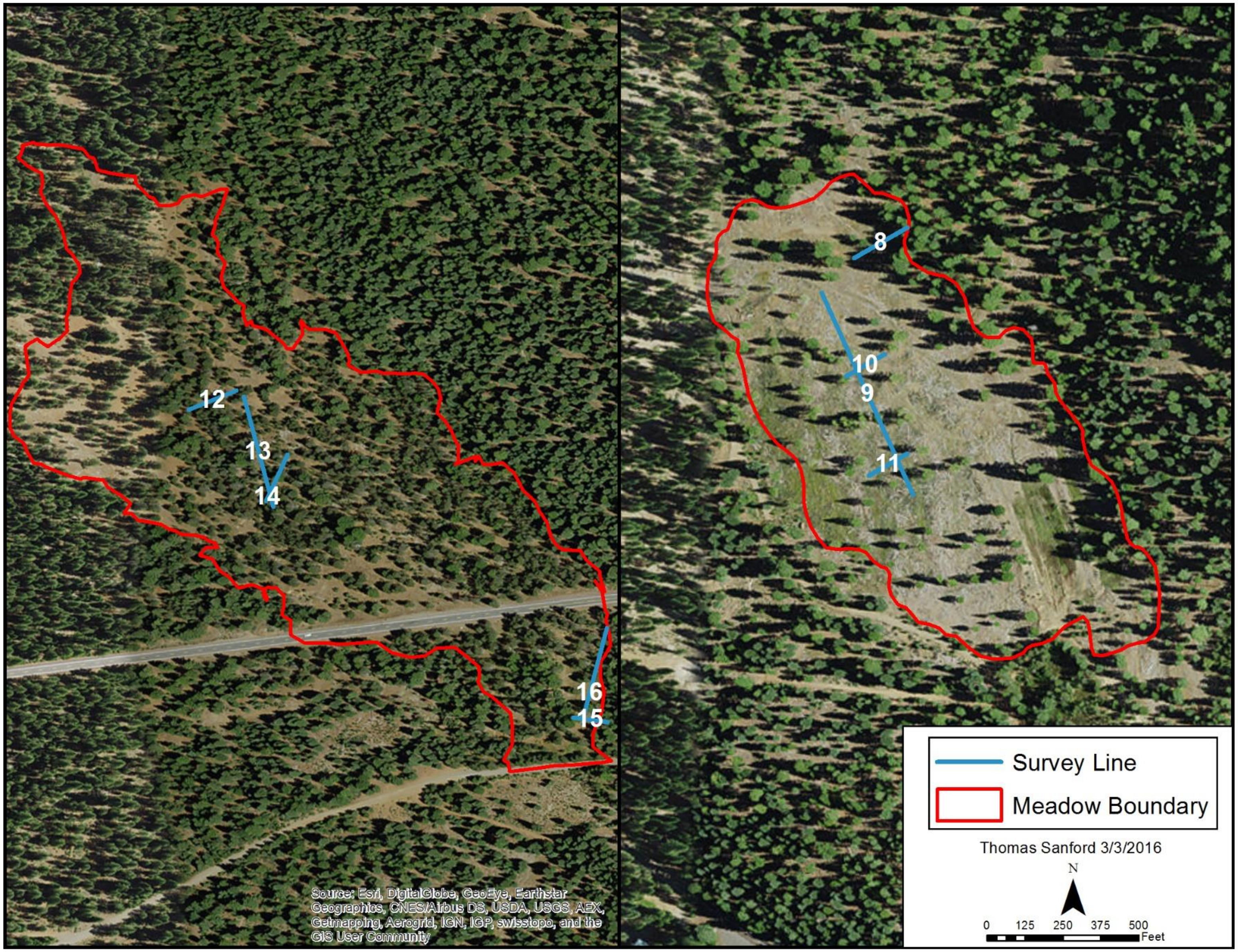



Figure 3.10: September 2014 ERT surveys

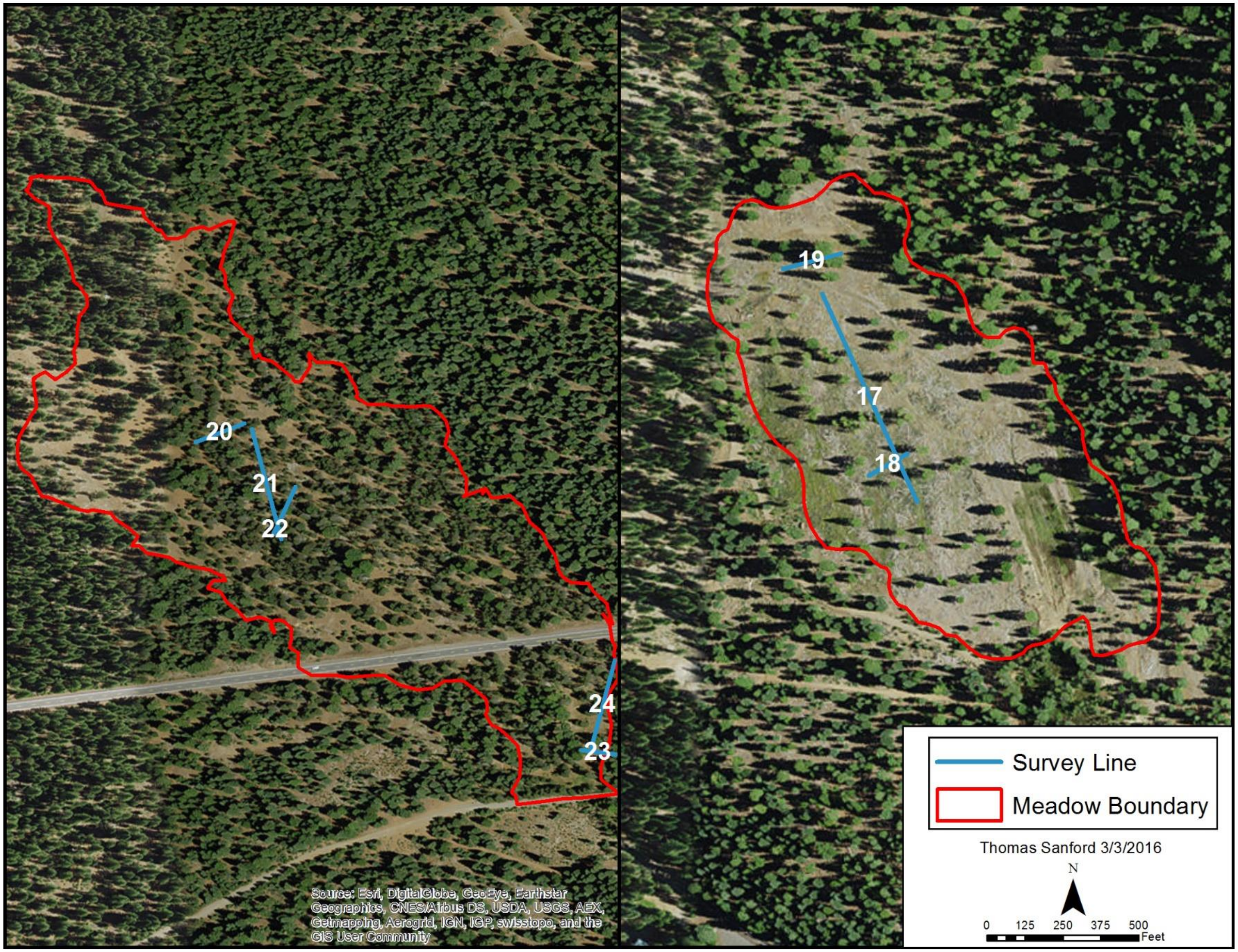



Figure 3.11: March 2015 ERT surveys

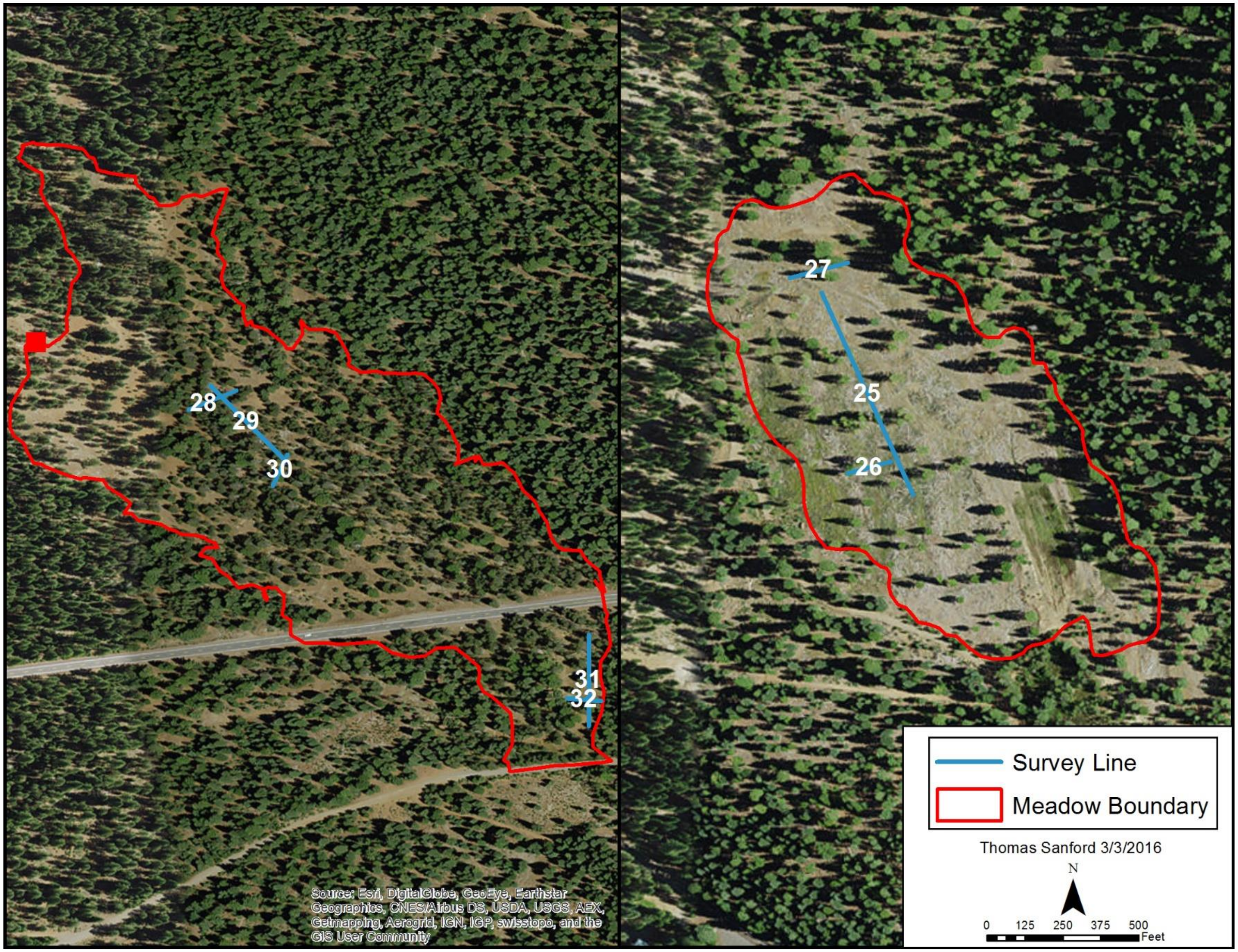



Figure 3.12: September 2015 ERT surveys

ERT derived water table depths were used to model water table elevations during periods when the water table was below the range of the sensors. The recession curve equation below, which accounts for precipitation, was used for the modeling (Beschta et al., 2000). During periods when the groundwater depth was receding, the last average weekly sensor measurement was fit to ERT derived depths measured during the 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 sensors weekly average.

$$G_d = (k * m) - P \tag{11}$$

Where:

$G_d$ =Depth to water table (ft)

k=Recession coefficient

m=Measured depth (ft)

P= precipitation (ft)

**3.3.2.3 Soil Porosity**

Soil porosity was used to calculate equivalent water depth of the saturated zone. The soil porosity in CM and MM was calculated using the equation below that relates soil bulk density and particle density to soil porosity. The particle density was assumed to be 2.65 g/cm$^3$ for both MM and CM. Average porosity in MM was calculated to be 44.3% and average porosity in CM was calculated to be 47.0% (Van Oosbree, 2015).

$$n = \left(1 - \frac{P_b}{P_s}\right) * 100\% \tag{12}$$

Where:

n =porosity (%),

$P_b$ = Bulk density of soil ($\frac{\text{g}}{\text{cm}^3}$)

$P_s$ =Particle density of soil (2.65 $\frac{\text{g}}{\text{cm}^3}$).

### 3.3.2.4 Change in groundwater storage

Equivalent groundwater content was determined by multiplying the thickness of the saturated zone by soil porosity.

$$G_{Ed} = n \times (G_c - G_d) \tag{13}$$

Where:

$G_{Ed}$ = equivalent depth of water stored in groundwater (ft)

n= porosity

$G_d$= average weekly depth to groundwater (ft)

$G_c$= base of the aquifer (ft)

Saturated zone thickness was determined by subtracting the depth to the base of the aquifer by the depth to groundwater. ERT was used to determine the depth to base of the aquifer, which was determined to be 66 feet. Using measured groundwater depth values and recession curve estimated values, total average weekly groundwater depth was calculated for each meadow. Change in groundwater storage was calculated with the following equation:

$$\Delta G = G^1{}_{Ed} - G^0{}_{Ed} \tag{14}$$

Where:

$G_{ED}^{1}$= Current groundwater equivalent water depth (ft)

$G_{ED}^{0}$= Preceding groundwater equivalent water depth (ft)

### 3.3.3 Evapotranspiration

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 deployed near the control meadow. Temperature and solar radiation data measured with this weather station were incorporated into the Priestly-Taylor analyses. For time periods prior to the deployment of the CM weather station, the data was extended with standard least-squares regression equations using solar radiation and temperature data from Chester and Buntingville, California. 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 CM from 09/13/2013 to 08/15/2015 (Table 3.4).

Table 3.4: Parameter estimates used to correct Chester, CA daily average, minimum, and maximum temperatures.

| 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 |

There was a significant difference between average daily net solar radiation values between CM and Buntingville, CA (P value <0.001). The parameter estimates below were used to extend average daily net solar radiation data measured in the CM from 9/13/2013 to 8/15/2015 (Table 3.5).

Table 3.5: Parameter estimates used to correct CM temperature from 9/13/2013-5/15/2015

| 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 CM weather station data from August 8th to December 15th, 2015. A Priestley-Taylor (PT) coefficient of 0.35 was used for all CM evapotranspiration calculations. A PT coefficient of 0.35 was calculated for sparse vegetation or bare soil in a study that utilized remotely sensed temperature data and Normalized Difference Vegetation Index (NDVI) values (Khaldi and Hamimed, 2014). A PT coefficient of 0.65 was used for MM calculations from

09/13/2013 to 7/31/2015. Following restoration, a PT coefficient of 0.35 was used for MM evapotranspiration calculations. A PT  coefficient of 0.65 was the mean value (*n* = 35) for temperature coniferous forests in a study that summarized data from previous research (Komatsu, 2005).

$$PET = \frac{\Delta_{svpc}(R_n - Gf)}{\Delta_{svpc} + \gamma} \cdot \alpha \tag{15}$$

Where:

$$R_n = Net\ solar\ radiation\ \left(\frac{mJ}{(day)m^2}\right), R_{ns} - R_{nl} \tag{16}$$

$$R_{ns} = Net\ shortwave\ radiation\ \left(\frac{mJ}{(day)m^2}\right), (1 - \alpha) \cdot R_s \tag{17}$$

$$\alpha = Albedo, \frac{R_{S\ reflected\ average}}{R_{S\ incoming\ average}} \tag{18}$$

$$R_s\ = Incoming\ shortwave\ solar\ radiation\ \left(\frac{mJ}{(day)m^2}\right) \tag{19}$$

$$R_{nl} = Net\ longwave\ radiation\ \left(\frac{mJ}{(day)m^2}\right), f_c \cdot f_h \cdot \sigma \cdot f(T_K) \tag{20}$$

$$f_c = Cloudiness\ factor, 1.35 \frac{R_s}{R_a} - 0.35 \tag{21}$$

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

$$\frac{24 \cdot 60}{\pi} \cdot G_{sc} \cdot d_r(\omega_s \cdot sin\,\varphi \cdot sin\,\delta + cos\,\varphi \cdot cos\,\delta \cdot sin\,\omega_s) \tag{22}$$

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

$$d_r = inverse\ relatove\ dostamce\ Earth - Sun, 1 + 0.033\,cos \frac{2\pi}{365} \cdot J \tag{23}$$

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

$$\omega_s = sunset\ hour\ angle\ (rad), arccos(-tan\,\varphi \cdot tan\,\delta) \quad (24)$$

$$\varphi = latitude\ (rad)$$

$$\delta = solar\ decimation\ (rad), 0.409\,sin(\frac{2\pi}{365} \cdot J - 1.39) \quad (25)$$

$$f_h = Humidity\ correction\ factor, 0.34\ - 0.14\sqrt{(e_a)} \quad (26)$$

$$e_a = vapor\ pressure\ (kPa)$$

$$\sigma = Stefan - Boltzmann\ constant, 4.903 \cdot 10^{-9}\,\frac{mJ}{(day)m^2} \quad (27)$$

$$f(T_K) = T^4_{daily\ average\ ^\circ K} \quad (28)$$

$$Gf\ = soil\ heat\ flux, \frac{mJ}{(day)m^2} = 0\ for\ daily\ calculations \quad (29)$$

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

$$\frac{4098(0.6108 \cdot e^{\left(\frac{17.27T}{T+237.3}\right)})}{(T^2 + 237.3^2)} \quad (30)$$

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

$$\gamma = Psychrometric\ constant\ \left(\frac{kPa}{^\circ C}\right), \frac{C_p \cdot P}{\varepsilon \cdot \lambda} \quad (31)$$

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

$$Pa\ = Atmospheric\ pressure\ kPa, P_0 \cdot (\frac{L \cdot h}{T_0})^{\frac{g \cdot M}{R \cdot L}} \quad (32)$$

$$P_0 = Sea\ level\ standard\ atmospheric\ pressure, 101.325\ kPA$$

$$T_0 = Sea\ level\ standard\ temperature, 288.15\ K$$

$$L = temperature\ lapse\ rate, 0.0065\ \frac{K}{m} \quad (33)$$

$h = elevation\ of\ meadow\ m$

$$g = earth\ surface\ gravitational\ acceleration, 9.80665\ (\frac{m}{s^2}) \tag{34}$$

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

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

$$\lambda = Latent\ heat\ of\ vaporization\ \left(\frac{mJ}{kg}\right), 2.501 - 0.002361T \tag{35}$$

$T = daily\ mean\ air\ temperature$ ℃

$$\varepsilon = ratio\ of\ molecular\ weight\ of\ water\ vapor\ to\ dry\ air, 0.622 \tag{36}$$

$a = Priestley - Taylor\ coefficient$

### 3.3.4 Marian Meadow Surface Water Outflow (Q)

To quantify outflow from MM an Odyssey water level sensor was installed in Marian Creek, directly downstream of the project meadow (Figure 2). The sensor was installed adjacent to a 57" x 38" steel pipe-arch culvert with 2 2/3" x 1/2" corrugations. Outflow from MM into the culvert was calculated using Manning's equation based on measured depth, cross section area of the culvert and roughness coefficient for a corrugated metal pipe.

$$Q = \frac{1.486}{n} \cdot A \cdot R^{0.667} \cdot S^{0.5} \tag{37}$$

Where:

$Q = outflow\ (cfs)$

$n = Manning's\ roughness\ coefficient$, 0.025 (Wilke et al., 2008)

$A = cross - sectional\ area\ of\ flow, ft^2$

$R = hydraulic\ radious, ft$

$$= \frac{A}{WP}$$

$$WP = wetted\ perimeter, ft$$

$$S = slope\ (\frac{ft}{ft})$$

## 3.4 Statistical Analysis

Standard least squared regression and ANCOVA was used to test changes in weekly average groundwater depth and volumetric soil moisture content. Only sensor measured groundwater values, not modeled values, were included in this analysis. Volumetric soil moisture content was analyzed in the wet (October 1$^{st}$-March 31$^{st}$) and dry (April1st-September 30$^{th}$) seasons. All assumptions of regression were tested including linearity, serial autocorrelation, normal distribution, and homoscedasticity. The pre-restoration time period assessed in this analysis was 09/13/2013-07/31/2015. The post-restoration time period assessed in this analysis was 8/1/2015-6/24/2016. In order to account for serial autocorrelation a lag of 3 weeks was used for all soil moisture and water table depth analysis.

# CHAPTER 4 RESULTS

The three main sections of this chapter are: 4.1) results of each component of the water balance equation, 4.2) the water balance results, and 4.3) the results of the statistical analysis. Unless otherwise stated, the monitoring period used in this assessment starts 9/13/2013 and ends 6/24/2016, and all calculations are based on weekly averages.

## 4.1 Components of Water Balance

The following subsections describe the results for each component of the water balance including soil moisture content, water table depth, precipitation, evapotranspiration and surface water flow.

### 4.1.1 Volumetric Soil Moisture Content

#### 4.1.1.1 Marian Meadow

Weekly average soil moisture content measured from sensors buried 1.0 foot below the surface ranged from 10.6% to 47.4%.  Prior to restoration, the average weekly soil moisture content was 24.3%. Following restoration, the average weekly soil moisture content was 34.5%. The average weekly soil moisture content during the entire monitoring period was 27.5%. The peak weekly average soil moisture content for water years 2014, 2015, and 2016 was 32.4%, 36.7%, and 47.4% respectively. The lowest weekly average soil moisture for water years 2014 and 2015 was 17.2% and 19.5% respectively (Figure 4.1, Table 4.1). On Average, February had the highest average soil moisture content of 38.0% while September and October had the lowest; 17.9% and 17.6% respectively (Figure 4.2).

The average weekly soil moisture from instruments buried 3.0 feet below the surface ranged from 21.4% to 47.9%. Average volumetric soil moisture content during the entire monitoring period (8/7/2015-6/24/2016) was 36.9%. During the same time period, average soil moisture content for the 1.0 foot sensors was 34.5%. During the dry season and prior to the first significant precipitation event, the 3.0-foot soil moisture sensors exhibited a higher and earlier peak soil moisture content than the 1.0 foot sensors. Peak average soil moisture content (47.9%) for the 3.0 foot sensors occurred in March 2016, although soil moisture content greater than 45% occurred by mid-January. During the same time period, peak soil moisture measured by 1.0 foot sensors was 47.4%, which occurred in April 2016 (Figure 4.3).

**4.1.1.2 Control Meadow**

Weekly average soil moisture content measured from sensors buried 1.0 foot below the surface ranged from 11.4% to 40.0%. Prior to restoration, the average weekly soil moisture content was 21.5%. Following restoration, the average weekly soil moisture content was 30.0%. The average weekly soil moisture content during the entire monitoring period was 24.1%. The peak weekly average soil moisture content for water years 2014, 2015, and 2016 was 30.4%, 34.0%, and 40.3% respectively. The lowest weekly average soil moisture for water years 2014 and 2015 was 11.4% and 13.8% respectively (Figure 4.1). On average, March had the highest average soil moisture content of 35.0% while September had the lowest, 13.5% (Figure 4.2).

The average weekly soil moisture content for the 3.0 foot sensors ranged from 16.6% to 46.4%. Average volumetric soil moisture content during the entire monitoring period was 36.9%. During the same time period, average soil moisture content for the 1.0 foot sensors was 30.7%. During the dry season and prior to the first significant precipitation event, the 3.0-foot soil moisture sensors exhibited a higher soil moisture content than the 1.0 foot sensors. During the dry season and prior to the first significant precipitation event, the 3.0-foot soil moisture sensors exhibited a higher and earlier peak soil moisture content than the 1.0 foot sensors. Peak soil moisture content (43.4%) measured by the 3.0 foot sensors occurred in February. During the same time period peak soil moisture for the 1.0 foot sensors was 40.47%, which occurred in March 2016 (Figure 4.3).

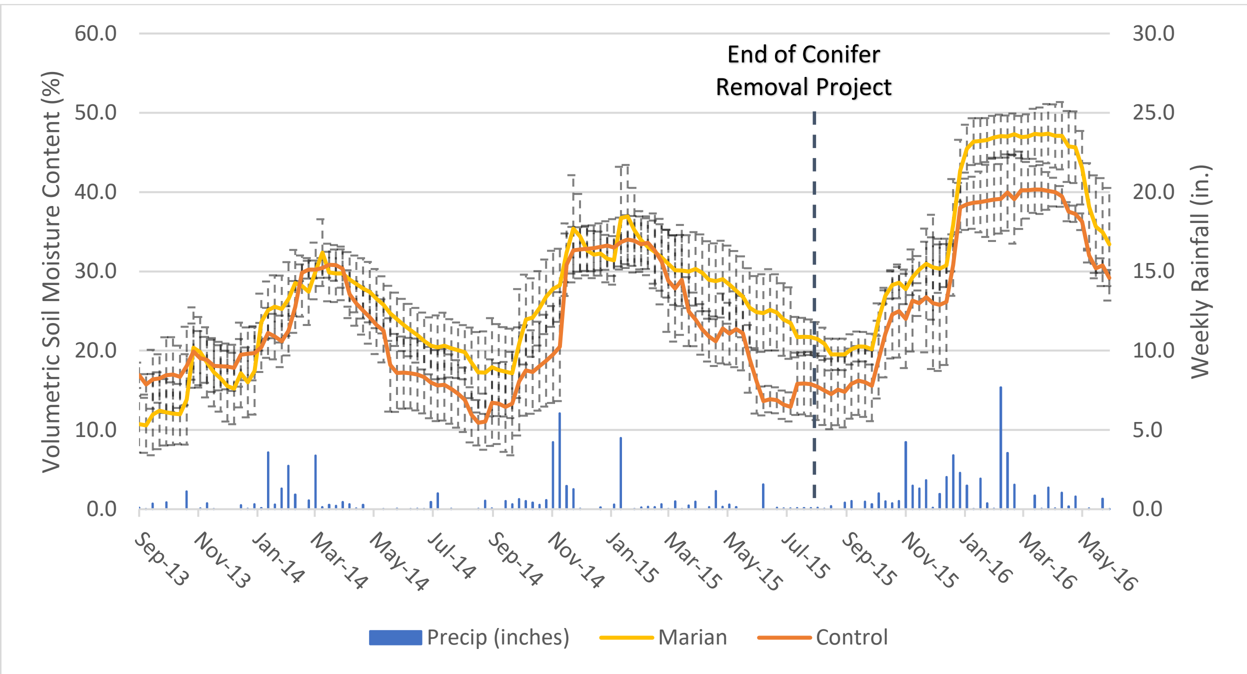



Figure 4.1: MM and CM weekly percent volumetric soil moisture content (%) and weekly rainfall total (in.). The error bars depict the standard deviation of MM and CM weekly average sensor values.

Table 4.1: MM and CM average volumetric soil moisture content (%) for 1 ft. sensors

| | 2014 WY | 2015 WY | 2016 WY | Pre Restoration | Post Restoration | Entire Monitoring Period |
|---|---|---|---|---|---|---|
| Marian Meadow | 21.3 | 27.3 | 37.4 | 24.3 | 34.5 | 27.5 |
| Control Meadow | 20.0 | 22.6 | 31.5 | 21.5 | 30.0 | 24.1 |

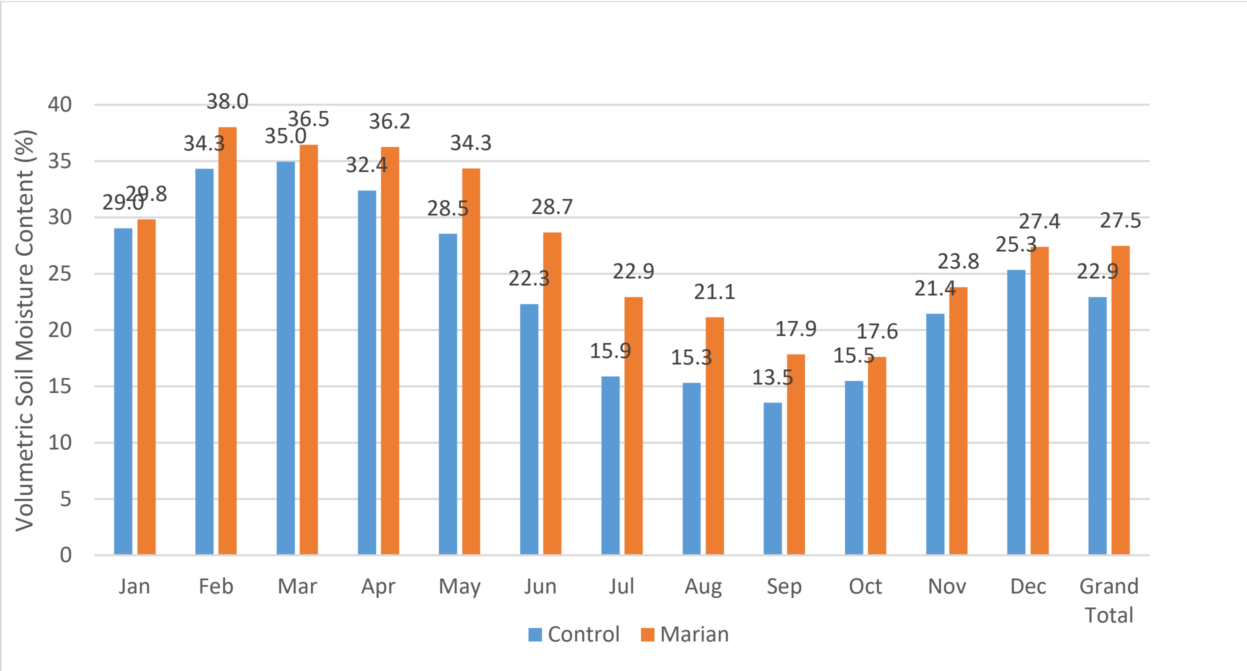



Figure 4.2: MM and CM average monthly volumetric soil moisture content (%)

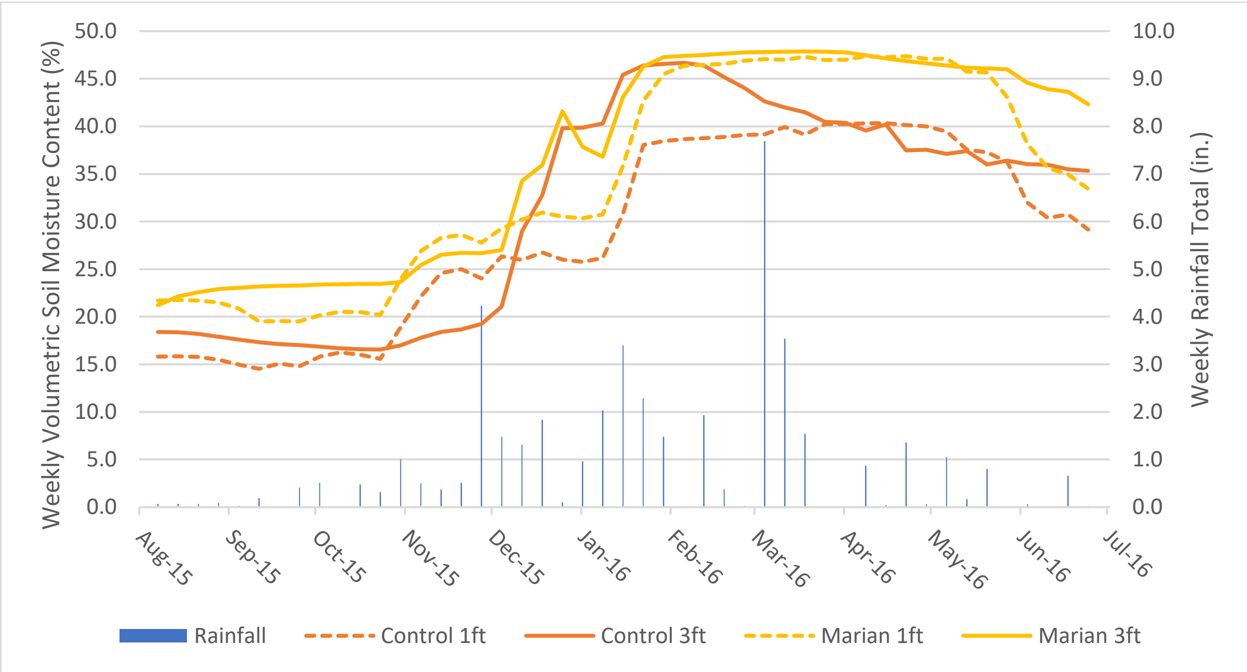
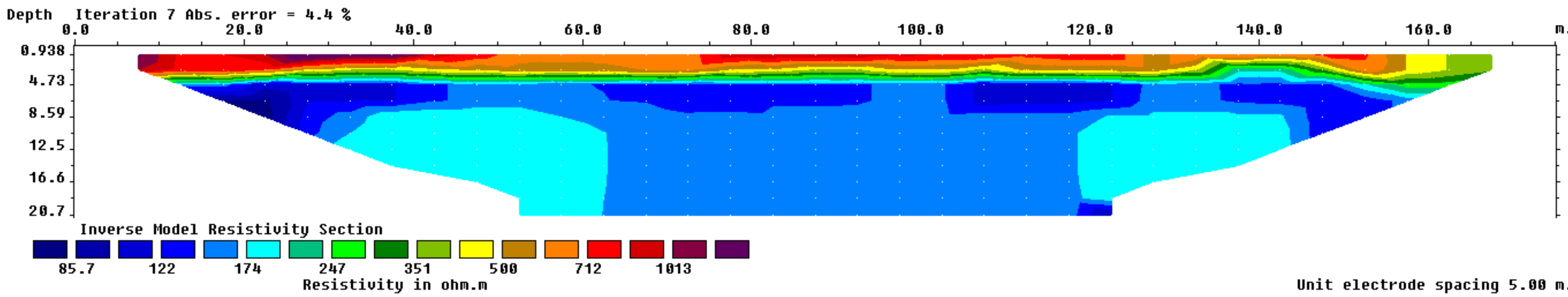



Figure 4.3: MM and CM 1ft and 3ft depth volumetric soil moisture content and rainfall (in.)

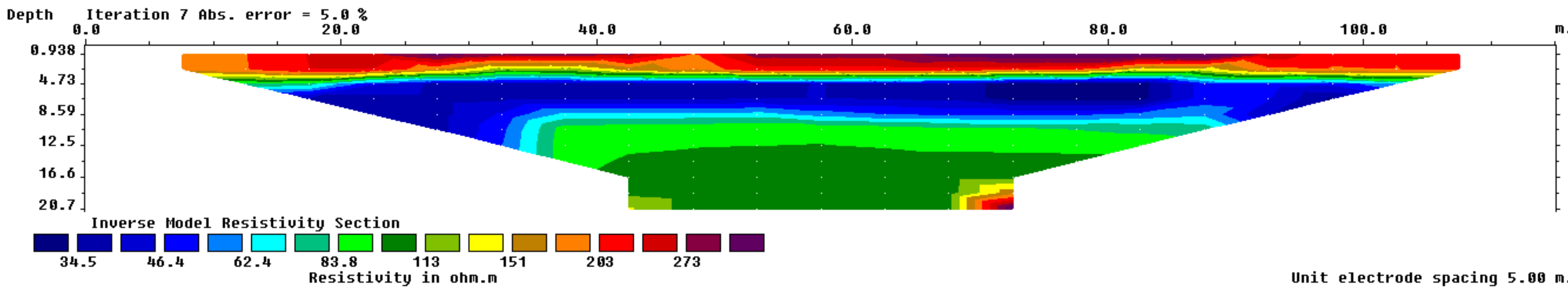
#### 4.1.2 Water Table Depth

##### 4.1.2.1 Electrical Resistivity Tomography

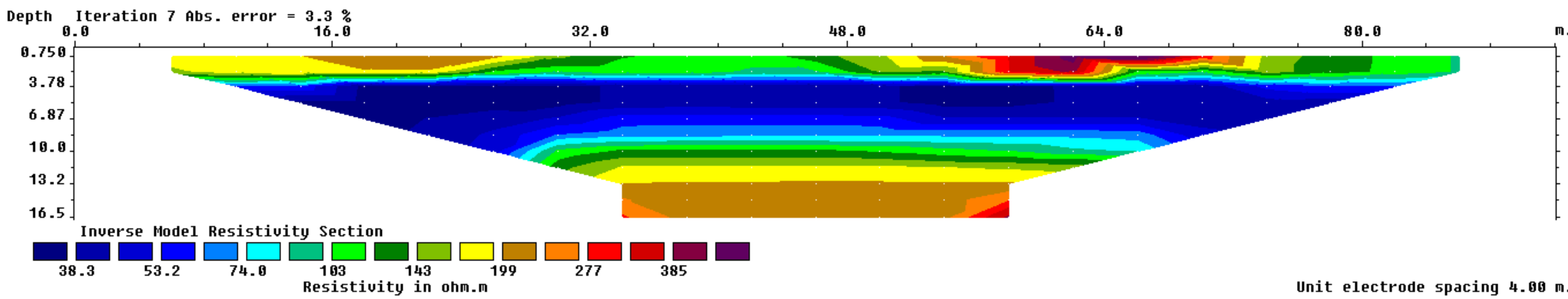
September 10th, 2014 EMT surveys yielded an approximate depth of 41.0ft (12.5m) to the bottom of MM's aquifer.  This depth was used as a reference datum to calculate the equivalent depth of water stored in the aquifer. The depth to the bottom of the aquifer in CM was greater than the maximum penetration depth of the ERT equipment used; which was approximately 66ft (Figure 4.4). For consistency and comparison of the two meadows the depth to the bottom of the MM aquifer was also used to calculate equivalent depth of water in CM. 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, 8.5feet, and 10.4 feet respectively for MM (Figure 4.5). ERT surveys conducted on 9/6/2014 and 9/9/2015 yielded depth to groundwater values of approximately 10.7 feet and 8.5 feet for CM (Figure 4.7).




a.

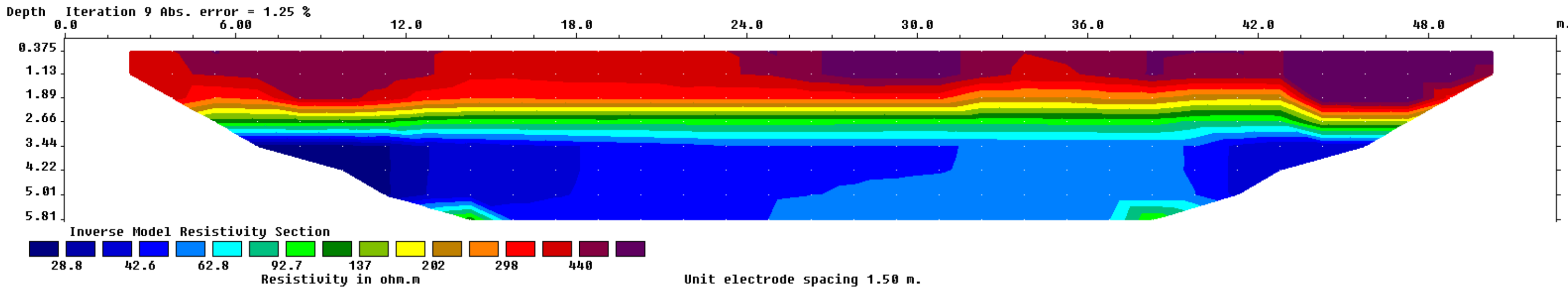



b.

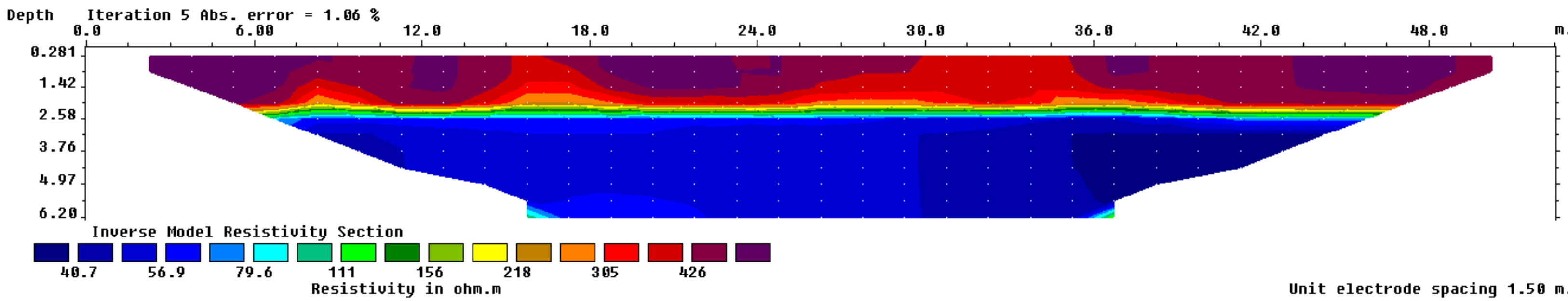



c.

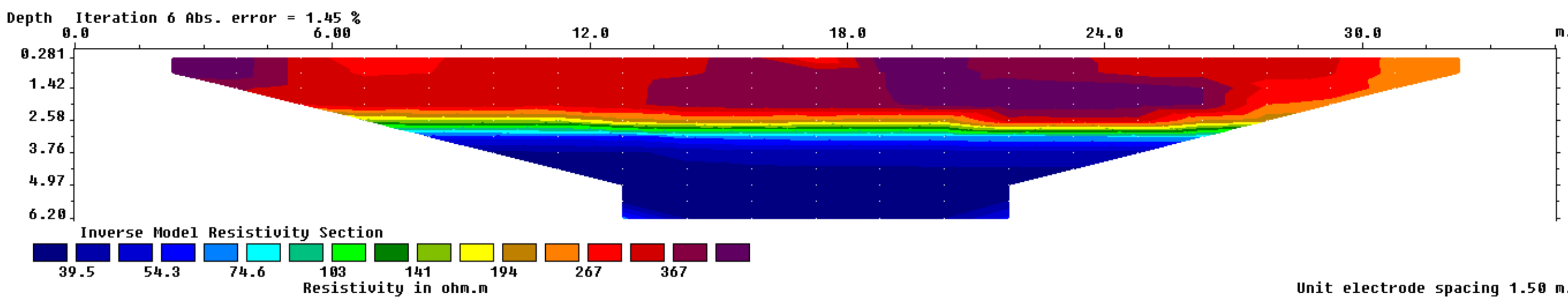
Figure 4.4: ER values in $\Omega \cdot m$ vs. depth (m) and distance (m) used to determine depth to bottom of aquifer. a: Control Meadow, survey #9 (9/6/2014); b. Marian meadow transect, survey #13 (9/7/2014), C. Lower Marian creek transect, survey #16 (9/7/2014)




a.

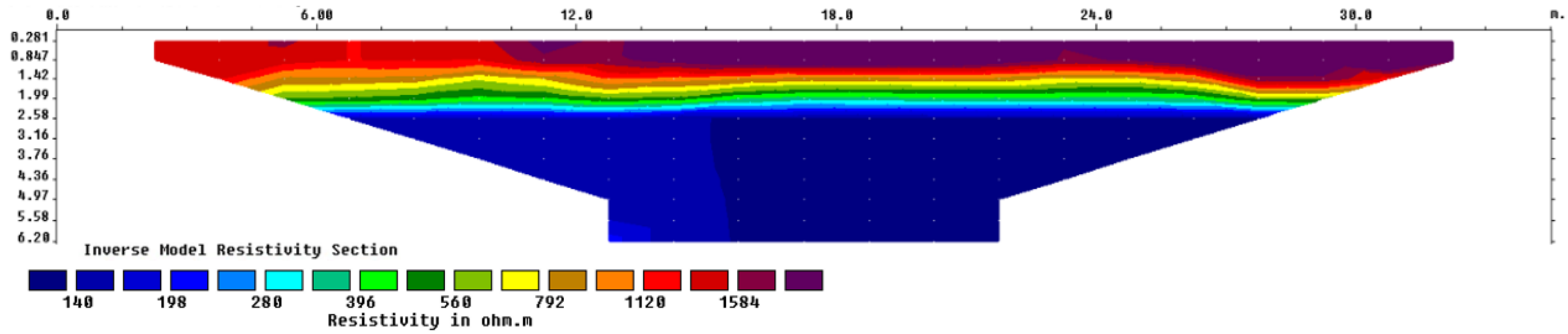



b.

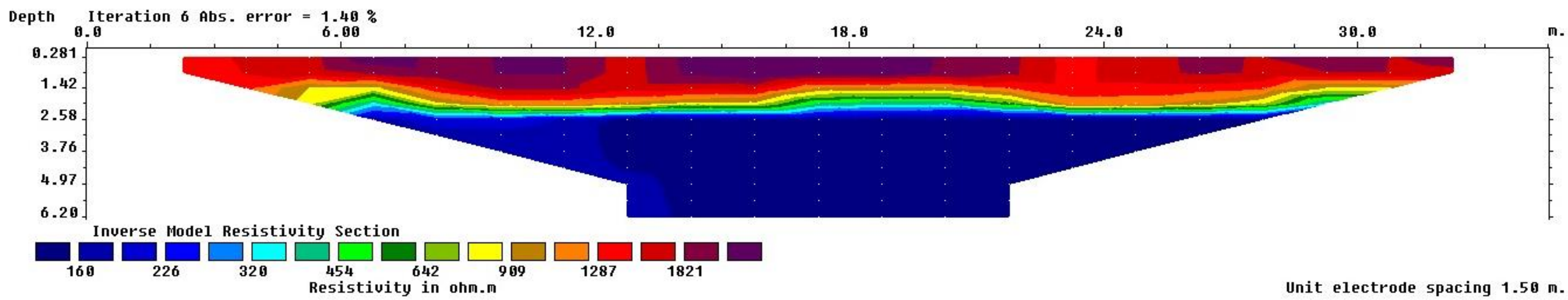



c.

Figure 4.5: ER values in Ω·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)




a.




b.

Figure 4.6: ER values in Ω·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)

#### 4.1.2.2 Marian Meadow

Average weekly depth to the water table, including measured and modeled values, ranged from 0.21 feet to 10.40 feet. Average weekly depth to the water table for the monitoring period was 4.06 feet. Average weekly depth to the water table prior to conifer removal was 4.29 feet. Average weekly depth to the water table following conifer removal was 3.29 feet. Peak water table depths for each water year were 0.96 feet, 0.65 feet, and 0.21 feet for water years 2014, 2015, and 2016 respectively. Maximum depth for each water year was assumed to be the measured depth using electrical resistivity tomography which was 8.26 feet, 8.87 feet and 8.53 feet respectively (Figure 4.7,

Table 4.2). Average growing season water table depth for the 2014, 2015, and 2016 water years was 4.02 feet, 4.81, feet, and 0.98 feet. During the 2014, 2015, and 2016 growing seasons, water table was at or above 2.3 feet for 46 days, 7 days, and 85 days respectively (
Table 4.3).

#### 4.1.2.3 Control Meadow

Average weekly depth to the water table, including measured and modeled values, ranged from 0.15 feet to 10.70 feet. Average weekly depth to the water table for the monitoring period was 3.93 feet. Average weekly depth to the water table prior to conifer removal was 4.17 feet. Average weekly depth to the water table following conifer removal was 3.08 feet. Peak groundwater elevations for each water year were 0.16 feet, 0.25 feet, and 0.15 feet for water years 2014, 2015, and 2016 respectively. Maximum depth for 2014 and 2015 water years was assumed to be the measured depth using electrical resistivity tomography which was 8.5 feet for both years. Because ERT measurements were not measured in September 2013, the initial rising limb (9/27/2013-2/21/2014) of the CM's groundwater hydrograph was modeled. Maximum modeled depth for CM in water year 2013 was 9.91 feet (Figure 4.7,

Table 4.2). Average growing season water table depth for the 2014, 2015, and 2016 water years was 3.68 feet, 4.32, feet, and 1.06 feet. The number of days the water table was at or above 2.3 feet was 53, 24, and 71 for the 2014, 2015, and 2016 water years respectively. During the 2014, 2015, and 2016 growing seasons, water table was at or above 2.3 feet for 53 days, 24 days, and 71 days respectively (

Table 4.3).

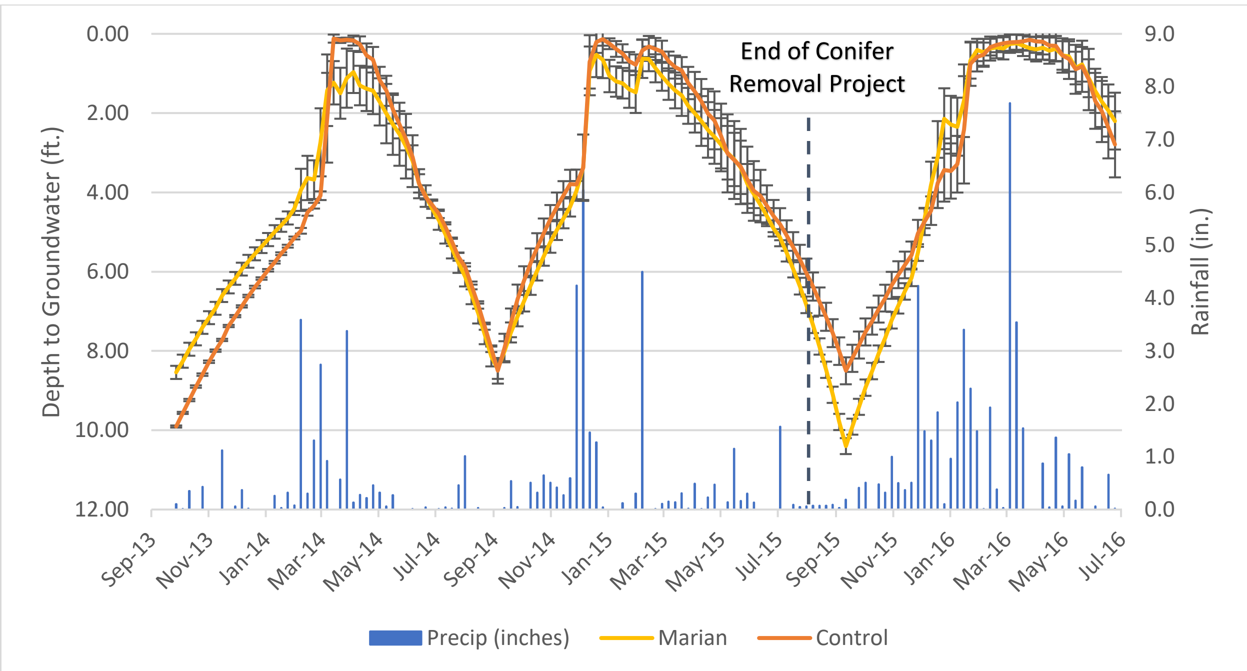



Figure 4.7: Depth to groundwater (ft.) for MM and CM and rainfall (in.). The error bars depict the standard deviation of MM and CM weekly average sensor values.

Table 4.2: Average depth to groundwater (ft.) for MM and CM

| | 2014 WY | 2015 WY | 2016 WY | Pre Restoration | Post Restoration | Entire Monitoring Period |
|---|---|---|---|---|---|---|
| Marian Meadow | 4.88 | 4.12 | 2.61 | 4.29 | 3.29 | 3.99 |
| Control Meadow | 5.10 | 3.52 | 2.57 | 4.17 | 3.08 | 3.84 |

Table 4.3: Growing season (April 1st through August 31st) water table depths (ft)

| | Marian Meadow | | | | Control Meadow | | | |
|---|---|---|---|---|---|---|---|---|
| | 2014 WY | 2015 WY | 2016 WY | Total | 2014 WY | 2015 WY | 2016 WY | Total |
| WTD average | 4.02 | 4.81 | 0.98 | 3.63 | 3.68 | 4.32 | 1.06 | 3.33 |
| WTD minimum | 0.96 | 2.01 | 0.39 | 0.39 | 0.17 | 1.46 | 0.19 | 0.17 |
| WTD maximum | 8.14 | 9.11 | 2.2 | 9.11 | 7.94 | 7.55 | 2.79 | 7.94 |
| WTD range | 7.18 | 7.1 | 1.81 | 8.72 | 7.77 | 6.09 | 2.6 | 7.77 |
| Days WTD < 2.3 | 46 | 7 | 85 | 138 | 53 | 24 | 71 | 148 |
| Days WTD < 1.0 | 4 | 0 | 50 | 54 | 25 | 0 | 50 | 75 |

### 4.1.3 Total Equivalent Water Stored in Unsaturated Soil and Groundwater

#### 4.1.3.1 Marian Meadow

In MM, the weekly average equivalent water depth stored in the unsaturated soil ranged from 0.10 feet to 2.34 feet. For the entire monitoring period, the average equivalent water depth stored in the unsaturated soil was 0.90 feet. The peak equivalent water depth stored in the unsaturated soil for water years 2014, 2015, and 2016 was 1.33 feet, 1.56 feet, and 2.34 feet respectively. The lowest equivalent water depth stored in the unsaturated soil for water years 2014, 2015, and 2016 was 0.31 feet, 0.13 feet, and 0.03 feet respectively (Figure 4.8).

The weekly equivalent water depth stored in the groundwater ranged from 15.26 feet to 19.14 feet. For the entire monitoring period, the average equivalent water depth stored in the aquifer was 17.40 feet. The peak equivalent water depth stored in the groundwater for water years 2014, 2015, and 2016 was 18.83 feet, 19.03 feet, and 19.14 feet respectively. The lowest equivalent water depth stored in groundwater for water years 2014, 2015, and 2016 was 15.26 feet, 15.30 feet, and 14.39 feet respectively (Figure 4.9).

The total weekly water depth stored in the unsaturated soil and groundwater ranged from 16.18 feet to 19.14 feet. For the entire monitoring period, the average equivalent water depth stored in unsaturated soil and the aquifer was 18.31 feet. The peak equivalent water depth stored in unsaturated soil and groundwater for water years 2014, 2015, and 2016 was 19.09 feet, 19.22 feet, and 19.29 feet respectively. The lowest equivalent water depth stored in unsaturated soil and groundwater for water years 2013, 2014, and 2015 was 16.18 feet, 16.86 feet, and 16.73 feet respectively. On average, groundwater was 95.4% of total equivalent water depth stored in unsaturated soil and groundwater combined (Figure 4.10).

#### 4.1.3.2 Control Meadow

In CM, the weekly average equivalent water depth stored in the unsaturated soil ranged from 0.00 feet to 1.67 feet. For the entire monitoring period, the average equivalent water depth stored in the unsaturated soil was 0.72 feet. The peak equivalent water depth stored in the unsaturated soil for water years 2013, 2014, and 2015 was 1.67 feet, 1.01 feet, and 1.36 feet respectively. The lowest equivalent water depth stored in the unsaturated soil for water years 2014, 2015, and 2016 was 0.04 feet, 0.04 feet, and 0.00 feet respectively (Figure 4.8).

The weekly equivalent water depth stored in the groundwater ranged from 12.54 feet to 16.31 feet. For the entire monitoring period, the average equivalent water depth stored in the aquifer was 14.83 feet. The peak equivalent water depth stored in the groundwater for water years 2014, 2015, and 2016 was 16.29 feet, 16.31 feet, and 16.28 feet respectively. The lowest equivalent water depth stored in groundwater for water years 2014, 2015, and 2016 was 12.54 feet, 12.97 feet, and 13.09 feet respectively (Figure 4.9).

The total weekly water depth stored in the unsaturated soil and groundwater ranged from 13.98 feet to 16.34 feet. For the entire monitoring period, the average equivalent water depth stored in unsaturated soil and the aquifer was 15.54 feet. The peak equivalent water depth stored in unsaturated soil and groundwater for water years 2014, 2015, and 2016 was 16.35 feet, 16.34 feet, and 16.40 feet respectively. The lowest equivalent water depth stored in unsaturated soil and groundwater for water years 2013, 2014, and 2015 was 14.05 feet, 13.98 feet, and 14.38 feet respectively. On average, groundwater was 95.4% of total equivalent water depth stored in unsaturated soil and groundwater combined (Figure 4.10).

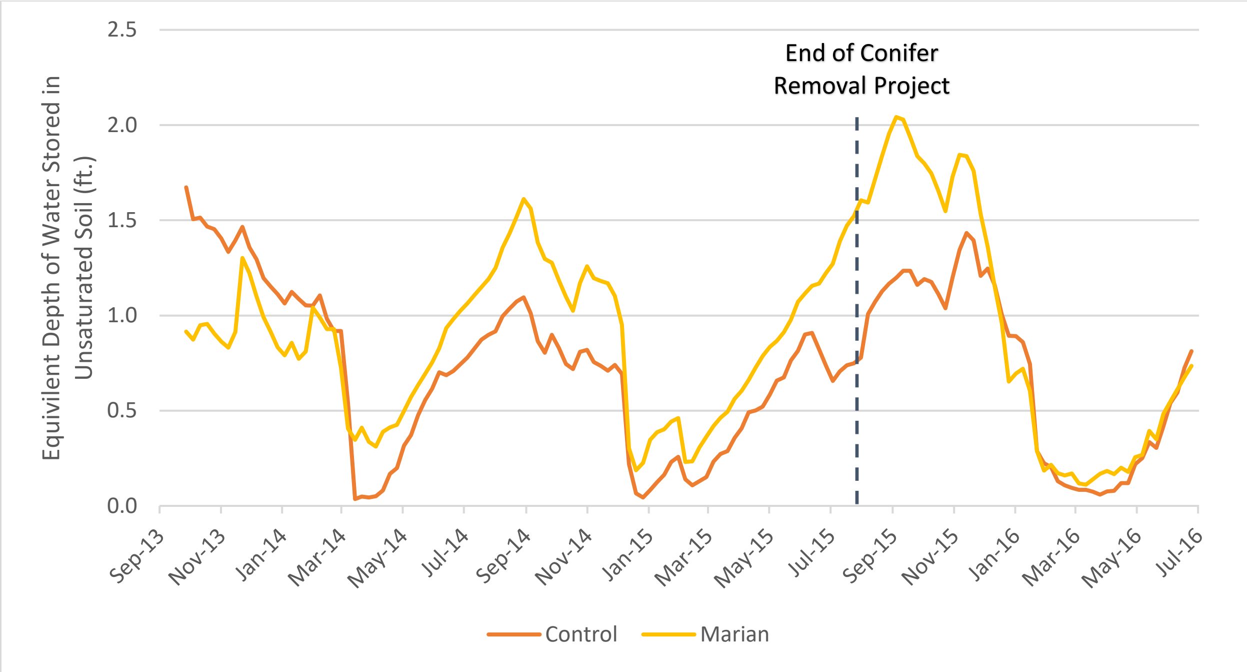


Figure 4.8: Equivalent Depth of Water Stored in Unsaturated Soil (in.)

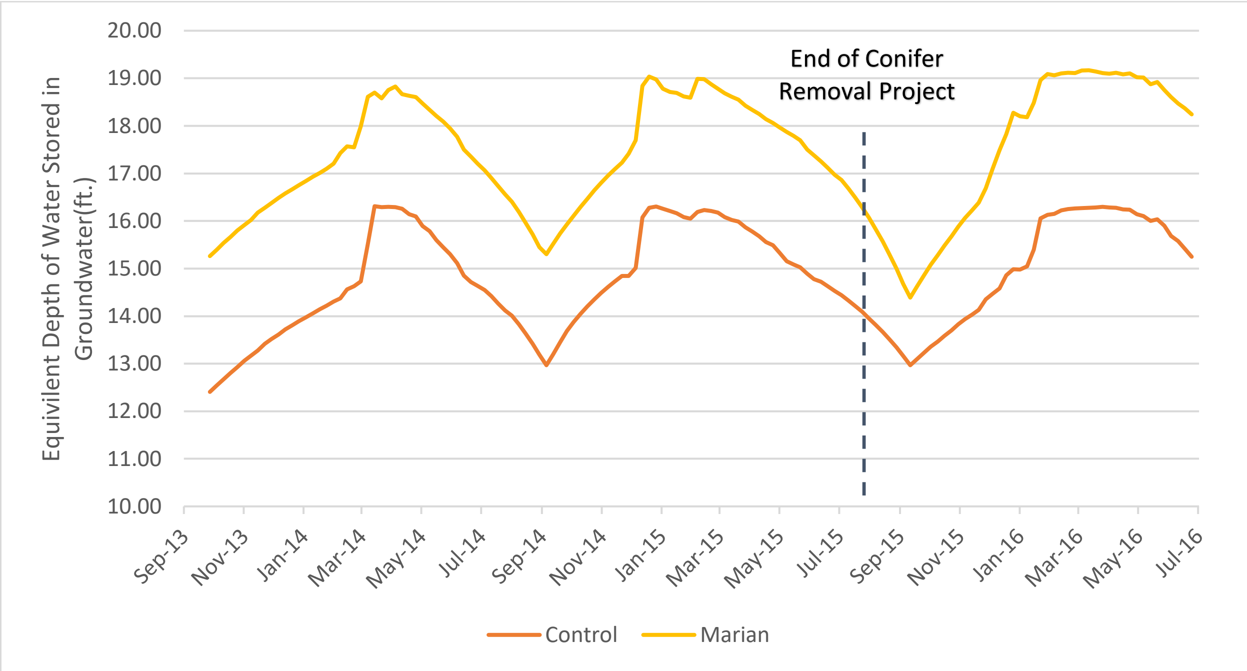


Figure 4.9: Equivalent Depth of Water Stored in Groundwater and Unsaturated Soil (ft.)

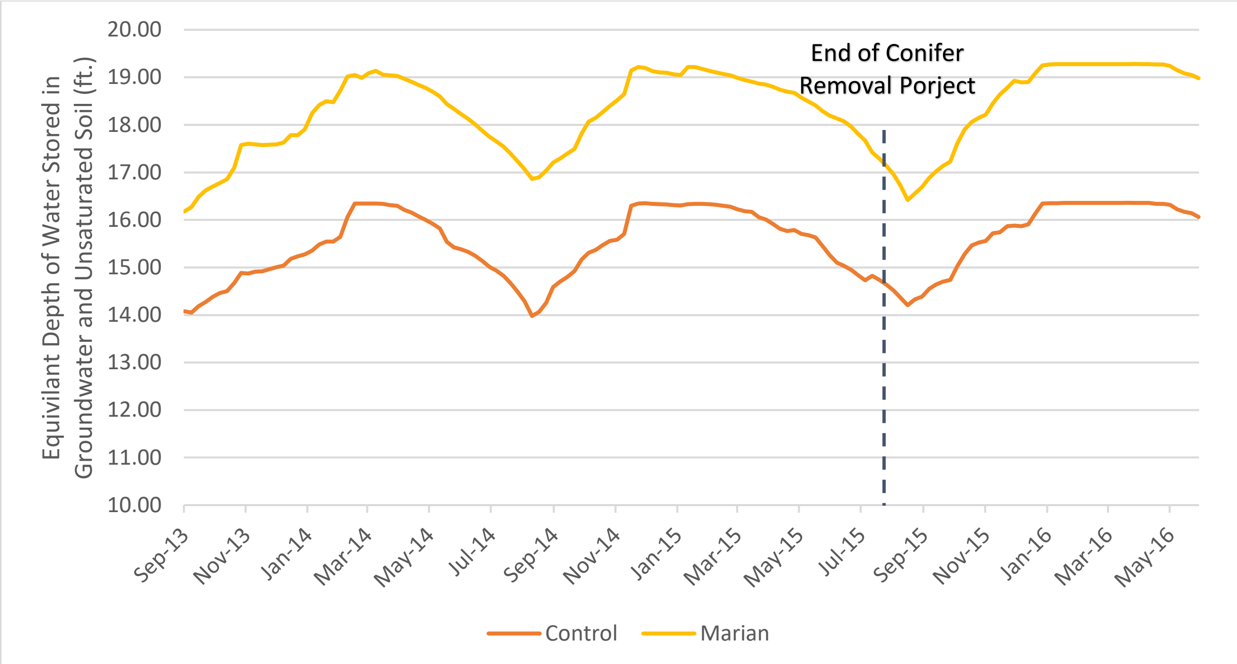


Figure 4.10: Equivalent Depth of Water Stored in Groundwater and Unsaturated Soil (ft.)

### 4.1.4 Evapotranspiration, Temperature, Precipitation, and Surface Water Flow

Albedo and average daily net solar radiation are required inputs into 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. The average daily net solar radiation for the entire monitoring period was 7.50 MJ/kg. The peak daily average net solar radiation for water years 2014, 2015, and 2016 is 16.00 MJ/kg, 16.8 MJ/kg, and 18.3 MJ/kg respectively. The lowest daily average net solar radiation for water years 2014, 2015, and 2016 is -0.70MJ/kg, -0.70MK/kg, and -2.01 MJ/kg respectively (Figure 4.11).

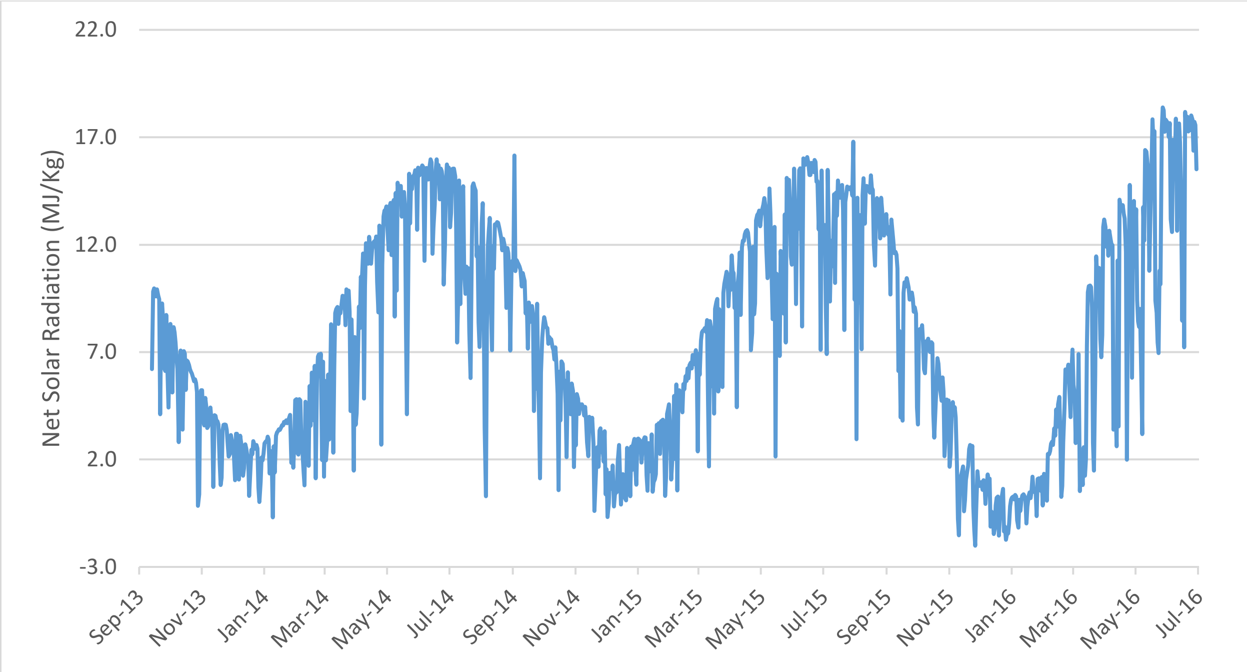


Figure 4.11: Net solar radiation in (MJ/kg) used in Priestly Taylor Analysis for MM and CM

#### 4.1.4.1 Marian Meadow Evapotranspiration

Evapotranspiration was estimated to range from 0.00 in/week to 0.79 in/week with an average of 0.28 in/week for the entire monitoring period. Peak evapotranspiration for water years 2014, 2015, and 2016 was estimated to be 0.76 in/week, 0.79 in/week, and 0.45 in/week respectively. The lowest evapotranspiration estimated for water years 2013, 2014, and 2015 was 0.02 in/week, 0.02 in/week, and 0.00 in/week (Figure 4.12).

#### 4.1.4.2 Control Meadow Evapotranspiration

Evapotranspiration was estimated to range from 0.00 in/week to 0.45 in/week with an average of 0.18 in/week for the entire monitoring. Peak evapotranspiration for water years 2014, 2015, and 2016 was estimated to be 0.41 in/week, 0.42 in/week, 0.45 in/week respectively. The lowest evapotranspiration estimated for water years 2013, 2014, and 2015 was 0.01 in/week, 0.02 in/week, and 0.00 in/week (Figure 4.12).

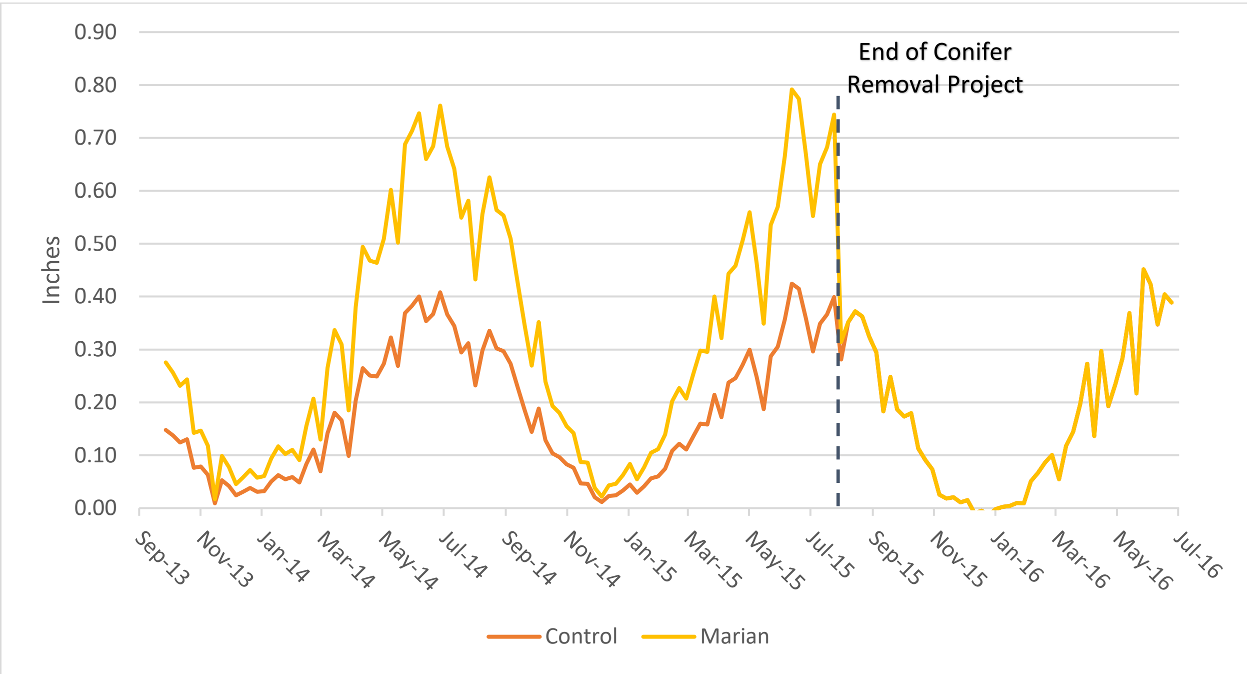



Figure 4.12: Evapotranspiration (in./day) for MM and CM estimated using Priestly Taylor

Weekly average daily temperature ranged from -5.7°C to 21.4°C. The average weekly temperature for the entire monitoring period was 7.2°C. The peak weekly average air temperature for water years 2014, 2015, and 2016 was 21.2°C, 21.4°C, and 17.3°C respectively. The lowest weekly average temperature for water years 2014, 2015, and 2016 was -8.1°C, -3.4°C, and -5.7°C respectively (Figure 4.13).

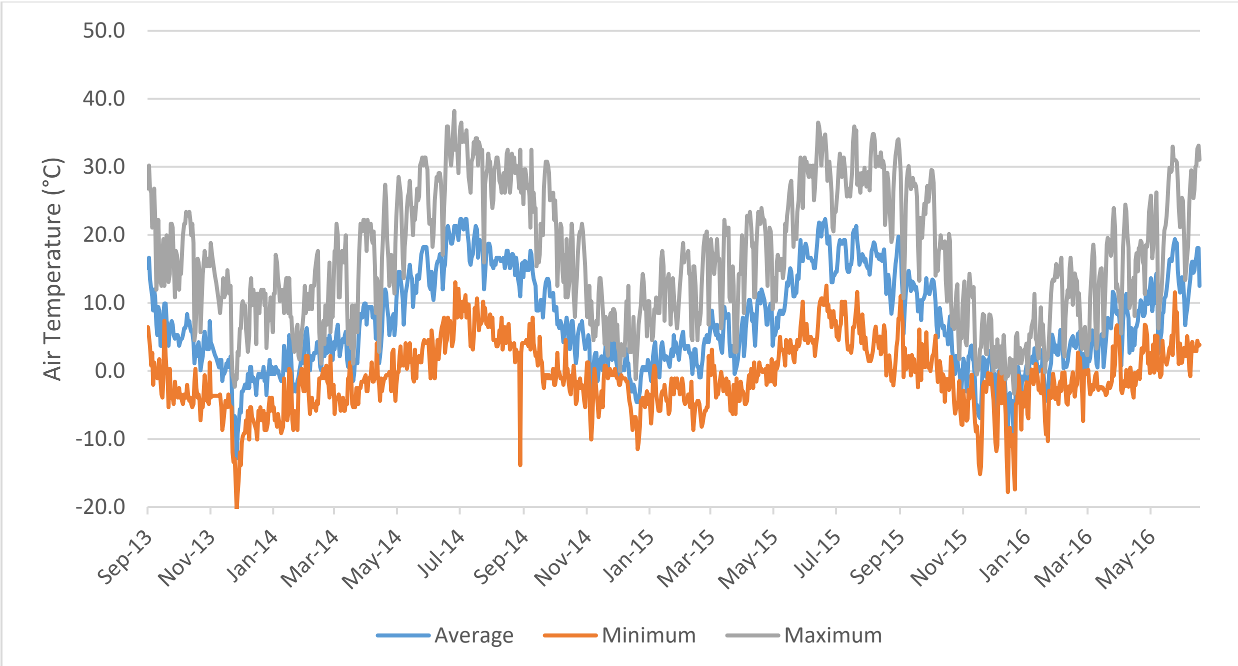


Figure 4.13: CM daily average, minimum, and maximum temperature values (°C)

#### 4.1.4.3 Precipitation

Total rainfall for water years 2013, 2014, 2015, and 2016 (through July 25th) was 31.62", 19.85", 27.35", and 43.51" respectively (Figure 4.14). In nearby Chester, CA, average annual precipitation is 31.8" (Table 3.1).

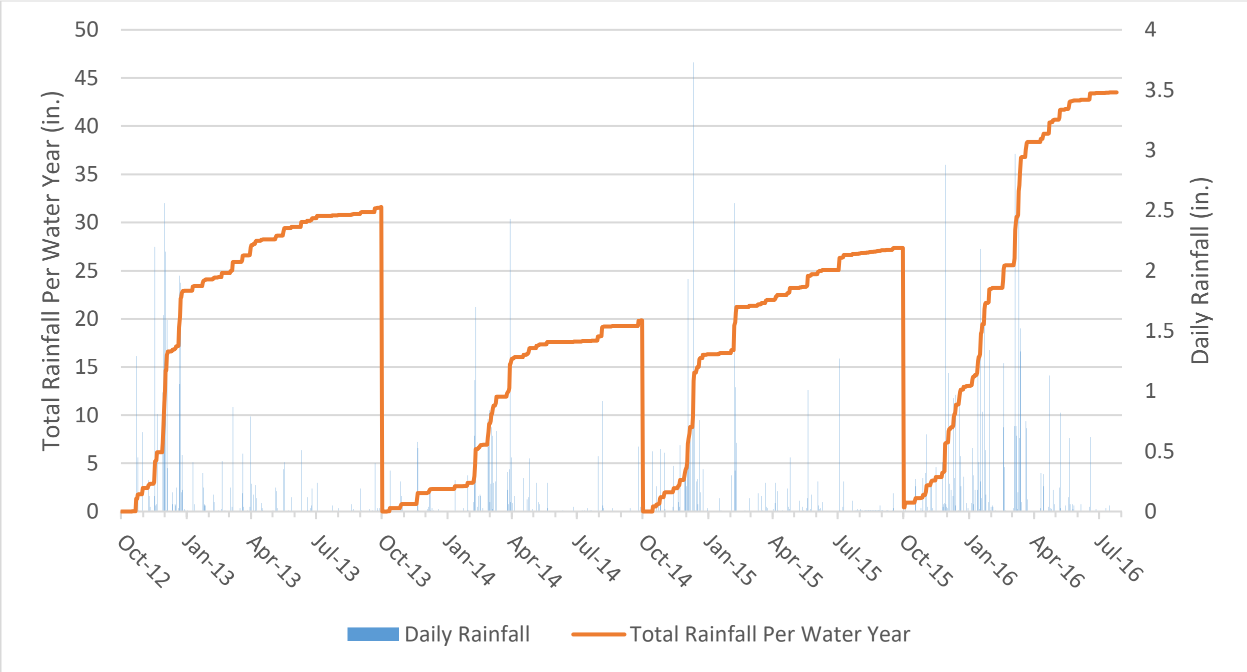


Figure 4.14: Total accumulated rainfall per water year (in.) and daily rainfall totals (in.)

### 4.1.4.4 Marian Meadow Outflow

During the 2014 water year there was no measurable flow exiting MM. During the 2015 water year measurable flow exiting MM started 12/11/2014 and ended 4/26/2015. During this time period peak out flow was 4.17 cfs and average outflow was 2.10 cfs (Figure 4.15). A total of 12.44 feet of surface water exited MM during the 2015 water year (Figure 4.16). During the 2016 water year measurable flow exiting MM started 1/17/2016 and continued to the end of the monitoring period (6/29/2016). During this time period peak out flow was 12.34 cfs and average outflow was 6.66 cfs (Figure 4.15). A total of 48.00 feet of surface water exited MM during the 2016 water year (Figure 4.16).

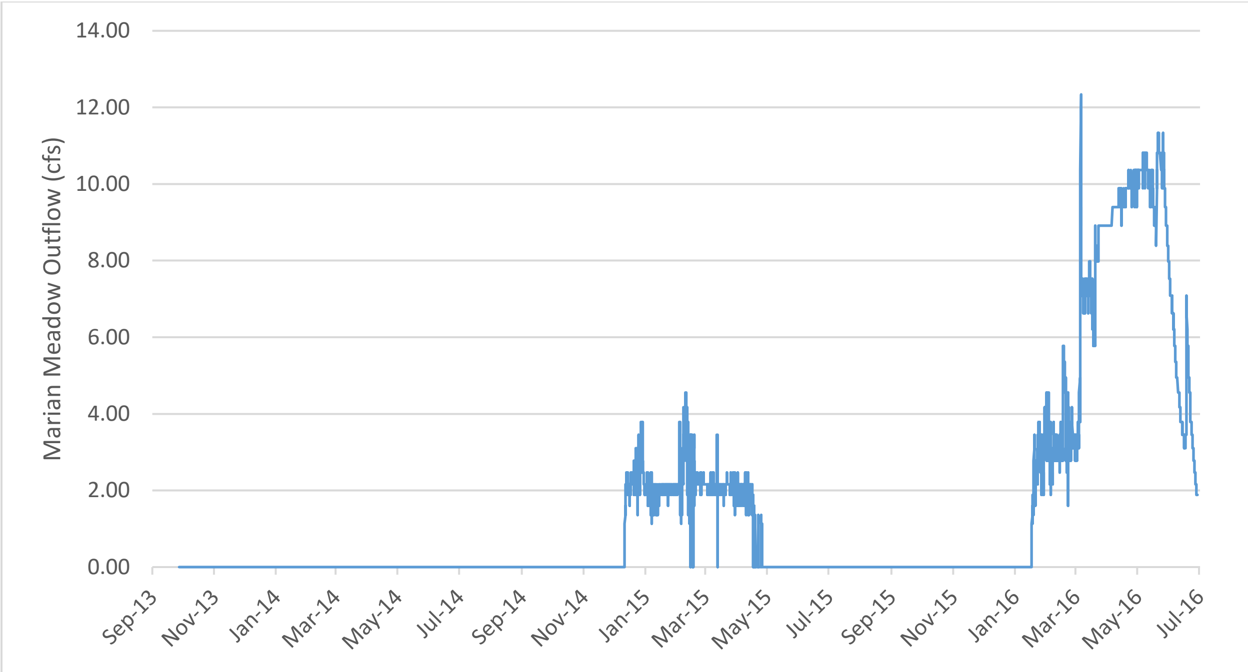


Figure 4.15: Marian Meadow outflow in CFS

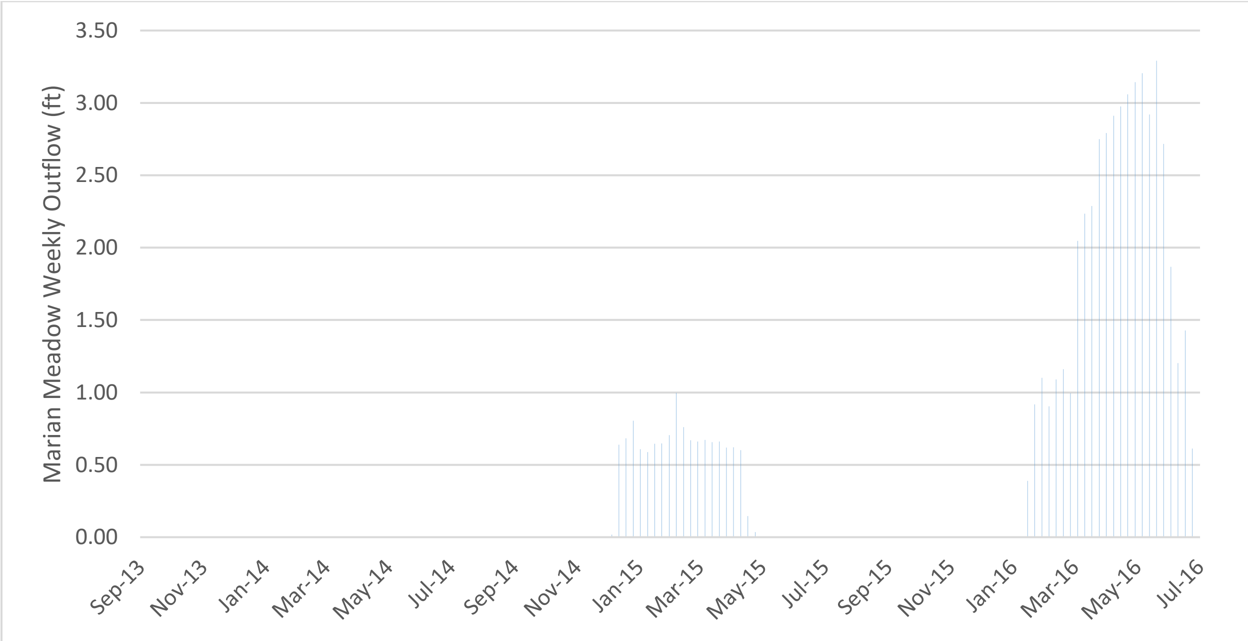


Figure 4.16: Marian Meadow weekly outflow in feet

### 4.2 Water Balance

In this water balance analysis flow into and out of MM and the CM are not included. The MM outflow measurements will be used to help interpret results and errors associated with the water balance. Total water available to meadow storage was calculated by subtracting evapotranspiration from precipitation. This was calculated for the entire monitoring period, for each water year, and for the wet season and dry season of each water year. Positive values indicate there is a water surplus available for meadow water storage. Negative values indicate that evapotranspiration is greater than precipitation and there is a water deficit. A positive change in storage indicates that total meadow water storage (groundwater and soil water), increased. This was calculated for the entire monitoring period, for each water year, and for the wet season and dry season of each water year. A negative change in storage indicates that total meadow water storage (groundwater and soil water), decreased. This was calculated for the entire monitoring period, for each water year, and for the wet season and dry season of each water year.

#### 4.2.1 Marian Meadow

Throughout the monitoring period, MM exhibited a total water surplus of 4.19 feet and a 3.06-foot change of storage. This resulted in an error of 1.13 feet. Because surface runoff was not included into this analysis, some of this error can be associated with surface water flow coming into and out of the meadow. During the 2014 water year, total water surplus was 0.22 feet and total change in storage was 0.31 feet. The 2015 water year had a total water surplus of 0.91 feet and 1.91 foot decreases in water storage; the only water year with a negative change in storage. . During the 2016 water year, total water surplus was 3.12 feet and total change in storage was 4.75 feet (Table 4.4).

Throughout the monitoring period, MM exhibited a greater range in monthly water storage values and greater water storage responses as a result of precipitation. MM monthly water storage values ranged from +2.43 feet to -1.53 feet, while the CM water storage values from +0.76 to -0.73 feet (Figure 4.17, Figure 4.18). Although MM exhibited greater positive and lower negative water storage values than the CM, the timing in groundwater storage change are similar (Figure 4.17 and Figure 4.18).

#### 4.2.2 Control Meadow

Throughout the monitoring period, CM exhibited a total water surplus of 5.44 feet and a 2.03 foot change in storage. This resulted in an error of 3.41 feet. During the 2014 water year, total water surplus was 0.84 feet and total change in storage was 0.51 feet. The 2015 water year had a total water surplus of 1.48 feet and 0.07 foot decreases in water storage; the only water year with a negative change in storage. During the 2016 water year, total water surplus was 3.12 feet and total change in storage was 1.59 feet (Table 4.4).

#### 4.2.3 Post Restoration Comparison

Water surplus is assumed to be the same in both MM and CM in the 2016 water year due to our shared precipitation values and modelled ET values. Therefore, only a change in water storage would indicate a change due to conifer removal. In the 2016 water year, following conifer removal restoration, the MM change in storage was 3.16 feet higher than CM (Table 4.4, Figure 4.19). Prior to conifer removal, 2014 and 2015 water years, MM change in storage was below CM (Figure 4.19). Additionally, the increase in change in storage for MM is greater than the water balance error of -1.63 feet in MM suggesting a positive change in soil and groundwater following conifer removal.

Table 4.4: MM and CM water budget components, sum of

| Marian Meadow | Water Surplus (P-ET) | Water Deficit (P-ET) | Total Water Surplus/Deficit (P-ET) | Change in Storage (ΔS) | Error |
|---|---|---|---|---|---|
| Total | 6.39 | -2.20 | 4.19 | 3.06 | 1.13 |
| WY2014 | 1.20 | -1.08 | 0.22 | 0.31 | -0.09 |
| Oct 1st-Mar 31st | 1.14 | -0.14 | 1.00 | 3.99 | -2.99 |
| Apr 1st-Sep3th | 0.06 | -0.93 | -0.87 | -3.68 | 2.90 |
| WY2015 | 1.82 | -0.88 | 0.94 | -1.91 | 2.85 |
| Oct 1st-Mar 31st | 1.64 | -0.15 | 1.49 | 3.21 | -1.72 |
| Apr 1st-Sep3th | 0.18 | -0.73 | -0.55 | -5.12 | 4.57 |
| WY2016 | 3.37 | -0.24 | 3.12 | 4.75 | -1.63 |
| Oct 1st-Mar 31st | 3.07 | -0.04 | 3.03 | 6.22 | -3.19 |
| Apr 1st-Sep3th | 0.29 | -0.20 | 0.09 | -1.47 | 1.56 |
| Control Meadow | Water Surplus (P-ET) | Water Deficit (P-ET) | Total Water Surplus/Deficit (P-ET) | Change in Storage (ΔS) | Error |
| Total | 6.68 | -1.24 | 5.44 | 2.03 | 3.41 |
| WY2014 | 1.35 | -0.51 | 0.84 | 0.51 | 0.33 |
| Oct 1st-Mar 31st | 1.22 | -0.07 | 1.15 | 2.27 | -1.11 |
| Apr 1st-Sep3th | 0.13 | -0.44 | -0.31 | -1.76 | 1.44 |
| WY2015 | 1.96 | -0.48 | 1.48 | -0.07 | 1.55 |
| Oct 1st-Mar 31st | 1.71 | -0.06 | 1.65 | 1.63 | 0.02 |
| Apr 1st-Sep3th | 0.25 | -0.42 | -0.17 | -1.70 | 1.53 |
| WY2016 | 3.37 | -0.24 | 3.12 | 1.59 | 1.53 |
| Oct 1st-Mar 31st | 3.07 | -0.04 | 3.03 | 1.84 | 1.20 |
| Apr 1st-Sep3th | 0.29 | -0.20 | 0.09 | -0.25 | 0.34 |

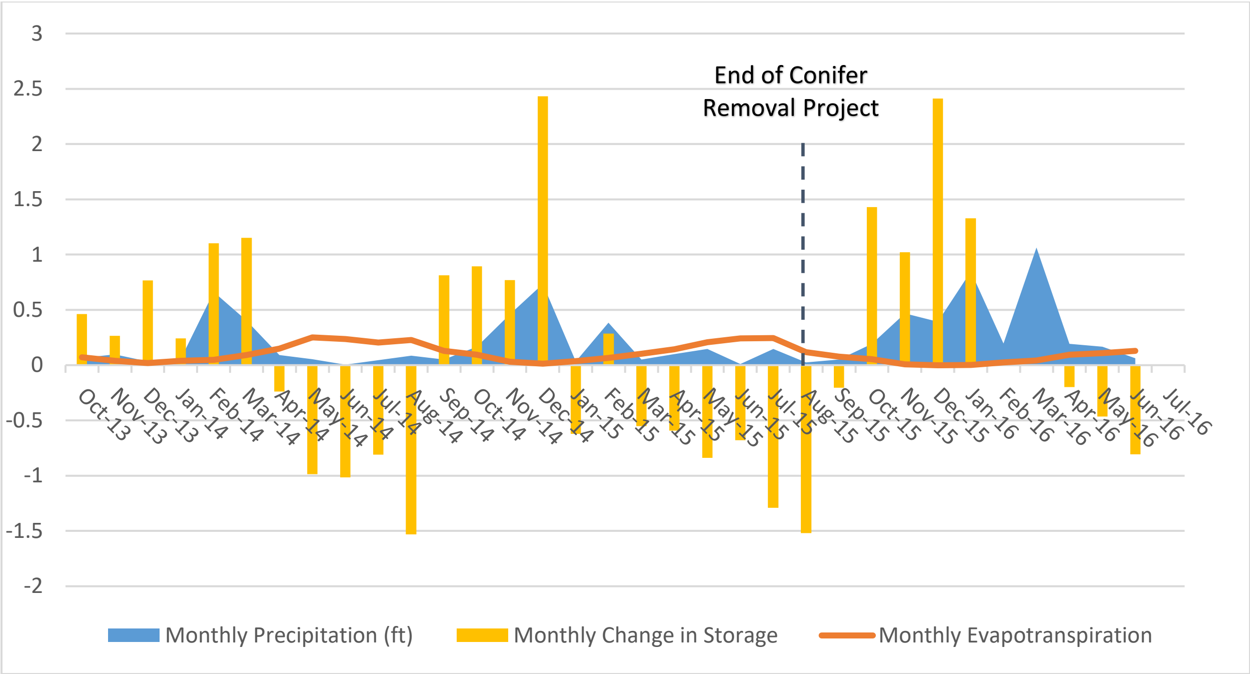


Figure 4.17: Monthly MM evapotranspiration, precipitation, and total change in storage

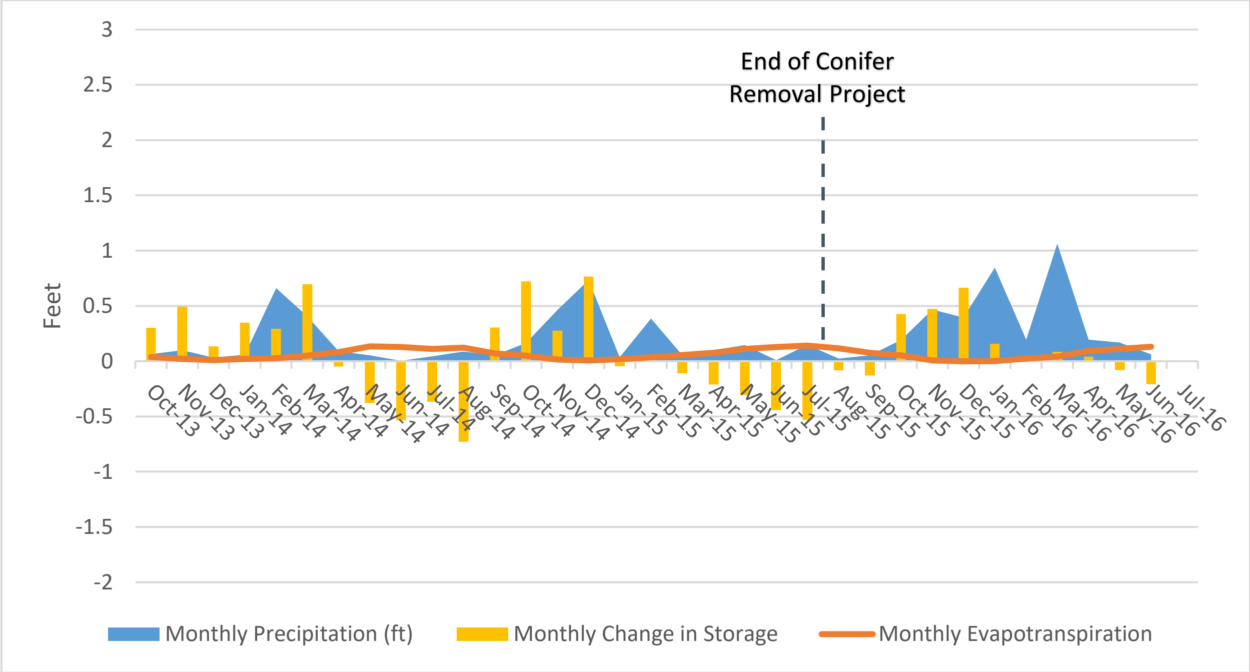


Figure 4.18: Monthly CM evapotranspiration, precipitation, and total change in storage

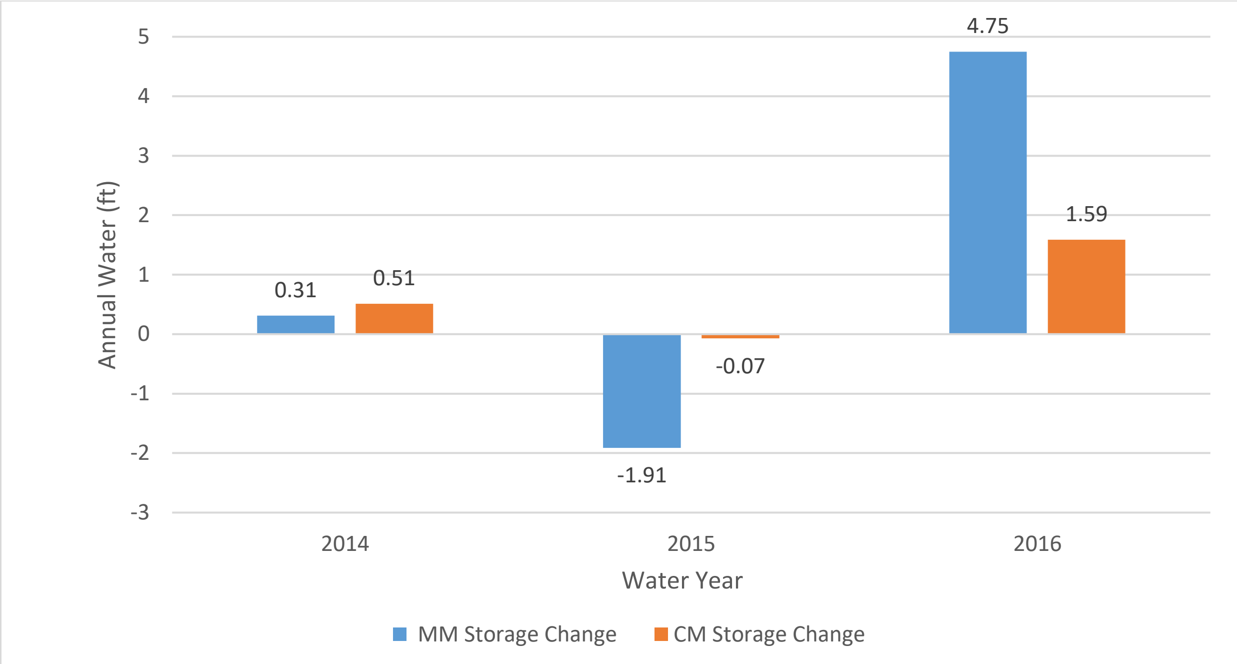



Figure 4.19: Change in storage in MM and CM for 2014-2016 water years. The 2016 water year is following conifer removal in MM.

### 4.3 Statistical Analysis

Standard least squared regression was used to determine changes in weekly average groundwater depth and volumetric soil moisture content. Only measured groundwater values were included in this analysis. All assumptions of regression were tested including linearity, serial autocorrelation, normal distribution, and homoscedasticity. All statistical tests were performed using JMP 12 (SAS Institute Inc., 2016) software.

#### 4.3.1 Groundwater Depth

The mean CM and MM depth to groundwater prior to and following restoration were significantly different ($P < 0.0001$) (Table 4.5). The intercept of MM water table depth pre restoration and post restoration were significantly different from one another indicating a 0.60 foot increase in groundwater for MM ($P < 0.0001$) (Table 4.6). The slopes of pre and post restoration depth to groundwater regression models were not significantly different (p-value: 0.4775). With an $R^2$ of 0.93, the regression equation used to predict MM depth to groundwater prior to restoration is:

$$MM\ depth\ to\ groundwater\ (ft) = 0.81 + 0.74 * \left(CM\ depth\ to\ groundwater\ (ft)\right)$$

The regression equation used to predict MM depth to groundwater following restoration is:

$$MM\ depth\ to\ groundwater\ (ft) = 0.21 + 0.74 * \left(CM\ depth\ to\ groundwater\ (ft)\right)$$

These equations are formulated from all significant parameter estimates with an α value <0.05 (Table 4.6).

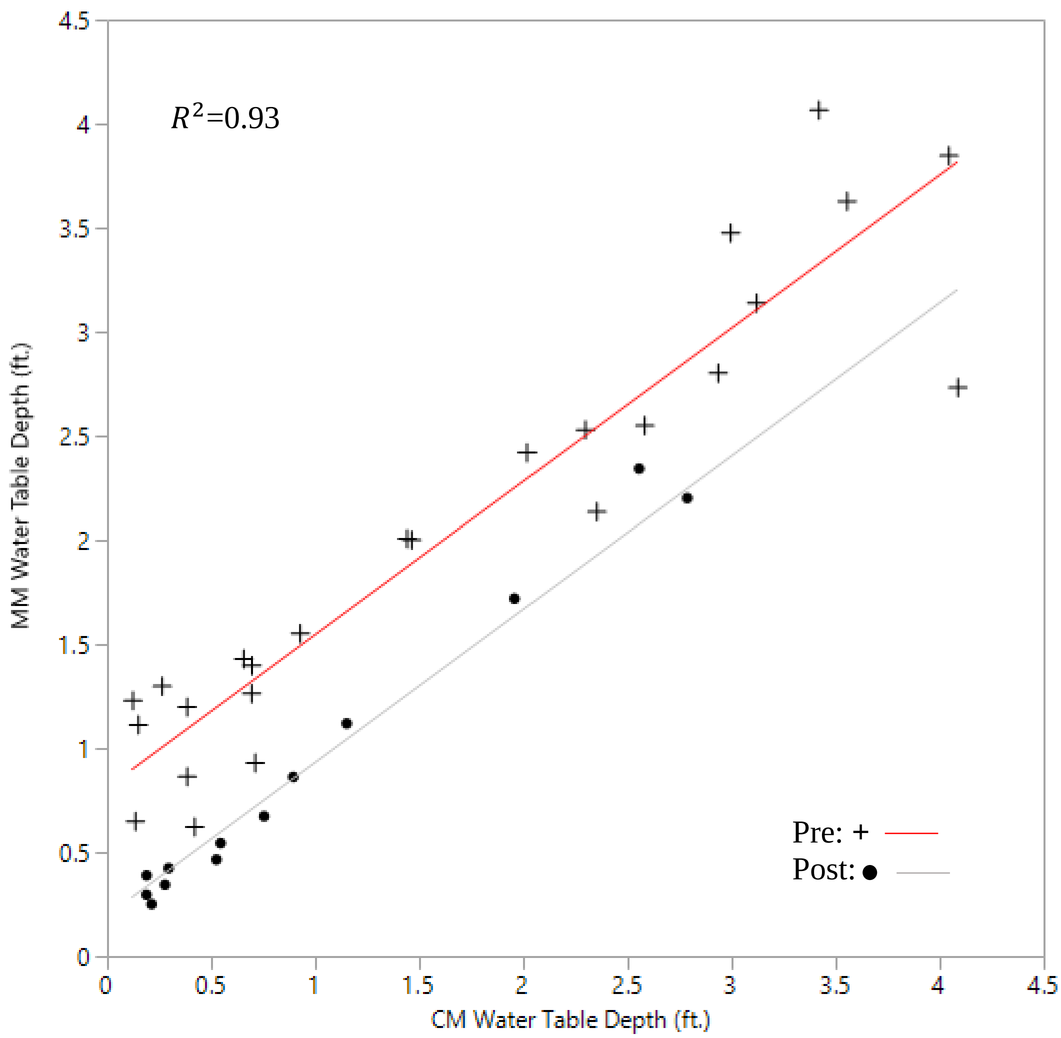



Figure 4.20: Pre restoration and post restoration depth to groundwater regressions

Table 4.5: Pre restoration and post restoration depth to groundwater ANOVA

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| model | 2 | 40.30 | 20.15 | 22.81 | |
| error | 35 | 3.17 | 0.09 | | |
| total | 37 | 43.48 | | | <.0001 |

Table 4.6: Pre restoration and post restoration depth to groundwater parameter estimates

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 0.81 | 0.09 | 2.13 | <.0406 |
| CM Depth to Groundwater (ft.) | 0.74 | 0.04 | 17.90 | <.0001 |
| Intercept Post – Pre | -0.60 | 0.11 | -5.72 | <.0001 |

### 4.3.2 Soil Moisture Content

Throughout the monitoring period, MM generally had higher soil moisture values than the CM. However, from September 2013 through February 2014, MM exhibited lower soil moisture values. While we are fairly confident that MM and the CM receive similar precipitation amounts for a given period of time, it is clear that from September 2013 through February 2014 they did not. For that reason, soil weekly moisture values from September 2013 through February 2014 were not included in this statistical analysis.

The mean CM and MM soil moisture content prior to and following restoration are significantly different from one another (P value < 0.0001) (Figure 4.5). The intercept and slope of MM soil moisture content pre restoration and post restoration were significantly different from one another (P value < 0.0001) (Figure 4.6). With an $R^2$ of 0.96, the regression equation used to predict MM soil moisture content prior to restoration is:

$$MM\ soil\ moisture\ content\ (\%) = 12.39 + 0.63 * CM\ soil\ moisture\ content\ (\%)$$

The regression equation used to predict MM soil moisture content following restoration is:

$$MM\ soil\ moisture\ content\ (\%) = 3.15 + 1.09 * CM\ soil\ moisture\ content\ (\%)$$

These equations are formulated from all significant parameter estimates with an α value <0.05 (Figure 4.6).

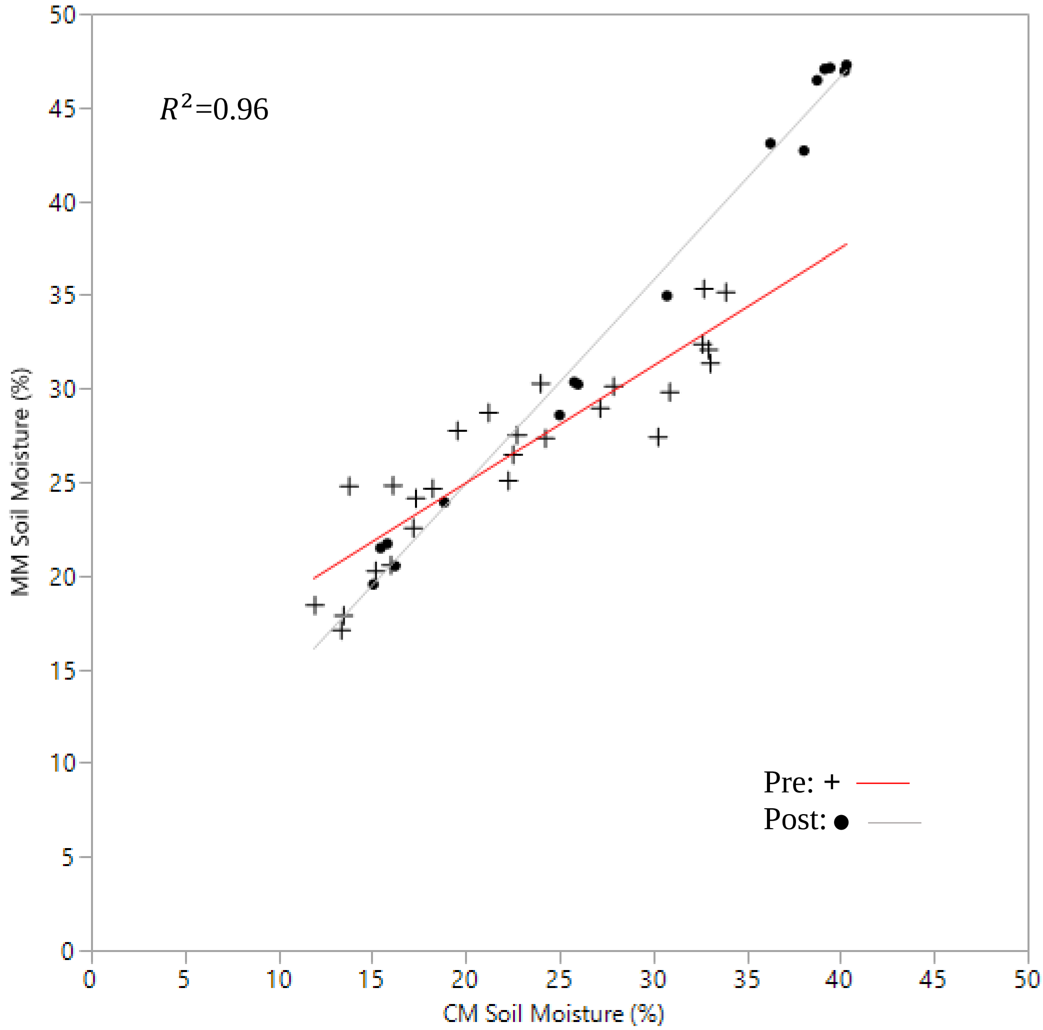



Figure 4.21: Pre restoration and post restoration soil moisture content regressions.

Table 4.7: Pre restoration and post restoration soil moisture ANOVA

| Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| model | 3 | 2731.59 | 910.53 | 292.40 | |
| error | 38 | 118.33 | 3.11 | | |
| total | 41 | 2849.93 | | | <.0001 |

Table 4.8: Pre restoration and post restoration soil moisture estimates

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 12.39 | 1.23 | 10.09 | <.0001 |
| CM Depth to Groundwater (ft.) | 0.63 | 0.05 | 12.14 | <.0001 |
| Pre/Post | 2.27 | 0.63 | 3.58 | 0.0010 |
| Slope (CM%-25.02)*-0.46(pre1/post0) | 0.46 | 0.07 | 6.55 | <.0001 |

# CHAPTER 5 DISCUSSION

## 5.1 Water Table depth

Prior to restoration, the average weekly (measured with sensors) water table depth in MM and CM was 1.90 feet and 1.35 feet, respectively. Following restoration, the average weekly (measured with sensors) water table depth in MM and CM was 0.97 feet and 1.02 feet, respectively. Utilizing the pre restoration groundwater depth regression equation and the average weekly post restoration CM water table depth, the predicted average weekly water table depth in MM was 1.55 feet. The 0.58-foot difference between the measured and predicted groundwater depth represents a 63% increase in measured values and a gain of 12.7 acre feet of water stored as groundwater as a result of restoration activates. The difference between predicted and measured groundwater depth values ranged from 0.3 feet to 1.21 feet. The greatest variability in the model appeared to occur when water table levels were increasing (December through February) (Figure 5.1).

The timing of the last significant rainfall appears to influence groundwater depth, especially during the growing season. While the 2014 WY and the 2015 WY were both drought years and the 2015 WY had greater annual precipitation amounts, the 2014 WY exhibited greater growing season groundwater depths. This is likely due to the fact that the last significant rain event during the 2014 WY was March 29, 2014 and in the 2015 WY it was February 6, 2015.

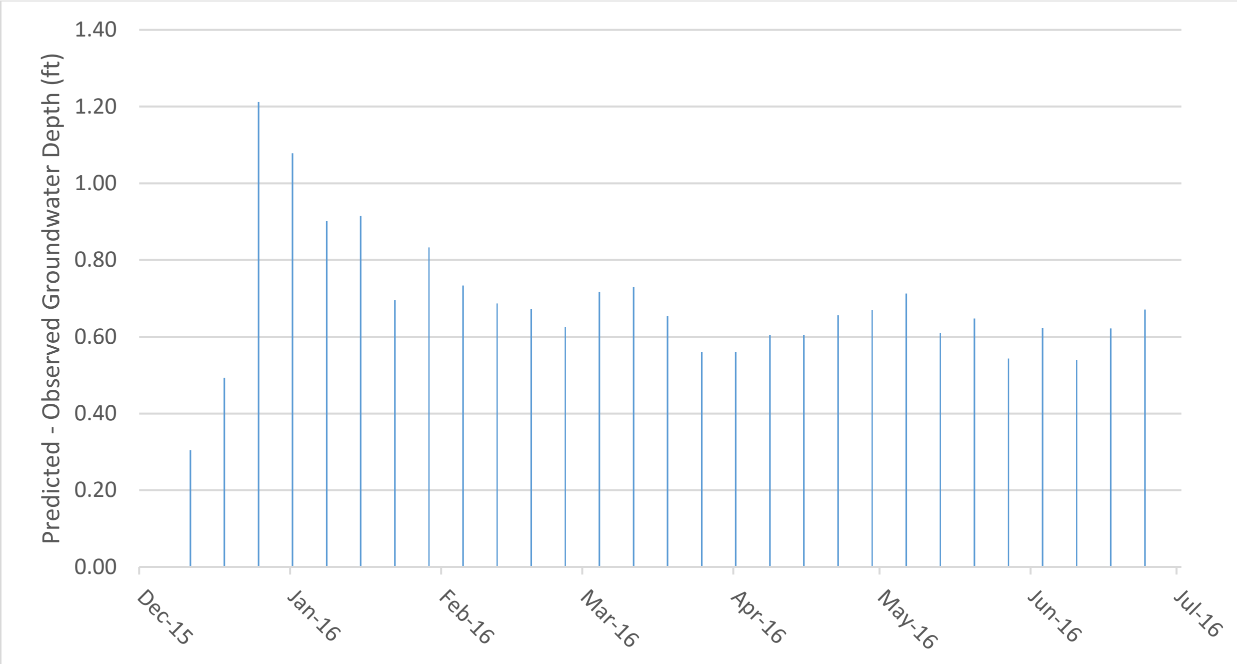


Figure 5.1: Post restoration predicted - observed weekly average groundwater depth values.

During the 2014 growing season and prior to restoration, MM and the CM experienced groundwater depths indicative of a dry meadow as classified by Weixelman et al. (2011). Groundwater elevations were on average deeper than 3.28 feet (1 meter), and although it was a drought year, there were significant periods of time that the groundwater was within the rooting zone of 2.3 feet of common dry meadow plant species (Hammersmark et al., 2010). During the 2015 growing season, MM and the CM did not experience groundwater depths indicative of meadows. The ground water spent an insufficient amount of time within the rooting zone (2.3 feet) of common dry meadow plant species. However, if the post restoration water table depth regression equation is applied to the 2015 average growing season water table depth, it is predicted that in MM the average growing season water table depth would have reduced from 4.81 feet (measured average value) to 3.39 feet (predicted average value). Therefore, it is suggested that even in a drought year where a significant amount of the precipitation fell prior to

January, MM would have exhibited growing season water table depth elevations of a dry meadow.

Following restoration, MM exhibited similar growing season water table depths to meadows that are dominated by *Poa pratensis and Bromus japonicas* (Table 2.2), which are facultative and facultative upland species and common in dry meadows (Hammersmark et al., 2010). While the average growing season water table depth following restoration of 0.98 feet may strongly suggest the hydrologic characteristics of a wet meadow, these calculations do not include water table depth values from July and August 2016. Future analyses of the entire post restoration water year, and subsequent water years, will determine what type of meadow the average groundwater depth suggests. However, utilizing the MM water table depth recession rate in May and June 2016, the predicted maximum water table depth for the end of the 2016 growing season was approximately 4.25 feet. This depth is indicative of a meadow with a high proportion of obligate, facultative wetland, and facultative plant species (Table 2.2).

When assessing the number of days the water table depth was within 2.3 feet and 1.0 feet of the surface, MM exhibited growing season water table depths indicative of a meadow with a high proportion of obligate, facultative wetland, and facultative plant species. In a study (Hammersmark et al., 2010) that assessed meadow vegetation plots with varying levels of obligate, facultative wetland, facultative, facultative upland, and upland plant species with water table depths, MM exhibited growing season water table depths similar to plots with a high proportion of *Downingia bacigalupii*, *Psilocarphus brevissimus*, *Carex nebrascensis*, and *Juncus balticus*; all of which are obligate and facultative wetland species. In the study conducted by Hammersmark et al. (2010) the water table was within 2.3 feet from the surface for *Downingia bacigalupii, Psilocarphus brevissimus, Carex nebrascensis*, and *Juncus balticus* dominated community types for approximately 65 days, and the water table was within 1.0 foot from the surface for 42-47 days. (Table 2.2). In this study, the post restoration water table of MM was within 2.3 feet and 1.0 foot from the surface in MM for 85 days and 50 days, respectively ( Table 4.3).

Within the first 3 feet, MM tended to have lower water table depth elevations than CM. However, MM exhibited greater water stored as groundwater. This was likely due to differences in soil porosity. Soil porosity heavily influences the total amount of water stored in saturated soil. Saturated soils with higher porosity (MM: 47%) are able to hold more water than soils with lower porosity (CM: 40%). The effect of soil porosity was apparent on MM and CM. Throughout the monitoring period MM exhibited lower groundwater elevations but had significantly more water stored as groundwater. The effect of soil porosity on water stored as groundwater was especially apparent when water table elevations were near the surface in both meadows. February through May 2016 MM and CM groundwater depth levels were within 0.25 feet from the surface. However total water stored in the aquifer was greater in MM by nearly 3 feet during that same period.

Lower soil porosity in CM may have also influenced peak groundwater elevation levels. CM consistently exhibited greater peak groundwater elevations. As given amount of water fills empty pore space within a soil column, the soil type with greater porosity exhibits a lower saturated zone elevation. Also, MM appears to drain less quickly than the CM. Within the first 3 feet, water table elevations in CM decreased more rapidly than MM, even though MM has greater soil porosity. During the spring of 2014 and 2015 water table elevations depleted to 3 feet at approximately the same time for MM and CM, but CM had greater peak elevations. Following restoration and during the spring of 2016, the water table in MM and CM were near the surface, however the CM water table was able to deplete to 3 feet before MM.

### 5.2 Soil Moisture

Initially, the soil moisture response to meadow restoration was assessed independently between dry season (October 1st-March 31st) and wet seasons (April 1st-September 30th). However, it was determined that there was no statistical significant difference in the relationship between MM and CM soil moisture content among wet and dry seasons. This can be attributed to presence of high and low soil moisture values and fewer data points in the dry season and wet season time periods. However, Figure 4.21 indicates that MM soil moisture values decreased during periods with relatively low soil moisture. This was likely caused by an increase in direct sunlight and higher soil temperatures following restoration. Figure 4.21 also indicates that during periods with elevated soil moisture content, soil moisture increased in MM. The increase was likely attributed to a decrease in tree interception. The switch from a decrease in soil moisture to an increase in soil moisture occurred in November (Figure 5.2). On average, soil moisture decreased on by 1.4% during the months of August through October and increased by 6.1% during the months of November 2015 through June 2016. Overall, there was an increase of volumetric soil moisture content of approximately 4.0%. Assuming that the 4.0% 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 3.29 feet following restoration, this increase represents an increase of 5.92 acre-feet of water stored in the soil as a result of removing the conifers.

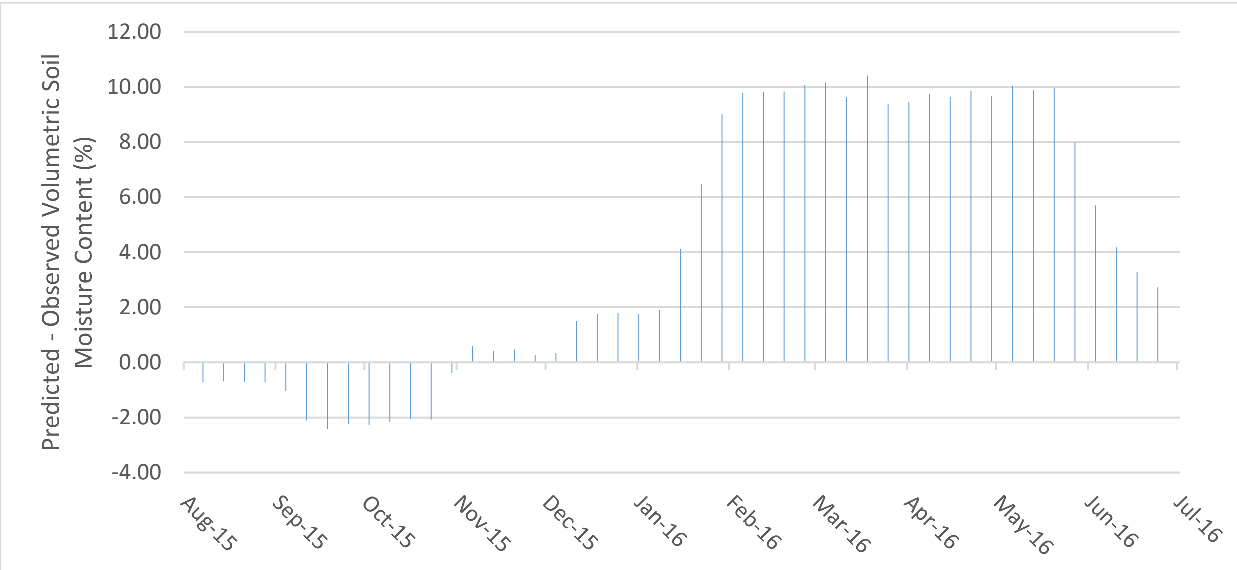



Figure 5.2: Post restoration predicted - observed weekly average percent soil moisture values.

### 5.3 Water Budget

Again, in this water budget analysis, snowfall and surface water flow into and out of MM and the CM were not included. The water budget results do indicate that this caused errors in this analysis. During the 2014 water year, where there was no measurable surface water flow coming from MM and precipitation was far below average, errors in the water budget analysis were at their lowest.

While MM had an increase in soil and groundwater storage, and exhibited water table depths indicative of a meadow, especially after restoration, the water budget suggests that MM is susceptible to climactic variability. The timing and extent of precipitation had a great effect on

MM water storage. Although the 2014 water year was an extreme drought year, MM and the CM both showed a modest increase in water storage. It appears that because precipitation occurred through the end of March, water table depths and soil moisture were high enough to result in a net increase in water storage. Also, the water budget indicates that MM water storage and depletion are more variable than in CM. MM shows a greater response following precipitation events and greater magnitudes of depletion during the dry season (Figure 4.17, Figure 4.18). This is likely a result of differences in soil porosity in the two meadows.

However, during the 2015 water year, MM lost 1.91 feet of groundwater storage, while the CM only lost 0.07 feet. Although the 2015 water year was slightly below normal in terms of total precipitation, the majority of precipitation that did fall occurred before January 2015. During the 2016 water year, and after restoration, MM exhibited a 4.75 foot increase in water storage while the CM had a 1.59 foot increase in water storage. Because of the statistically significant increase in groundwater elevation following restoration, it is reasonable to assume that some of this increased storage is a result of restoration, in addition to the increase in precipitation.

Although this budget analysis did not assess flow into and out of MM and the CM, the water budget suggests that during drought years the majority of the meadow inputs in from precipitation and not upland sources such as surface and groundwater flow. However, during the first half of 2016 water year, the change in groundwater storage was 3.19 feet greater than the water available. This suggests that during a normal to wet year, groundwater storage in MM relies heavily on upland sources.

# CHAPTER 6 CONCLUSION AND SUMMARY

Removing conifers from an encroached meadow is not a new practice. The National Park Service has been conducting conifer removal projects within meadows in Yosemite National Park for over a century (National Park Service, 2016). While these projects were taking place, it was unknown if the hydrologic characteristics of meadows were encouraged. The methods and analysis employed in this study provided enough insight and understanding to indicate that the removal of conifers from an encroached meadow can encourage the hydrologic characteristics indicative of a meadow and meadow plant communities.

The statistical analysis of soil moisture and water table depth proved to be an important component to this study. It detected changes the water balance alone could not measure. The statistical analysis indicated that following conifer removal, soil moisture decreased by 1.4% during the months of August 2015 through October 2015 and increased by 6.1% during the months of November 2015 through June 2016. Overall, there was an increase of volumetric soil moisture content of approximately 4.0%. The initial decrease in soil moisture was an unexpected result in this study. A consistent increase throughout the post restoration monitoring period was expected. The initial decrease is perhaps a result in greater soil temperatures and evaporation of antecedent soil moisture. The 6.1% increase was likely a result of a reduction of tree interception and perhaps greater snow accumulation in the open area. As meadow vegetation establishes and soil temperatures decline, future soil moisture conditions during the months of August through October will likely revert back to pre-conifer removal levels. The elevated soil moisture conditions observed from November through June will likely decrease as meadow vegetation establishes and interception increases, but will likely remain higher than pre-conifer removal levels. The statistical analysis also indicated that following conifer removal, the depth to the water table decreased on average by 0.58 feet. Again, this was likely a result of a reduction in tree interception and perhaps greater snow accumulation in the open area. As meadow plants establish within Marian Meadow, the depth to water table will likely increase, but will likely remain higher than pre conifer removal levels.

The use of shallow water table sensors appeared to be satisfactory in measuring the hydrologic properties of MM and the CM especially during the growing season, when water table depths were within the sensors range. If quantifying growing season water table depths are the main objectives of a study, the use of deeper sensors and wells may not be necessary. Prior to restoration, it appeared that Marian Meadow periodically had the growing season hydrologic characteristic of a dry meadow dominated with facultative and facultative wetland plant species. Following restoration, Marian Meadow exhibited growing season water table depths that can support wet meadow plant species.

Even with the hydrologic characteristics indicative of a dry to wet meadow, periodic removal of encroaching conifers within Marian Meadow are recommended. Periodic removal of conifers may especially be needed during the immediate years following the initial project. Prior to the recolonization of meadow plant species, elevated soil moisture conditions may provide more susceptible conditions for conifer establish, especially for lodgepole pine. If these newly established conifers go unchecked, additional colonization and conversion back to forest is inevitable. Also, depending on the rate of future meadow plant establishment, re-seeding of meadow flora maybe required.

The water balance in this study did not include surface water flow into and out of MM and the CM and neglected precipitation in the form of snow. Although there were errors associated with this, the water balance did suggest that the majority of water contributing to meadow water storage is a result of precipitation and not upland surface water or groundwater sources, which is a characteristic of dry meadows. If the MM and the CM relied more heavily on upland water sources and if the water years were significantly above average in terms of precipitation, these errors would have been exponentially greater and interpreting the water budget would be more difficult. It is recommended that future water budget analyses for similar projects include snow measurements and surface water flow measurements. These measurements are likely to be more important than measuring soil moisture storage because in this study, 95% of the equivalent depth of water was held in groundwater and only 5% as soil water. Nonetheless, the water balance, growing season water table depth analysis, and statistical analysis of this study provided enough insight to conclude that the removal of conifers from an encroached meadow encourages the hydrologic characteristic of a meadow.

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