# THE WATER TABLE, SOIL MOISTURE AND EVAPOTRANSPIRATION CONDITIONS FOLLOWING THE REMOVAL OF CONIFERS FROM TWO ENCROACHED MEADOWS

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Tyler J. Davis

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| AUTHOR: | Tyler J. Davis |
| DATE SUBMITTED: | December 2019 |
| COMMITTEE CHAIR: | Christopher G. Surfleet, Ph.D.<br>Professor of Natural Resources<br>Management and Environmental Sciences |
| COMMITTEE MEMBER: | John Jasbinsek, Ph.D.<br>Professor of Geology and Geophysics |
| COMMITTEE MEMBER: | Bwalya Malama, Ph.D.<br>Associate Professor of Natural Resources<br>Management and Environmental Sciences |

ABSTRACT

The Water Table, Soil Moisture, and Evapotranspiration Conditions
Following the Removal of Conifers from
Two Encroached Meadows

Tyler J. Davis

Montane meadows provide essential habitat for a variety of unique species and important ecosystem services in the western United States. Although important, meadows have experienced increased rates of conifer encroachment due to climate change, fire suppression and grazing. To combat meadow degradation from conifer encroachment, land managers have employed various restoration strategies one of which is conifer removal. Multiple studies have investigated the relationship between meadow hydrology and vegetation; however, few have assessed the effect of conifer removal on meadow groundwater. The goal of this study is to determine if the removal of conifers from an encroached meadow has an effect on depth to the groundwater table (WTD) and soil moisture content (SMC), and to investigate the accuracy and potential usefulness of evapotranspiration (ET) calculation methodologies for montane meadows. This goal will be accomplished by the subsequent objectives: 1) perform an analysis of WTD and SMC in an encroached meadow preceding and following conifer removal and upland thinning; 2) calculate and compare daily ET estimates in a previously restored meadow using diurnal groundwater table fluctuation, diurnal groundwater fluctuation modelling, and SMC.

Miranda Cabin Meadow (MC) is located within the Upper American River Watershed, southeast of French Meadows Reservoir, at an elevation of 6,200 feet. MC received conifer removal, upland thinning and road decommissioning in the fall of 2018 as part of the American River Conservancy's American River Headwaters Restoration Project. This study found the average WTD in MC during the growing season decreased from 4.91 feet prior to restoration, to 3.39 feet after restoration. In addition, the number of days the WTD was within 0.98 feet and 3 feet increased from 12 days and 34 days, to 31 and 49 days. Analysis of SMC in MC was limited due to gaps in data, however this study found that after restoration the average weekly SMC decreased at a slower rate than prior to restoration, possibly indicating decreased hydrologic output from ET. Based upon WTD during the growing season and the limited SMC data it appears that removal of conifers and upland thinning at MM promotes SMC and WTD conditions conducive to meadow vegetation communities.

Marian Meadow (MM), located in Plumas County, CA at an elevation of 4,900 feet, received conifer removal as part of a timber harvest plan carried out by Collins Pine Company in July 2015. The soil moisture sensors used in this study were installed in MM in September 2013 for previous graduate thesis research. Groundwater table data was collected using 10-foot wells installed in July of 2018. Daily ET was calculated during August 2018 using three methodologies, and during September 2018 using two methodologies. Daily ET estimates calculated using diurnal groundwater table fluctuation and the White method averaged 11.8 mm per day in August and 9.1 mm in September.

Using diurnal groundwater table fluctuation modelling this study calculated an average daily ET of 4.2 mm in August and 3 mm in September. Daily ET estimates based on SMC were calculated for August 2018 using two methods which produced estimates of 0.9 mm and 1.2 mm per day. All three methods for calculating ET produced some daily estimates that compare well to previous research of Et in Sierra Nevada meadows, however the White method generally overestimated daily Et while SMC methods underestimated ET. Groundwater table fluctuation modelling produced the best estimates of daily ET for both August and September. ET results in this study support previous research on the applicability of the White method; and they also suggest that the applicability of groundwater fluctuation modelling to estimate meadow daily ET in Sierra Nevada montane meadows be investigated further.

## ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Chris Surfleet for providing me this opportunity to continue my natural resources studies; and my committee members Dr. John Jasbinsek and Dr. Bwalya Malama for providing their scientific and professional contributions to this research. In addition, I would like to thank the graduate students, that include Noel Fie, Cody Morse, John Hardy and Ben Cook, whom I had the opportunity to work with. I would also like to the thank Simon Marks for providing assistance with field work, as well as my family and friends for providing support throughout my extended studies.

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# 1. Introduction

Montane meadows in the western United States provide unique habitat for diverse biological communities and provide important ecosystem services for humans (Allen-Diaz, 1991; Viers et al., 2013). Due to impacts such as animal grazing, fire management, and climate change, meadow habitats have experienced degradation through conifer encroachment (Miller & Halpern, 1998; Ratliff, 1985). In response to degradation, land managers have attempted to restore meadows through the removal of conifers, or through vegetation and hydrologic enhancement (Halpern & Swanson, 2009; Hammersmark, Rains, Wickland, & Mount, 2009). Although studies have investigated the relationship between hydrology and vegetation in Sierra Nevada montane meadows, few have investigated specific hydrologic characteristics following removal of conifers (Allen-Diaz, 1991; Dwire et al., 2006; Hammersmark et al., 2009). It is important to determine if restoration actions maintain and restore proper hydrologic conditions to further sustain these areas ecosystem functions (Roche et al., 2014).

The goal of this study is to determine if the removal of conifers from encroached meadows has an effect on depth to the groundwater table (WTD) and soil moisture content (SMC) and to investigate the accuracy and potential usefulness of evapotranspiration (ET) calculation methodologies for montane meadows. This research goal will be accomplished by the subsequent objectives: 1) perform an analysis of the restored Miranda Cabin Meadow (MC) WTD and SMC preceding and following conifer removal and upland thinning; 2) calculate and compare daily ET estimates using diurnal groundwater table fluctuations, diurnal groundwater fluctuation modelling, and SMC at Marian Meadow (MM).

WTD and SMC data were collected from MC, located near French Meadows Reservoir, CA in the central Sierra Nevada. MC received conifer removal and upland thinning during the Summer of 2018 as part of a forest restoration effort in the Upper American River Watershed. WTD and SMC data were collected from August 2016 until June 2019, results from before and after the restoration were compared. ET was calculated using data from Marian Meadow, located outside of Chester, CA in the northern Sierra Nevada. Marian Meadow received a 45-acre restoration in 2015 as part of a timber harvest plan implemented by the Collins Pine Company. Data for ET calculations was collected from July 2018 till December 2018 and compared against ET results from studies of other Sierra Nevada meadows.

# 2. Literature Review

## 2.1. Meadow Encroachment by Conifers

Montane meadows occupy a small fraction of land in the western United States, yet these habitats are a critical element of western forest ecosystems. Meadow habitats provide critical habitat for flora and fauna; as well as support a variety of ecosystem services such as water storage, water filtration, flood attenuation and carbon sequestration (Miller & Halpern, 1998; Norton et al., 2011; Roche et al., 2012; Viers et al., 2013). Although these habitats provide a large benefit to the greater ecosystem, they have experienced declines in both abundance and quality over the past century due in large part to conifer encroachment (Takaoka & Swanson, 2008).

The ecotones separating meadows and forests are sensitive to variation in environmental and anthropogenic influences (Norman & Taylor, 2005). The meadow-forest ecotone's sensitivity to environmental conditions has made them susceptible to encroachment by conifers, which studies indicate accelerated during the late 19$^{th}$ century and peaked at the beginning of the 20$^{th}$ century (Lubetkin et al., 2017; Norman & Taylor, 2005). Changes in land management policy that increased the popularity of fire suppression and grazing regulations are implicated as the primary drivers of conifer encroachment; however research also indicates that climate plays a large influence on the success of establishment (Norman & Taylor, 2005; Takaoka & Swanson, 2008).

## 2.2. Causes of Conifer Encroachment

### 2.2.1. Fire Regime

Historically the fire regime in the western United States was characterized by more frequent and variable return intervals, in conjunction with lower fire intensities (Norman & Taylor, 2005; Skinner & Chang, 1996). Fires, often started by Native Americans or lightning, were effective at maintaining complex forest-meadow ecotones and limiting invasion of conifers (Norman & Taylor, 2003; Taylor et al., 2016). However, due to the initiation of fire suppression policies in the late $19^{th}$ and early $20^{th}$ century, this fire regime shifted dramatically and became dominated by less frequent and more intense fire events which are less effective at preventing conifer invasion (Boisramé et al., 2017; Norman & Taylor, 2005; Skinner & Chang, 1996; Taylor et al., 2016). Research indicates that the shift in fire regime resulted in a decreased frequency (fires per 100 years) from 7.7 prior to 1850, to 0.3 after 1904 (Norman & Taylor, 2005). This reduced fire regime was a major cause of conifer encroachment rates peaking during the first two decades of the $20^{th}$ century, however there is evidence that these effects were also augmented by livestock grazing practices (Norman & Taylor, 2005; Skinner & Chang, 1996).

### 2.2.2. Livestock Grazing

Grazing has a 150-year history in the Sierra Nevada's, and prior to 1910 was mostly unregulated (McIlroy & Allen-Diaz, 2012). Due to the lack of regulations and high intensities of grazing, meadow habitats experience degradation in the form of reduced competition from grasses and herbs, limited fuel loads, and lowered water tables (Norman & Taylor, 2005). In addition to direct degradation of meadow habitat, grazing also fragmented fuel loads in and around meadows further decreasing the frequency and spatial area of fires (Norman & Taylor, 2003; Norman & Taylor, 2005; Skinner & Chang, 1996). Together these two variables likely contributed to the increased rates of conifer encroachment during the first two decades of the 20th century (Norman & Taylor, 2005). Current research indicates that moderate grazing practices may be beneficial to meadow ecotones, however all levels of grazing have been shown to have some negative impacts (McIlroy & Allen-Diaz, 2012). Although grazing and fire regime have been shown to strongly influence rates of conifer encroachment, research also indicates that climate plays a strong role in the survivability of confer seedling.

### 2.2.3 Climate

In areas where disturbances are less common, encroachment drivers are less understood but are likely related to climate variability (Lubetkin et al., 2017). Current climate trends indicate that the Sierra Nevada and Cascade Ranges will continue to warm and experience reduced hydrologic input as snow (Boisramé et al., 2017; Surfleet & Tullos, 2013). With reduced hydrologic input as snow, the growing season will be increased which could increase potential for conifer establishment (Miller & Halpern, 1998). Further research investigating the potential effects of climate change found that under both low and high emissions scenarios summer temperatures are expected to increase, snow water equivalency decrease and conifer encroachment increase (Lubetkin et al., 2017). Although multiple studies have found evidence that indicates a relationship between conifer encroachment and climate, other research has shown that these relationships do not clearly explain historical trends of encroachment (Norman & Taylor, 2005). However, even in cases where climate doesn't seem to be the driving variable behind encroachment, it is evident that climate influences both conifer encroachment and the other variables driving encroachment, most importantly meadow hydrology.

### 2.3. Montane Meadow Hydrology

The composition and health of montane meadow habitats is dependent upon and governed by groundwater (Allen-Diaz, 1991; Lowry, Loheide II et al., 2011; Ratliff, 1985). Montane meadow groundwater is characterized by a shallow water table, most often the result of a shallow confining or low permeability layer (Lord et al., 2011). Inputs into meadow groundwater aquifers include local infiltration and recharge, recharge from the greater basin, and recharge from watercourses (Lowry et al., 2011). In the Sierra Nevada and the lower Cascade Ranges a majority of the water that comprises these inputs originates as snowfall (Lowry et al., 2011; Ratliff, 1985). Due to the Mediterranean climate of these regions, a majority of snowfall and total yearly precipitation occurs during the non-growing season, between November and March. Although the majority of precipitation occurs outside of the growing season, montane meadows still exhibit high water tables throughout the growing season (Loheide et al., 2009).The duration of high water tables create soil conditions that are highly saturated, low in oxygen, and in turn regulate vegetation composition (Lowry et al., 2011).

Multiple studies have investigated the relationship between groundwater and vegetation composition, and have found that there is a strong connection (Allen-Diaz, 1991; Lowry et al., 2011; Roche et al., 2014). Of the different groundwater components, metrics describing water table depth (WTD) are most strongly associated with vegetation type. Research by Hammersmark (2009), has shown that the period of high groundwater, the rate of water-table declines, and total range of WTD have strongest relationships to vegetation type. Further research reviewing water table depths determined that the growing season water depth for wet meadow species, such as *Eleocharis acicularis and Eleocharis macrostachya*, ranged from 0.57 to 2.05 feet. Dry meadow species including *Bromus japonicas and Poa pratensis* were associated with water table depths ranging from 1.30 to 4.01 feet (Hammersmark et al., 2009).

2.3.1. Evapotranspiration

Regional water budgets calculated for the Sierra Nevada have indicated that up to 70 percent of local precipitation is lost due to vegetation ET (Bales et al., 2011). ET is defined as the total amount of water transferred from the land to the atmosphere through the processes of surface evaporation and plant transpiration. A number of site specific and meteorological variables that include; vegetation distribution, SMC, groundwater inflow rates, relative humidity, air temperature, solar radiation and wind speed, affect ET processes.

Actual evapotranspiration (AET) is a function of climate, land cover and soil moisture (Loheide et al., 2005). Due to the variability of the forcing variables across time and space AET can be difficult to accurately quantify. Most of the commonly utilized ET models for forest ecosystems, such as Priestley-Taylor and Penman-Monteith, calculate potential evapotranspiration (PET) using meteorological and/or vegetation data. However, these methods do not take into account limited water availability and must utilize coefficients to account for other local variables, such as vegetation type and distribution, to achieve an estimate of AET (Fisher et al., 2005). In situations where vegetation utilizes groundwater as a significant water source, diurnal groundwater table fluctuations are created which can be utilized to estimate AET (Loheide et al., 2005; White, 1932). ET calculation methodologies based upon this principle are advantageous because they integrate important variables including water availability and vegetation distribution (Loheide et al., 2005).

Research quantifying ET in Sierra Nevada meadows found that daily ET for dry meadow habitats ranged from 1.5 to 4 mm, while wet meadow habitats ranged from 5 to 6.5 mm of ET per day (Loheide & Gorelick, 2005). Other researchers have quantified ET in primary forest environments in the Sierra Nevada at a range of elevations. For elevations at which montane meadows typically occur, forest ET consumption was measured at rates from 2 to 6 mm per day; and as high as 600 to 800 mm per year in Upper Kings Basin of the southern Sierra Nevada (Goulden et al., 2012).

*2.3.1.1 Diurnal Groundwater Fluctuation*

Research by White (1932) resulted in the development of a method for estimating ET using diurnal groundwater table fluctuations. The White method utilizes the following equation (equation 1) and variables. A visual description of the recharge rate (R) and the change in storage (∆s) can be found in figure 2.1.

$$Et_G = S_y(\frac{\Delta s}{t} + R) \qquad (1)$$

Where $ET_G$= ET resulting from groundwater consumption by vegetation and surface evaporation averaged over 24-hour, $S_y$= specific yield, ∆s= daily change in groundwater storage (maximum water table level day of interest- maximum level the following day), t= time period (one day), R= groundwater recovery rate (slope of best fit line from 00:00-04:00 when ET is negligible)

There are four major assumptions associated with the White method: 1) Diurnal water-table fluctuations are caused by vegetation ET. 2) Groundwater consumption by vegetation is negligible during the night (White utilized an assumption that ET was negligible from 00:00- 04:00). 3) Groundwater inflow (recharge) occurs at the same rate throughout the entire day. 4) Specific yield can be determined for the site (White, 1932). Although the White method has been shown to provide reliable estimates of ET compared to other methods, it has not been widely adopted or applied to a variety of habitats (Loheide et al., 2005).

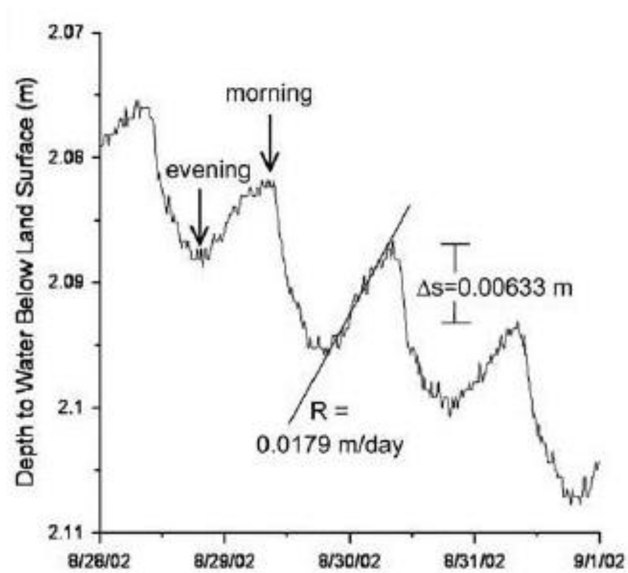


Figure 2.1. Example of diurnal fluctuations obtained from depth to groundwater table data. The groundwater recovery rate (R) and daily change in groundwater storage (Δs) are depicted on the graph. Adapted from “Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment”, Loheide et al., 2005.

A study conducted by Loheide et al., 2005 investigated the accuracy of the White method using a saturated-unsaturated flow assessment. They found that the White method often overpredicts ET due to difficulties determining a value to use for $S_y$. $S_y$ is difficult to obtain because it is influenced by a variety of sub-surface characteristics, such as soil moisture and depth to groundwater table, which are highly heterogenic over space and time (Loheide et al., 2005; Yin et al., 2013). Originally the White method utilized an approximation of Sy ($Sy = \theta_S - \theta_R$), however Loheide et al. ,2005, found that this definition led to overestimates of ET. If depth to the water table exceeds 1 meter and sediment texture is known it is suggested that values of 'readily available' specific yield be used (Loheide et al., 2005). Research investigating the White method has confirmed its usefulness and potential for estimating ET in a variety of habitats, but it also notes that more research of this methods applicability is needed because of its simplicity and cost effectiveness (Loheide & Gorelick, 2005; Yin et al., 2013).

A dissertation completed by Ran G. Lucas, 2016, utilized diurnal groundwater table fluctuation and the White method to investigate ET and groundwater patterns in montane meadows of the Sierra Nevada, CA (Lucas, 2016). This study utilized groundwater fluctuation data and ET estimates obtained by the Eddy Covariance method to determine more accurate specific yield (Sy) estimates. These improved Sy estimates were then used to calculate ET utilizing in-situ water table data and the White methodology. This work produced ET estimated ranging from 2.7 to 6.3 mm per day for the month of July 2013 (Lucas, 2016). In addition to investigation the applicability of the White method, ET was also estimated using Eddy Covariance methodology in combination with the White method and applied neural networks (ANN). This combination of diurnal water table data, meteorological data, and modelling arrived at a daily ET estimate of 4.6 mm per day (Lucas, 2016).

Although many researchers have studied diurnal groundwater table fluctuation due to ET, none had developed an analytical model to describe the diurnal fluctuations due to ET at the soil surface. Malama and Johnson (2009) developed an analytical solution describing groundwater table fluctuation by solving the transient saturated flow model where ET is treated as a boundary function at the top of the groundwater table and river stage is treated as a lateral boundary condition, or an infinite lateral boundary is used (Malama & Johnson, 2009). Similar to the White method, this model utilizes the assumption that all ET discharge is sourced from the groundwater table, ignoring the vadose zone. Inputs for the model include in-situ observed groundwater table fluctuation, aquifer parameters and daily estimates for ET. When in-situ groundwater table fluctuation data and estimates of daily ET are known the model can be used to estimate aquifer parameters. In addition, if in-situ groundwater fluctuation data is available and aquifer parameters are known, daily ET estimates can be derived (Malama & Johnson, 2009). The authors of this work provided the MathWorks® MATLAB script developed to implement their solution. Their MATLAB script was utilized in this thesis work to estimate daily ET.

#### *2.3.1.2 Diurnal Soil Moisture Fluctuation*

Another option for estimating vertical soil water flow is to analyze the soil moisture flux between day and night (Li et al., 2002). The vertical soil water flow is assumed to represent the evaporative flux from soil. Several different methods have been utilized to predict the evaporative flux from soil (Guderle & Hildebrandt, 2015; Rahgozar et al., 2012). Most commonly, root water uptake is applied as a sink term S, incorporated in the 1-D soil water flow equation (Richards equation, Eq. 2).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(z,t) \qquad (2)$$

where $\theta$= volumetric soil water content, t= time, z= vertical coordinate, h= soil matrix potential, K(h)= unsaturated soil hydraulic conductivity, $S(z,t)$= sink term (water extraction by roots, evaporation, etc). These methods use simple water balance approaches that have the benefit of requiring less data, yet they assume soil water depletion is the result of ET and that soil water flux is negligible. Research indicates that highly resolved SMC measurements and water balance methods can provide reliable predictions of the sink term (Guderle & Hildebrandt, 2015). The approach is similar to White's groundwater method where the nighttime upward flux in soil moisture is assumed to be a constant upward flux throughout the day. The decrease in soil moisture during daytime, is the downward flux. The difference between the total incoming moisture extrapolated for a day and the lowest soil moisture measurement represents the ET flux. The following methods are presented in order of accuracy based on a simulated soil moisture experiment by Guderle and Hildebrandt (2015). The single step single layer (sssl) estimate is a sum of differences of decreases and increases in soil moisture between each single time step in a single layer of soil. The single step multiple layer (ssml) estimate of evaporative flux is calculated at a single step but integrated by multiple soil layers (ssml). This was the approach used by Rahgozar et al. (2012) and Surfleet et al., (2019). The multiple step multiple layer (msml) uses the slope of a regression line through multiple night time steps to estimate the upward soil moisture flux. The downward flux is represented by the lowest soil moisture during or immediately following the daylight time periods. The final evaporative flux is integrated over multiple soil layers.

### 2.4. Conifer Removal

Land managers have utilized multiple methods to restore meadow habitats degraded by conifer encroachment. Some restoration methods, such as pond-and-plug and check dams, attempt to restore hydrologic conditions within meadows (Loheide et al., 2009). While methods such as prescribed burns and targeted vegetation removal attempt to restore meadows through the direct removal of encroached conifers (Halpern & Swanson, 2009). Restoration methods that focus on conifer removal have proven to be effective at restoring native meadow vegetation communities. However, research also indicates that there is a risk of conifer reinvasion after this type of treatment (Halpern, Haugo, Antos, Kaas, & Kilanowski, 2012). In cases where reestablishment is rapid, evidence suggests prior meadow processes, such as groundwater, that previously perpetuated meadow vegetation has been degraded (Kremer et al., 2014). Results from these studies indicate the importance of reestablishing both meadow vegetation and meadow processes in order for restoration efforts to be successful. Previous research on meadow dynamics highlights the importance or meadow processes, specifically groundwater, on maintaining meadow vegetation gradients (Hammersmark et al., 2009). Thus, it is important for meadow groundwater to be monitored during meadow restoration efforts to determine if conditions are capable of supporting native vegetation communities.

Two graduate theses completed by Noel Fie (2018) and Tom Sanford (2016), investigated the hydrologic conditions in Marian Meadow following the removal of encroaching conifers. These projects utilized soil moisture, water table depth, meteorological, and electrical resistivity tomography (ERT) data to complete a water balance and to analyze hydrologic metrics that have been related to meadow quality (Fie, 2018; Sanford, 2016). The water balance completed prior to and after conifer removal, in 2015, indicates that a majority of the hydrologic input for MM is sourced from precipitation. Statistical analysis of water table depths shows that on average WTD decreased by 0.62 feet (Fie, 2018). Statistical analysis of post-conifer removal hydrologic conditions reveals that the average weekly water table height increased 0.62 feet and that SMC was significantly higher. During the growing season, MM experienced average WTD of 4.5 feet prior to restoration, after restoration the average WTD was 2.26 feet which could support meadow vegetation (Fie, 2018; Hammersmark et al., 2009; Sanford, 2016).

# 3. Materials and Methods

The hydrologic conditions of montane meadows following conifer removal is analyzed at two locations in the Sierra Nevada range, California. Due to data constraints, two different hydrologic analyses are performed for each respective location. Two meadows located within the American River Headwaters (ARH), west of the Lake Tahoe basin, are utilized to investigate the effect of conifer removal on water WTD and soil SMC. A restored meadow site, Marian Meadow, in northwestern Plumas County is used to investigate methods of calculating evapotranspiration.

## 3.1 American River Headwaters

### <u>3.1.1. Study Area</u>

#### *3.1.1.1 Location & Climate*

Miranda Cabin Meadow (MC) is located within the Upper American River Watershed or American River Headwaters (ARH), southeast of French Meadows Reservoir. The Upper American River Watershed is 1,850 square miles, includes 50 miles of rivers and streams, and has elevations ranging from 8,000 to 200 feet (Heiman & Knecht, 2010). MC was approximately 1 acre in area prior to restoration and is located at an elevation of 6,200 feet (1890 m) above sea level (Figure 3.1). Grayhorse Creek runs adjacent to the meadow and is a tributary to the 312 square mile Middle Fork American River (Heiman & Knecht, 2010). The control meadow (CM1) is located approximately 7 miles to the northwest of MC. This meadow is approximately 2 acres in area and is at an elevation of 6,280 feet above sea level.

Within the Upper American River Watershed average annual precipitation is 35 inches and the average snowpack on April 1$^{st}$ is 36.1 inches. Most of the precipitation in this watershed occurs between October and May making snowpack on April 1st an indicator of late seasonal runoff. Temperatures range from below freezing in winter to nearly 100˚ F (38˚C) during the summer.

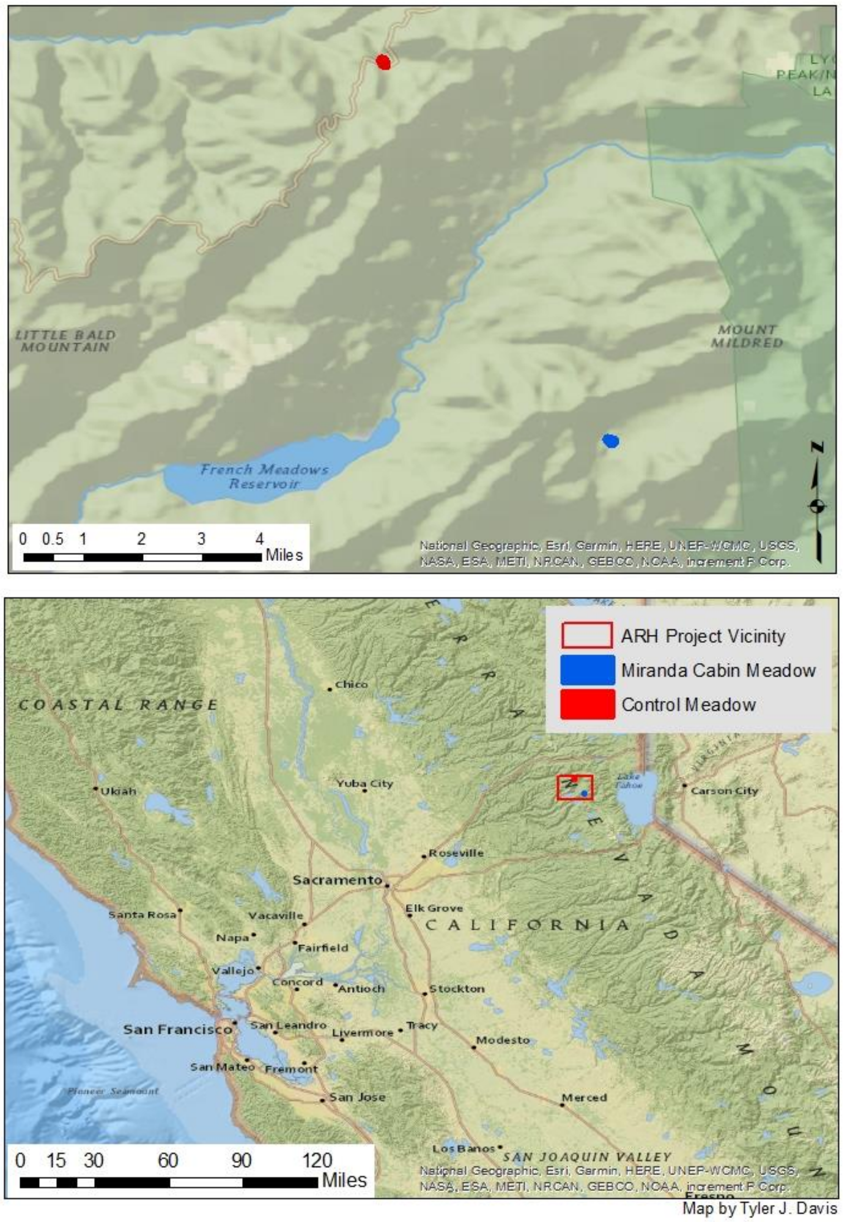


Figure 3.1. American River Headwaters Project Vicinity Map. Miranda Cabin Meadow is depicted in in blue while the Control Meadow is depicted in red.

*3.1.1.3. Vegetation*

The forest vegetation surrounding MC is composed primarily of Sierra mixed conifer stands with some patches of Red Fir *(Abies magnifica)*, Lodgepole Pine (*Pinus contorta*), and Montane Hardwood nearby. Stands of *Pinus contorta* are located generally north of the MC site, while stands of *Abies magnifica* and Montane hardwood occur to the south of the site (Heiman & Knecht, 2010). Based on observation, this site supports a variety of species that are typically found in wet meadows in the Sierra Nevada, such as sedges and rushes (Ratliff, 1985)

*3.1.1.4. Soils*

Nearly the entire MC site is composed of the Gefo-Aquolls-Celio soil mapping unit (55% Gefo soil series, 20% Aquolls soils series, 15% Celio soil series). A typical profile of this soil consists of gravelly sandy loam to a depth of around 15 inches and loamy coarse sand to a depth of up to 60 inches. All three of these series are characterized as being deep, however Gefo is typically more well drained compared to Aquolls and Celio which are typically poorly drained. The CM1 site is composed entirely of the Tallac-Cryumbrepts soil mapping unit (60% Tallac, 25% Cryumbrepts). A typical profile of this soil consists of 12-15 inches of gravelly sandy loam, underlain by extremely gravelly loam. Both series are characterized as deep and are typically moderately to poorly drained (Natural Resource Conservation Service, 2019).

During the summer of 2017 soil core samples were taken with an AMS Power Probe in MC and CM1. Soil cores were collected at four depth intervals (0-2’, 2-4’, 5-7, and 7-8’) in MC and at five depth intervals (0-2’, 2-3’, 3-4’, 4-6’ and 6-8’) in CM1. Samples from each meadow were utilized to determine soil texture, porosity and hydraulic conductivity. Soil porosity was determined using an empirical equation (Vukovic & Soro, 1992):

$$n = A * (1 + B^{d60/d10}) \qquad (3)$$

where A=0.255, B=0.83, d60= 60% finer passing diameter, and d10= 10% finer passing diameter.

Hydraulic conductivity was calculated indirectly using the Kozeny-Carmen Equation (Carman, 1939):

$$K = \left(\frac{\rho g}{\mu}\right)\left(\frac{n^3}{(1-n)^2}\right)\left(\frac{d_{10}^2}{180}\right) \qquad (4)$$

where ρ = density of groundwater (kg/m$^3$), g= acceleration due to gravity (m/s$^2$), μ= dynamic viscosity of groundwater at 10˚C $(Pa \cdot s)$, n= porosity (dimensionless). Soil samples collected in MC between 0-7 feet were a sandy-clay-loam texture, while a sample taken from 7-9 feet deep was a clay-loam texture (Table 3.1). In CM1, soil samples taken from 0-4 and 6-8 feet were sandy-clay-loam texture and a sample taken from 4-6 feet was clay-loam texture (Table 3.1). The method of soil core extraction altered the soil structure only allowing for soil texture to be accurately determined, while accurate estimates of porosity and hydraulic conductivity were more difficult to determine. Analysis of porosity revealed little variance between sample and analysis of hydraulic conductivity using the site samples produced very low values.

Table 3.1. Texture and hydraulic properties of soil cores obtained from MC and CM1 during the summer of 2017, measured by Jaclyn Supkoff (2017). Porosity and hydraulic conductivity tests were attempted using the soil cores; however, due to alteration during soil core extraction only soil texture can be determined accurately.

| Soil Core | Texture | Porosity | K (m/s) |
|---|---|---|---|
| MC (0-2 ft.) | Sandy Clay Loam | 0.4 | 1.25E-07 |
| MC (2-4 ft.) | Sandy Clay Loam | 0.4 | 2.40E-07 |
| MC (4-5 ft.) | Sandy Clay Loam | 0.4 | 7.40E-08 |
| MC (5-7 ft.) | Sandy Clay Loam | 0.4 | 7.40E-08 |
| MC (7-8 ft.) | Clay Loam | 0.4 | 1.90E-08 |
| CM1 (0-2 ft.) | Sandy Clay Loam | 0.4 | 2.68E-07 |
| CM1 (2-3 ft.) | Sandy Clay Loam | 0.4 | 6.67E-07 |
| CM1 (3-4 ft.) | Sandy Clay Loam | 0.4 | 3.27E-07 |
| CM1 (4-6 ft.) | Clay Loam | 0.4 | 1.20E-08 |
| CM1 (6-8 ft.) | Sandy Clay Loam | 0.4 | 9.00E-08 |

### 3.1.2 Study Design

#### *3.1.2.1. Restoration*

MC and CM1 are located on land that was acquired by the American River Conservancy in 2015 and included in the organization's American River Headwaters Restoration

Project. Restoration of the MC site took place during the summer of 2018, from June through August. The restoration consisted of removing conifers from the meadow, thinning adjacent upland areas, and road  decommissioning (Ehrgott, 2016). Conifer removal from the meadow and upland thinning were completed utilizing mastication techniques which left mulched material on-site. Meadow expansion occurred only on the north, west and east sides of MC, as the site is bordered by Grayhorse Creek to the south. Prior to the start of restoration, operators graded water bars on the dirt fire road that leads to MC to allow for easier access and potential decommissioning in the future.

Conifer thinning surrounding MC was quantified using simple timber cruising transects during the summer of 2019. Pre- and post-restoration basal areas for the surrounding forest were determined by measuring the diameter at breast height (DBH) of standing trees within 10 feet of three 100 foot transects, as well as collecting the lower diameters (approximately 1 foot above ground) of both standing trees and stumps of cut trees. A relationship between DBH and lower diameter measurements of standing trees were utilized to interpolate DBH values for trees that were fallen during the restoration in 2018. The basal area of all trees along each transect was summed then the average calculated (Table 3.2).

Table 3.2. Basal area determined from timber cruise transects (1000 $ft^2$) conducted during June of 2019 at Miranda Cabin Meadow. Pre-restoration basal area was determined by forming a relationship between standing trees DBH and lower diameter to fallen trees lower diameters.

| Transect | Pre-Project Basal Area ($ft^2$) | Post-Restoration Basal Area ($ft^2$) |
|---|---|---|
| 1 | 29.90 | 24.71 |
| 2 | 33.37 | 19.37 |
| 3 | 66.35 | 58.71 |
| Average | 43.20 | 34.27 |

Figure 3.2. Miranda Cabin Meadow looking north towards snow course marking pre-restoration, summer 2017.

Figure 3.3. Miranda Cabin Meadow looking north towards snow course marking post-restoration, summer 2019.

### *3.1.2.1. Instrument Deployment*

Hydrologic instruments were deployed at the MC and CM1 on August 22$^{nd}$ and 23$^{rd}$ of 2016. In each meadow 5 wells and 8 soil moisture sensors were installed at locations chosen using a spatially balanced model. A bisecting line was established for each meadow with 10 points across equal intervals. Four of these points were randomly selected and additional bisecting lines were established in a perpendicular fashion. Once again points were established on these lines at equal intervals and final instrument locations were selected from the points using a random number generator.

Soil moisture data was collected with 10 HS soil moisture sensors and H21-USB data logger, manufactured by Onset Computer Inc. were used. The soil moisture sensors were installed at a depth of 2 feet (0.6 m) with 4 soil moisture sensors per data logger. Well holes were established utilizing an AMC Push Probe machine then cased with a two-inch diameter by ten feet long PVC pipe. An attempt was made to install all wells to a depth of nearly 10 feet, however due to restrictive layers and impermeable objects, multiple wells in CM1 were installed to shallower depths (Table 3.3). Water pressure in each well was collected using Odyssey Water Level Recorders (Model no. U20L-04). Actual water pressure was determined by adjusting by atmospheric pressure collected by an additional Odyssey Water Level recorder (Model no. U20L-02) on the weather station in MC. Well pressure data, once corrected for atmospheric pressure, was then converted to depth to groundwater table using the relationship between water pressure and known well depths. Climate data for the meadows was collected using an Odyssey weather station located within MC. The meteorological instruments established for this weather station included a Judd snow depth sensor, anemometer, relative humidity, air temperature, solar radiation, and the aforementioned atmospheric pressure.

Table 3.3: American River Headwaters well meta-data (well name, serial number, and well depth).

| Meadow | Well Name | Serial Number | Depth (feet) |
|---|---|---|---|
| Miranda Cabin | MW-1 | 10960657 | 9.58 |
| Miranda Cabin | MW-2 | 10960659 | 9.38 |
| Miranda Cabin | MW-3 | 10949901 | 9.67 |
| Miranda Cabin | MW-4 | 10960658 | 9.23 |
| Miranda Cabin | MW-5 | 10960660 | 9.58 |
| Control | CW-1 | 10766793 | 4.64 |
| Control | CW-2 | 10766796 | 9.25 |
| Control | CW-3 | 10766794 | 6.33 |
| Control | CW-4 | 10766795 | 3.00 |
| Control | CW-5 | 10766797 | 2.75 |


Figure 3.4. Miranda Cabin Meadow groundwater well and weather station locations. Wells and the weather station were installed in August 2016.

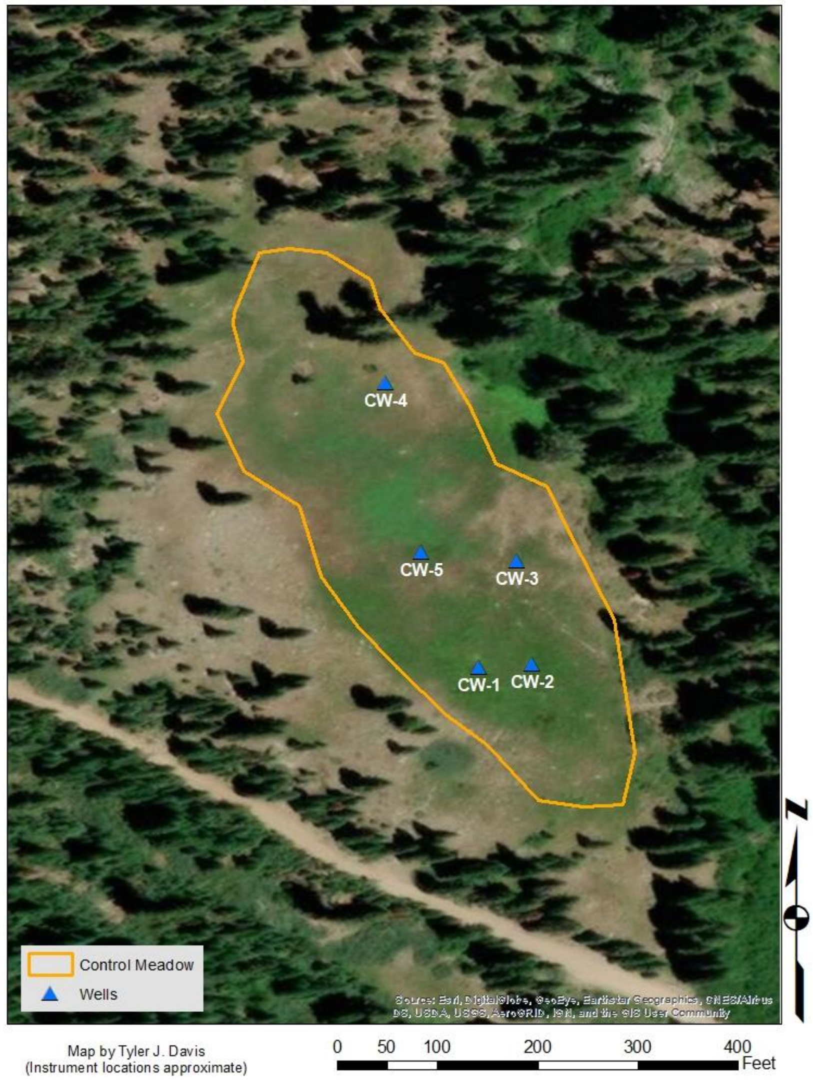


Figure 3.5. Control Meadow groundwater well and weather station locations. Instruments were installed in August 2016.

Due to multiple variables, many of the original soil moisture sensors and loggers failed and were reinstalled or replaced during both the summer of 2017 and 2018 (Figure 3.6). The original soil moisture sensors failed due to their wires, located in belowground trenches, being compromised. When these sensors were replaced in 2017 the wires were protected with conduit prior to burial, the number of sensors per data logger was reduced to 2, and all data loggers were placed within 2 waterproof cases Figure 3.8 & 3.9). This second deployment of soil moisture sensors did not experience issues pertaining to wires being compromised below ground due to the use of protective conduit, however snow and hydrologic conditions in the meadows overwhelmed the waterproof housings for the data loggers, causing multiple loggers to fail. Similarly, above average snowpack in MC cabin meadow during the winter of 2017 and 2018 caused extensive damage to the weather station, leaving significant gaps and errors in snow depth and other meteorological data.

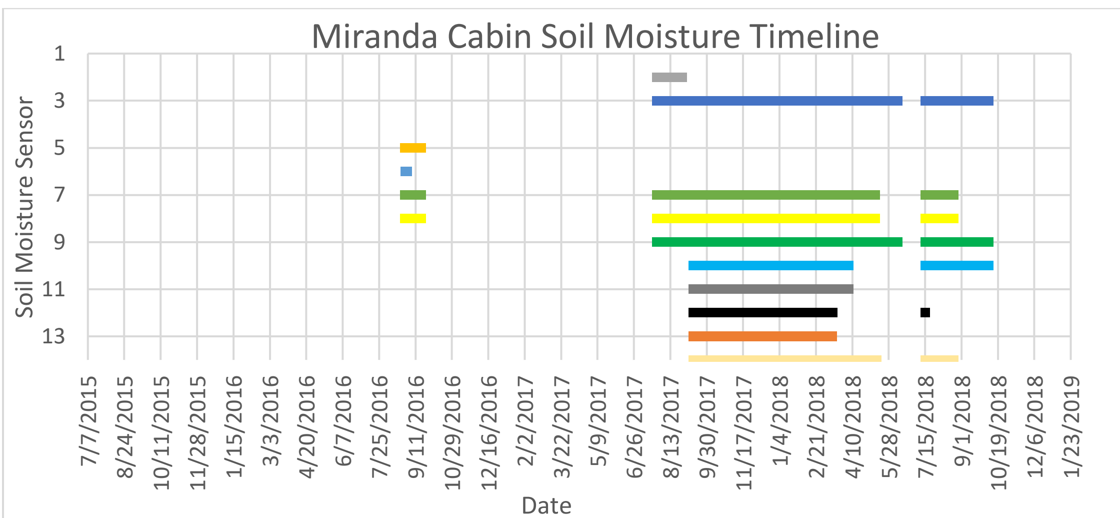


Figure 3.6. Miranda Cabin Meadow soil moisture instrument timeline. Soil moisture sensors are shown on the y-axis with each number pertaining to a unique sensor. For example, 1 refers to soil moisture sensor MS-1 and 2 refers to sensor MS-2.

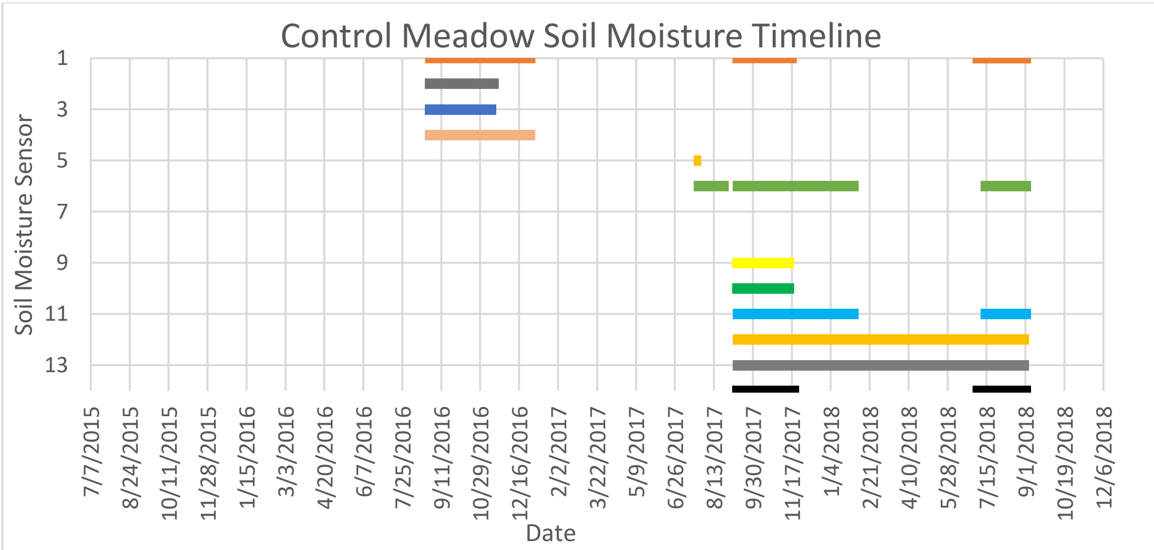


Figure 3.7. Control Meadow soil moisture instrument timeline. Soil moisture sensors are shown on the y-axis with each number pertaining to a unique sensor. For example, 1 refers to soil moisture sensor CS-1 and 2 refers to sensor CS-2.

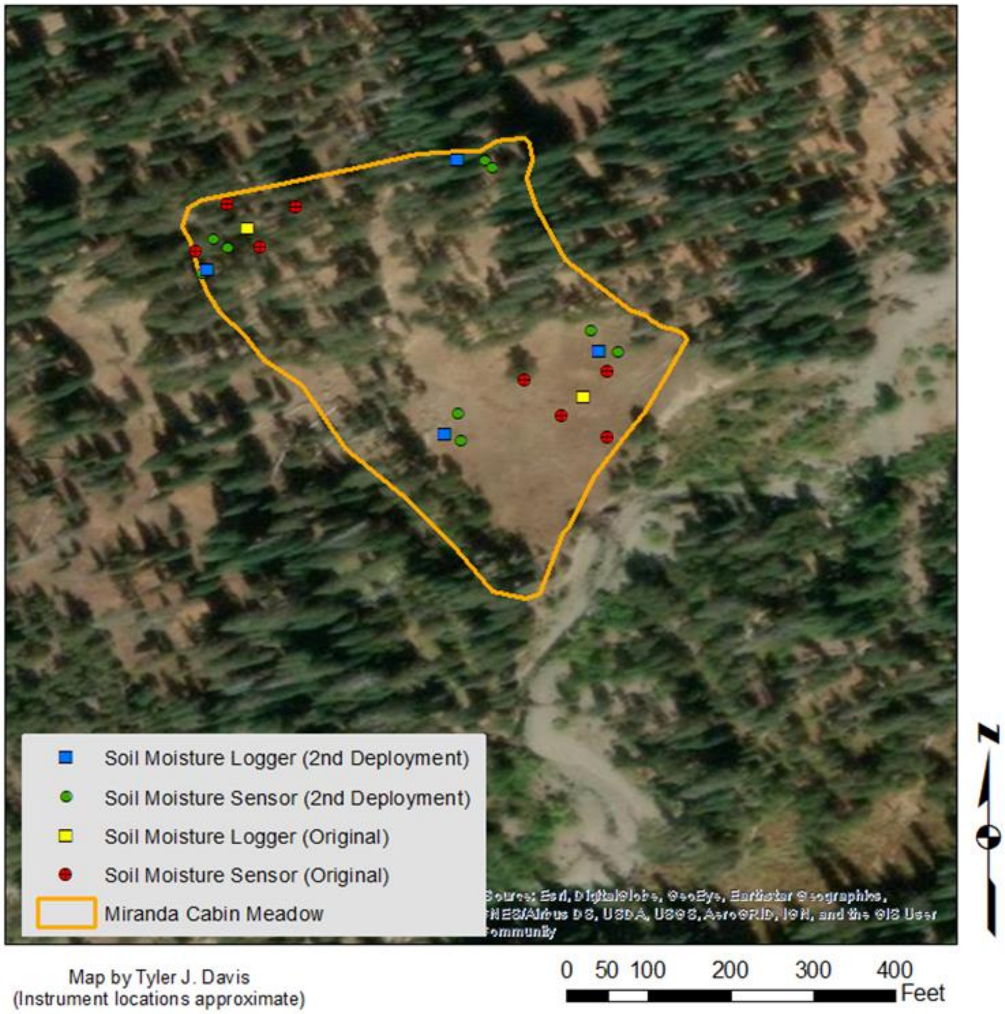


Figure 3.8. Miranda Cabin Meadow original soil moisture instrument locations (top) compared to the revised locations utilizing four data loggers (bottom).

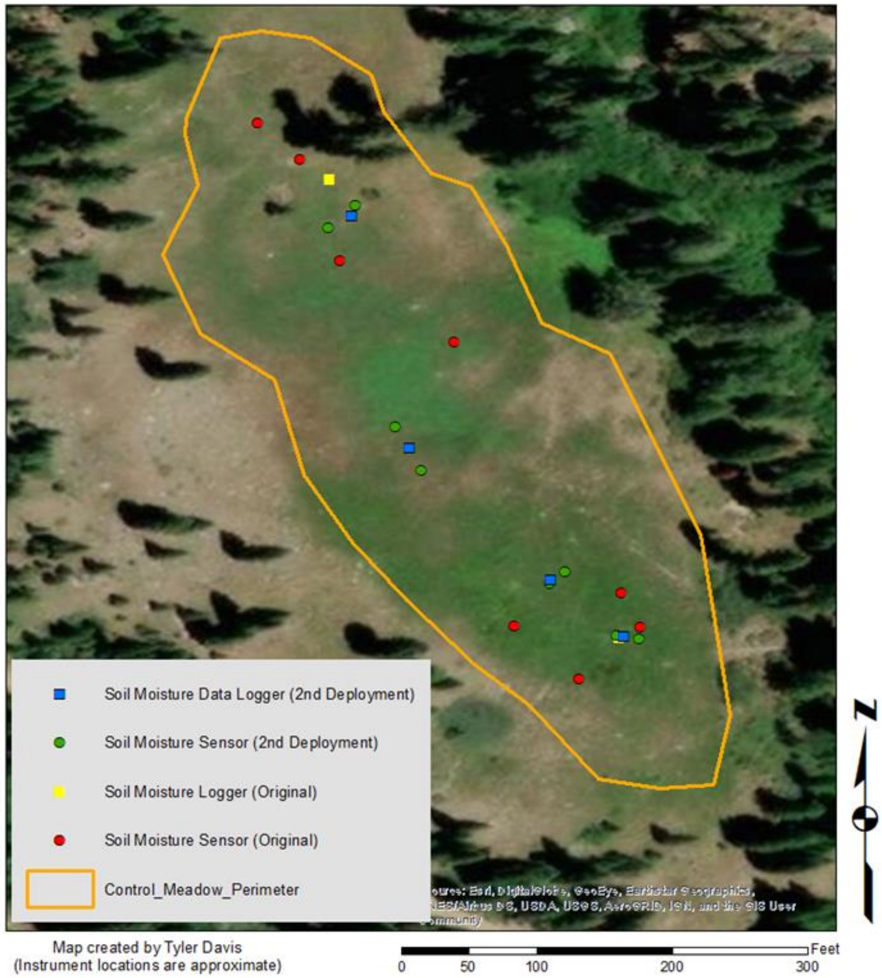


Figure 3.9. Control Meadow original soil moisture instrument locations (top) compared to the revised locations utilizing four data loggers (bottom).

Figure 3.10. *Top Left*- snowpack nearly covering the weather station in Miranda Cabin Meadow, winter 2017, *Top Right*- damage to weather station following deep snowpacks, *Bottom Left*- protective conduit being installed on sensor cables, *Bottom Right*- water within water-proof box housing data loggers.

3.1.3. Water Table Depth Analysis

Weekly average depth to the groundwater table for MC and CM1 were determined from 10 wells, 5 in each meadow, from September 20, 2017 to September 2, 2019. The weekly average was determined for each well, and for each meadow as a whole. Other metrics calculated from the groundwater depth data include range of depths, maximum depth, and minimum depth during the growing season. Additionally, the number of days the groundwater water table depths were within 0.3 and 0.7 m of the ground surface were compared, as the number of days within these two depths has been related to obligate wetland and facultative wetland vegetation occurrence (Hammersmark et al., 2009).

3.1.4 Soil Moisture Content Analysis

Due to the limited soil moisture data available, only minimal comparison could be made between MC and CM1 and the different years of this study. During the course of the monitoring period there were only two comparable periods of data, from 7/16/2017-10/21/2017 and from 7/15/2018-10/20/2018.

## 3.2 Marian Meadow, Chester, California

### 3.2.1. Study Area

#### *3.2.1.1. Location & Climate*

Marian Meadow (MM) is located outside of Chester, CA in northwestern Plumas County. This meadow location is at an elevation of approximately 4,900 feet above sea level and covers 45 acres (Figure 3.11). Marian Creek, a tributary to the Upper Fork North Fork Feather River, transects the meadow and is fed by the 7.5 square mile Marian Creek Watershed

Historical records from Chester, CA indicate that the average annual precipitation is 31.8 inches; with the majority of precipitation occurring between October and May. The average annual snowfall is 127.8 inches, with an average snow depth of 4 inches in April. Average winter temperatures in this region range from 41.8˚F-19.8˚F, while average summer temperatures range from 85.3˚F-44.8˚F. Average monthly climate data can be found on the Western Regional Climate Center (Sanford, 2016; Western Regional Climate Center, 2019).

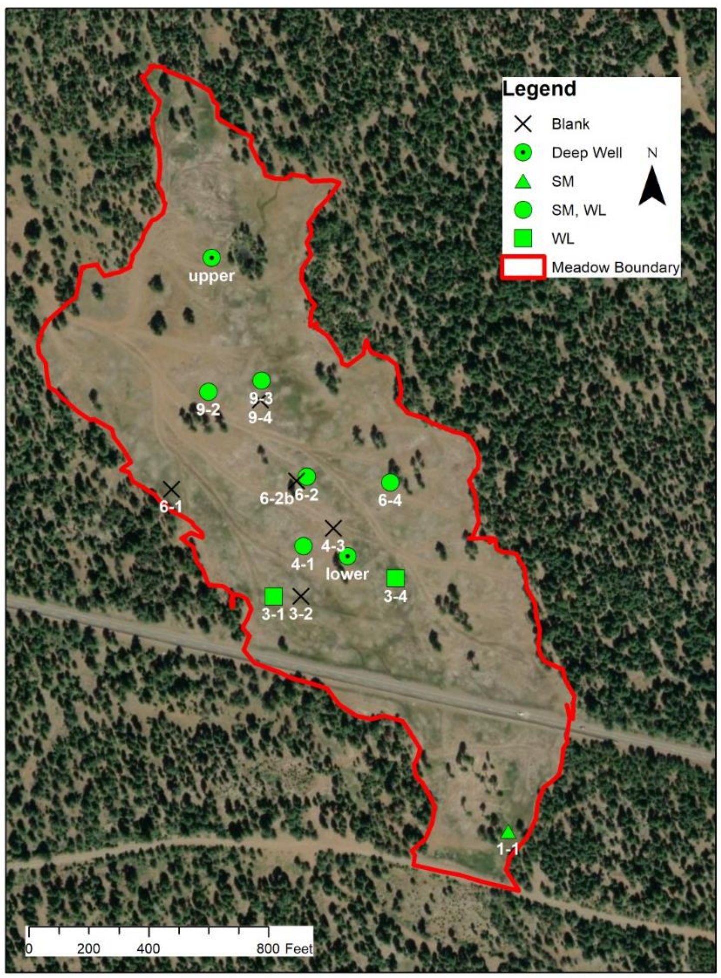


Figure 3.11. Marian Meadow located near Chester, CA. The deep well named 'upper' was utilized to obtain water table depth measurements at 1-hour intervals using piezometers.

*3.2.1.3. Vegetation*

The forest adjacent to the meadow is designated as Sierra mixed conifer and is dominated by a variety of conifer species that include ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*); predominant species are detailed in greater detail within the Marian Creek Timber Harvest Report and previous Thesis projects (Collins Pine Co, 2014; Sanford, 2016). Previous research and observations at MM indicate the presence of a variety sedges, rushes and grasses common to Sierra Nevada montane meadows (Fie, 2018; Ratliff, 1985).

*3.2.1.4. Soils*

Within MM, the primary soil mapping unit is the Holland-Skalan families association. This soil type is characterized by moderate to great depths and high rates of drainage (Natural Resource Conservation Service, 2019; Sanford, 2016).

During the summer of 2018 soil core samples were taken while installing new wells with an AMS Power Probe. Soil cores were collected at three depth intervals (0-4’, 4-8’ and 8-10’) and were then analyzed in a lab to determine their hydraulic properties. All three soil cores collected at Marian Meadow were a clay texture and had the same porosity. However this analysis, as well as one conducted by Van Oosbree, 2015, found that hydraulic conductivity decreases after 4 feet (Table 3.4) (Marks, 2018).

Table 3.4: Hydraulic properties of soil cores obtained from Marian Meadow during the summer of 2018, and measured by Marks (2018). Alternative porosity and K values from soil samples measured by Van Oosbree (2011) *.

| Soil Core | Texture | D10 (mm) | D60 (mm) | Porosity | Alt. Porosity (Van Oosbree) | K (m/s) | Alt K. (m/s) * |
|---|---|---|---|---|---|---|---|
| Marian 0-4' | Clay | 0.009 | 0.859 | 0.255 | 0.400 | 1.00E-07 | 6.10E-07 |
| Marian 4-8' | Clay | 0.006 | 0.983 | 0.255 | 0.400 | 4.00E-08 | 2.20E-07 |
| Marian 8-10' | Clay | 0.006 | 0.753 | 0.255 | 0.400 | 4.00E-08 | 2.30E-07 |

## 3.2.2 Study Design

### *3.2.2.1. Restoration*

MM is located on land owned by the Collins Pine Company and was restored as part of a 2,000-acre timber harvest plan. This timber harvest plan removed conifers, mostly lodgepole pine *(Pinus contorta)* and ponderosa pine *(Pinus ponderosa)*, from MM in July 2015 (Collins Pine Co, 2014; Sanford, 2016). Restoration efforts within the meadow removed a majority of encroached conifers, excluding *Pinus ponderosa* established prior to *Pinus contorta*; and a majority of the logging slash from the project was removed (Sanford, 2016; Van Oosbree, 2015). An upslope portion of the timber harvest report was completed in the two subsequent years, ending in 2017 (Sanford, 2016).

### *3.2.2.2. Instrument Installation*

Hydrologic equipment was first installed in MM in September of 2013 (Sanford, 2016; Van Oosbree, 2015). Originally soil moisture, groundwater table depth and meteorological sensors were installed to allow for the calculation of a water budget for the meadow sites before and after restoration. Details regarding the deployment and usage of these instruments can be found in previous graduate thesis work on MM (Fie, 2018; Sanford, 2016; Van Oosbree, 2015). The analysis presented in this report focused on calculating evapotranspiration and only utilizes soil moisture sensors that were installed during these previous projects. In July 2018 two new, approximately 10-foot wells, were installed at MM to obtain deeper groundwater data. The 2 deep wells at MM were equipped with a pressure transducer produced by Dwyer (model SBLT2) and Onset Water Level Recorder (Model no. U20L-02) respectively. An additional Onset Water Level recorder was placed on the climate station at CM2 for the atmospheric pressure correction of the Onset Water Level recorders in the wells.

### 3.2.3. Evapotranspiration Analysis

#### *3.2.3.1. Diurnal Groundwater Fluctuations*

ET, based upon diurnal groundwater fluctuations, was calculated using the White method (Equation 1)(White, 1932). Groundwater table was collected at a 1-hour time interval from August 2018 to December 2018 using the 'Upper Deep Well' in MM. The hydrograph produced from 1-hour measurements at the 'Upper Deep Well' site consistently showed upward fluctuation in the late afternoon and evening. Upward movement of the water table levels is typically seen when ET rates are negligible. The White method uses the assumption that ET is negligible from 00:00 till 04:00 and that the upward fluctuation observed during this time period is reflective of recharge occurring consistently throughout the day (White, 1932). Due to upward water table fluctuation being observed earlier in the day at the 'Upper Deep Well' site and the variance of the fluctuation throughout the period of time ET was calculated, a recharge (R) period of 15:00-19:00 was utilized.

Soil data was collected at each site via Push Probe core sampling; however, this method of soil core extraction altered the soil structure only allowing for soil texture to be accurately determined. Due to this constraint the soil texture analysis of the collected soil cores was used to select an estimate for Sy; for this work 'Readily Available' Sy values were utilized from Loheide et al., 2005 (Table 3.5).

Table 3.5: Summary of mean textural and hydraulic properties utilized for (Loheide et al., 2005) study; and specific yield values obtained from various sources. This study utilized soil texture analysis from site samples to select an estimate for Sy using 'Readily Available' Sy values determined by Loheide et al., 2005.

| | | **Specific Yield ($S_y$)** | | | |
|---|---|---|---|---|---|
| **Sediment Texture** | **Ks (m/d)** | **$\Theta_S$-$\Theta_R$** | **Depth Compensated** | **From Johnson (1967)** | **Readily Available** |
| *Sand* | 7.1 | 0.385 | 0.38 | 0.34 | 0.032 |
| *Loamy sand* | 3.5 | 0.353 | 0.34 | 0.26 | 0.26 |
| *Sandy loam* | 1.1 | 0.345 | 0.29 | 0.19 | 0.17 |
| *Loamy sand* | 0.25 | 0.352 | 0.19 | 0.095 | 0.075 |
| *Silt* | 0.06 | 0.426 | 0.11 | 0.06 | 0.026 |
| *Silt loam* | 0.11 | 0.383 | 0.12 | 0.07 | 0.037 |
| **Sandy clay loam** | **0.31** | **0.290** | **0.17** | **0.05** | **0.072** |
| ***Clay loam*** | **0.062** | **0.315** | **0.078** | **0.038** | **0.021** |
| *Silty clay loam* | 0.017 | 0.341 | 0.041 | 0.029 | 0.012 |
| *Sandy clay* | 0.029 | 0.280 | 0.068 | 0.025 | 0.015 |
| *Coarse sand* | 200 | 0.385 | 0.38 | - | 0.38 |

| | | | | | |
|---|---|---|---|---|---|
| *Medium sand* | 50 | 0.385 | 0.38 | - | 0.36 |
| *Fine sand* | 12.4 | 0.385 | 0.38 | - | 0.33 |
| *Very fine sand* | 3.1 | 0.385 | 0.38 | - | 0.31 |

3.2.3.2. *Diurnal Groundwater Fluctuation Modelling*

Daily ET values were estimated using an analytical model developed by Malama & Johnson (2009) that describes the diurnal fluctuations of the water table due to ET. This model describes water table flux through solving the transient saturated flow model by utilizing ET as a boundary function at the top of the water table. ET flux at the top of the water table is obtained through the use of the Priestley-Taylor equation:

$$\lambda ET = \emptyset \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n - G), \qquad (5)$$

where $\lambda$ is the latent heat of vaporization ($Jkg^{-1}$), ET is the evapotranspiration mass flux ($kg\ m^{-2}s^{-1}$), $\emptyset$ is the parameter to account for aerodynamic and canopy resistance, $\Delta$ is the slope of the saturated vapor pressure curve, $\gamma$ is the psychrometric constant (kPa/K), $R_n$ is the net heat radiation ($Wm^{-2}$), and G is the soil heat flux ($Wm^{-2}$).

The solution to the model uses a finite vertical extent and either a semi-finite lateral boundary defined by a watercourse location, or an infinite lateral boundary. MathWorks® MATLAB scripts developed by the authors to implement their solutions were provided for use in this work and the semi-infinite lateral boundary solution was utilized to produce daily ET estimates.

Similar to the White method, the model utilizes the assumption that all ET discharge is sourced from the groundwater table, ignoring the vadose zone. Input parameters for the model include vertical and horizontal conductivity (Kx, Kz), specific storage (Ss), specific yield (Sy), river head, aquifer thickness (b), and the normalized distance from the point of groundwater fluctuation observations to the nearest watercourse (xD). In addition to these parameters, the model also requires in-situ water table fluctuation observations and daily estimates of ET. Due to the inputs required, the model is capable of determining aquifer parameters when in-situ groundwater fluctuation data and accurate ET estimates are available; or capable of determining daily ET estimates when aquifer parameters and in-situ groundwater fluctuation data is available.

Aquifer parameters utilized in the provided solution, listed above, were selected using the soil textures found at MM and values provided in ET research by Loheide et al. (2005). The watercourse nearest the MM well site is typically dry during the time periods analyzed and thus a small head value was utilized. Aquifer depth was determined from resistivity surveys (ERT) conducted in 2013 and 2014, while the distance to the watercourse was determined using geographic information software. In-situ groundwater data was used from the first 14 days of August and September to allow for the model parameters to be tested during two distinct time periods. Daily ET estimates for the model were input from the range of daily ET values found in previous montane meadow ET research (Loheide & Gorelick, 2005; Lucas, 2016).

Table 3.6. Aquifer and soil parameters utilized for modelling of diurnal WT fluctuations caused by ET. xD is the normalized distance from the watercourse boundary which is equal to the distance to the watercourse divided by the depth of the aquifer.

| | | | |
|---|---|---|---|
| Kx (m/d) = | 0.31 | head (m) = | 0.0001 |
| Kz (m/d) = | 0.31 | b (m) = | 20.12 |
| Ss (1/m) = | 0.0008 | xD (m) = | 31.86 |
| Sy = | 0.072 | | |

### *3.2.3.3. Soil Moisture Content*

Daily soil ET, the combination of transpiration and soil evaporation, was calculated for August 2018 for sites at Marian Meadow. Sites 1-1 and 9-2 (3.11) were used with soil moisture collected by Onset time domain reflectivity (TDR) 10HS soil moisture sensors. Soil moisture was measured at 2-hour intervals at 300 mm and 900 mm depths. It was assumed the average soil moisture at these two depths was representative of the top 1 m of soil. Estimation of daily soil evaporative flux was by two methods: 1) multi-step multi-layer (msml) and 2) single-step multi-layer (ssml).

The msml method used the slope of a regression line of soil moisture recharge during the night when no evaporative flux was assumed to occur. The nighttime recharge period was set at the interval of 6 pm to 6 am the day following. The nighttime slope of the regression line represented mean increase in soil moisture per 2-hour time interval then multiplied by 12 to represent the total recharge for 24 hours. The assumption was made that the recharge rate was constant for the entire 24 hours. The daytime soil evaporative flux time period was from 6 am to 6 pm. The slope of a daytime regression line represented the mean evaporative flux per 2 hours. The daytime regression line slope was multiplied by 6 for the daytime soil moisture deficit for 12 hours. The recharge and soil moisture deficit were multiplied by the representative depth within the soil, 300 and 700 mm, for the two measurements per site. This resulted in $ET_S$ in mm. The difference between the recharge daily value and the daytime evaporative flux is the daily $ET_S$ (equation 6).

$$ET = \sum_{d=1}^{2}(\mathrm{SM_r} - \mathrm{SM_e}) \qquad (6)$$

where d = layer depth (mm), SMr is 24-hour soil moisture recharge ($m^3/m^3$), SMe is 12-hour soil moisture deficit ($m^3/m^3$). The ssml method used the change in soil moisture at each 2-hour time interval. When a decrease in soil moisture occurred in a 2-hour interval the change in volumetric soil moisture was converted to a volume based on the depth of soil. Soil moisture was measured at 2-hour intervals at 300 mm and 900 mm depths. The soil moisture decreases were summed for each day. It was assumed the soil moisture was representative of the top 1 m of soil. In a given time step either soil infiltration or soil evapotranspiration was assumed to be occurring. An inherent assumption made here is that, since small time intervals (2 hour) were used for the analysis, only evapotranspiration or infiltration took place in a given time step.

# 4. Results

This chapter is divided into two sections focused on each respective research area: 4.1) American River Headwaters (ARH) and 4.2) Marian Meadow. Section 4.1 will present an evaluation of the depth to the groundwater table (WTD) and soil moisture content (SMC) before and after meadow restoration treatments during the summer of 2018. Section 4.2 will present evapotranspiration calculation results from three respective methodologies: 1) diurnal groundwater table fluctuation, 2) diurnal groundwater table fluctuation modelling and 3) SMC.

## 4.1. American River Headwaters

Data collection for the ARH sites, Miranda Cabin Meadow (MC) and Control Meadow (CM1), began 8/22/2016. Due to instrument complications, only WTD and partial SMC data were usable for the evaluation of meadow restoration efforts. WTD results will be presented for 7/20/2017 through 9/2/2019, with growing season metrics calculated for the 2018 and 2019 growing seasons. Soil moisture sensors experienced a high rate of failures and thus soil moisture results will be presented for only those periods with usable data. It should be noted that climate data was collected at MC1 meadow; however, this set of instruments experienced significant failures each winter from 2016-2019 because of high snow levels (Figure 3.10). Due to the number of data gaps and poor quality of data series, these results are not presented in this report.

### 4.1.1. Water Table Depth

Wells installed in MC ranged from 9.23-9.67 feet deep, with an average well depth of 9.55 feet. While wells in CM1 ranged from 2.75-9.25 ft deep, with an average depth of 5.19 feet. Hydrographs of average weekly depths to the water table for MC and CM1 depict similar groundwater dynamics and depths throughout the entirety of the data collection period (Figure 4.1). The hydrograph depicting the average weekly depth to the water table for CM1 includes two gaps in data during the Fall/Winter of 2017 and 2018. These two gaps in the hydrograph are present due to water table depths receding below the reach of the wells during those periods.

Utilizing the average weekly WTD regression equations were determined to predict MC WTD pre- and post-restoration (Figure 4.2). To address serial autocorrelation a lag of three weeks was utilized to ensure independence of measurements. The regression equation produced to predict MC depth to the groundwater table pre-restoration is:

$$Y = 0.8636x + 0.7273 \quad (7)$$

The regression equation used to predict MC depth to the groundwater table post-restoration:

$$Y = 1.1023x + 0.9242 \quad (8)$$

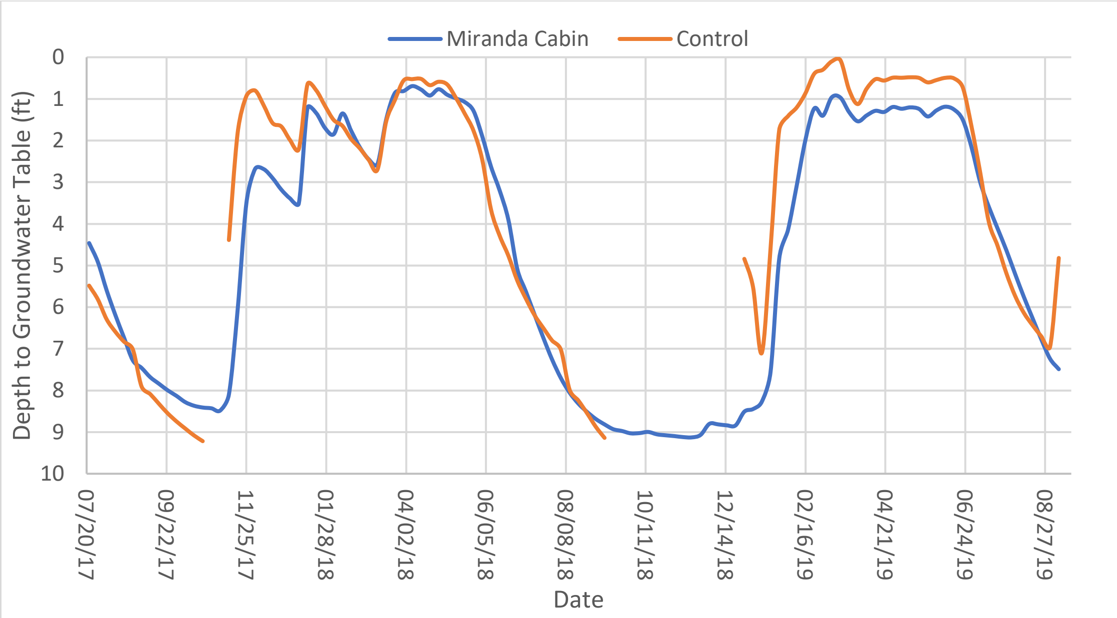


Figure 4.1. Hydrograph depicting average depth to the groundwater table in Miranda Cabin Meadow and the Control Meadow from 7/20/17 to 9/2/19. Gaps in the Control hydrograph are due to the depth to the water table exceeding the depths of the wells within the meadow.

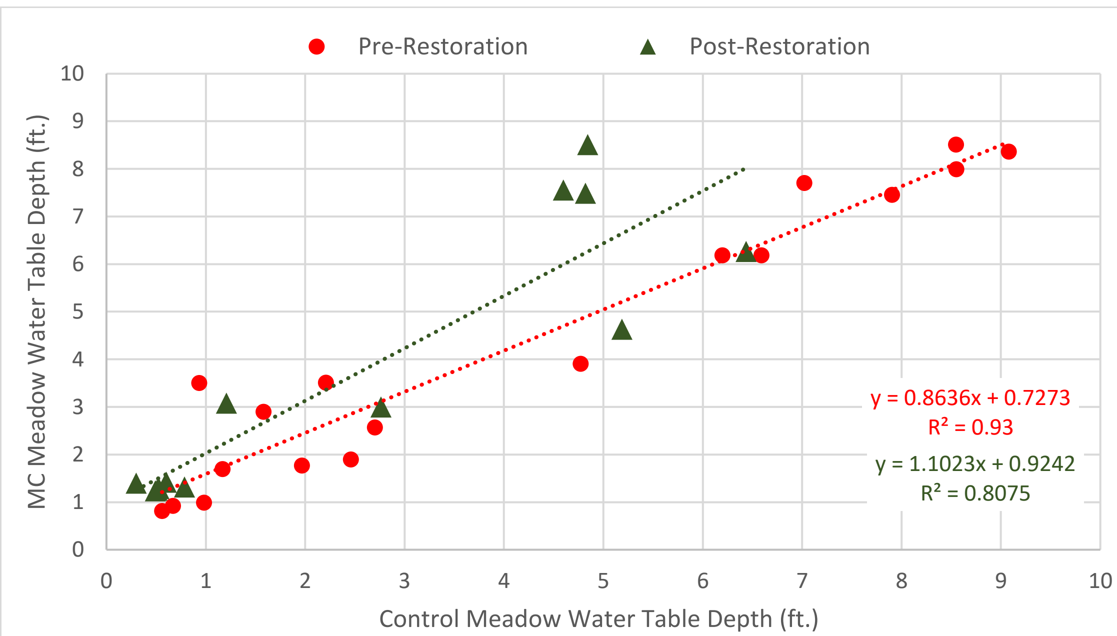


Figure 4.2. Pre- and post-restoration WTD regression equations determined using the weekly average WTD for every third week of the monitoring period. Pre- restoration regression is represented by the red line and circular markers, the post-restoration regression is depicted by the green line and triangle markers.

MC average weekly WTD during the growing season ranged from 0.27 feet to 9.22 feet in 2018, and from 0.14 feet to 8.76 feet in 2019 (Table 4.1). The average WTD during the 2018 growing season was 4.91 feet, while the average for 2019 was 3.39 feet. During the 2018 and 2019 growing seasons the WTD was within 0.98 feet of the surface for 12 and 31 days; and within 2.30 feet for 34 and 49 days.

Table 4.1. Growing season WTD metrics for Miranda Cabin Meadow for the 2018 and 2019 growing seasons.

| Miranda Cabin Meadow | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Year** | **Growing Season Water Table Depth (WTD) Metrics** | **MW 1** | **MW 2** | **MW 3** | **MW 4** | **MW 5** | **MC Average** |
| **2018** | WTD Average | 4.92 | 4.18 | 5.53 | 5.15 | 4.76 | 4.91 |
| | WTD Maximum | 7.98 | 7.66 | 9.67 | 9.18 | 9.22 | 8.74 |
| | WTD Minimum | 1.40 | 0.51 | 0.39 | 0.69 | 0.27 | 0.65 |
| | WTD Range | 6.58 | 7.15 | 9.27 | 8.49 | 8.96 | 8.09 |
| | No. days w/in 0.98 feet (0.3 m) | 0 | 15 | 23 | 1 | 23 | 12 |
| | No. days w/in 2.30 feet (0.7 m) | 26 | 34 | 38 | 33 | 38 | 34 |
| **2019** | WTD Average | 3.38 | 2.57 | 5.23 | 3.01 | 2.76 | 3.39 |
| | WTD Maximum | 6.86 | 6.36 | 8.76 | 7.82 | 7.82 | 7.53 |
| | WTD Minimum | 1.06 | 0.35 | 3.32 | 0.31 | 0.14 | 1.03 |
| | WTD Range | 5.81 | 6.02 | 5.44 | 7.51 | 7.68 | 6.49 |
| | No. days w/in 0.98 feet (0.3 m) | 0 | 52 | 0 | 47 | 56 | 31 |
| | No. days w/in 2.30 feet (0.7 m) | 56 | 62 | 0 | 64 | 64 | 49 |

CM1 average weekly WTD during the 2018 and 2019 growing seasons ranged from 0.39 feet to 8.98 feet and from 0.15 feet to 7.77 feet. The average depth to the water table during the 2018 and 2019 growing seasons was 2.91 feet and 1.81 feet. During the 2018-2019 growing seasons the water table was within 0.98 feet of the ground surface for 10 and 48 days and within 2.30 feet for 27 and 60 days in 2018 and 2019 respectively.

Table 4.2. Growing season water table depth metrics for the Control Meadow for the 2018 and 2019 growing seasons.

| Control Meadow | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Year** | **Growing Season Water Table Depth (WTD) Metrics** | **CW 1** | **CW 2** | **CW 3** | **CW 4** | **CW 5** | **CM1 Average** |
| **2018** | WTD Average | 2.53 | 5.46 | 3.41 | 1.36 | 1.76 | 2.91 |
| | WTD Maximum | 4.64 | 8.98 | 6.32 | 3.00 | 2.74 | 5.14 |
| | WTD Minimum | 0.64 | 0.39 | 0.18 | 0.39 | 0.80 | 0.48 |
| | WTD Range | 4.00 | 8.59 | 6.15 | 2.61 | 1.94 | 4.66 |
| | No. days w/in 0.98 feet (0.3 m) | 2 | 9 | 22 | 12 | 6 | 10 |
| | No. days w/in 2.30 feet (0.7 m) | 28 | 29 | 30 | 27 | 19 | 27 |
| **2019** | WTD Average | 1.36 | 3.33 | 2.55 | 0.70 | 1.10 | 1.81 |
| | WTD Maximum | 4.63 | 7.77 | 6.33 | 2.99 | 2.74 | 4.89 |
| | WTD Minimum | 0.36 | 0.31 | 0.15 | 0.38 | 0.91 | 0.42 |
| | WTD Range | 4.27 | 7.46 | 6.18 | 2.61 | 1.83 | 4.47 |
| | No. days w/in 0.98 feet (0.3 m) | 53 | 52 | 58 | 54 | 26 | 48 |
| | No. days w/in 2.30 feet (0.7 m) | 60 | 62 | 63 | 60 | 54 | 60 |

### 4.1.2. Soil Moisture Content Analysis

Soil moisture sensors and loggers in both MC and CM1 experienced high rates of failures throughout the monitoring period of this project. Based upon the limited data available, average yearly SMC was determined for 2016, 2017 and 2018, for both meadows (Table 4.3). There were only two-time periods, from 7/16/2017-10/21/2017 and from 7/15/2018-10/20/2018, that allowed for comparison between different years. Data was unavailable for 2019 as the soil moisture data loggers were removed during the winter to avoid further instrument failure.

The average yearly SMC in MC for 2016, 2017 and 2018, were 17.71%, 24.15% and 35.39% (Table 4.3). CM1 SMC averages for these years were 26.76%, 25.88% and 26.33%. Restoration of MC was concluded in the Summer of 2018 allowing for the determination of pre-restoration SMC averages. Pre-restoration SMC, the average from

2016-2018, for both MC and CM1 was 25.67% and 26.33% respectively. Post-restoration SMC is currently unavailable as 2019 soil moisture data has not yet been obtained, but will be added to this report at a future date.

Table 4.3. Average SMC percent per year in Miranda Cabin Meadow and the Control Meadow, calculated using available data.

| | 2016 | 2017 | 2018 | Pre-Restoration |
|---|---|---|---|---|
| **Miranda Cabin Meadow** | 17.71 | 24.15 | 35.39 | 25.67 |
| **Control Meadow** | 26.76 | 25.88 | 26.19 | 26.33 |

Weekly average SMC in MC and CM1 was determined for the time period of mid-July to mid-October in both 2017 and 2018 (Table 4.4). For this time period the average SMC for MC was 23% in 2017 and 21.27% in 2018 (Table 4.5). In 2017 the maximum SMC in MC was 29.33%, the minimum was 17.82%, and the range was 11.51%. During the same period in 2018 the maximum was 24.33%, the minimum was 19.63%, and the range was 7.7%. Average weekly SMC in CM1 was 21.17% in 2017 and 13.97% in 2018 (Table 4.5). In 2017, the maximum SMC for CM1 was 33.77%, the minimum was 10.07%, and the range was 23.7%. For 2018, the maximum SMC was 22.88%, the minimum was 10.68%, and the range was 12.2%.

Table 4.4. Miranda Cabin Meadow, Control Meadow and combined meadow average SMC (%) per week during periods with overlapping data 7/16/2017-10/21/2017 and 7/15/2018-10/20/2018.

| Week (2017) | MC | CM1 | *Average* | Week (2018) | MC | CM1 | *Average* |
|---|---|---|---|---|---|---|---|
| 07/16/17-07/22/17 | 29.33 | 33.77 | ***31.55*** | 07/15/18-07/21/18 | 23.14 | 22.88 | ***23.01*** |
| 07/23/17-07/29/17 | 28.99 | 32.58 | ***30.79*** | 07/22/18-07/28/18 | 24.33 | 21.72 | ***23.03*** |
| 07/30/17-08/05/17 | 28.23 | 31.91 | ***30.07*** | 07/29/18-08/04/18 | 22.81 | 20.09 | ***21.45*** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 08/06/17-08/12/17 | 27.58 | 30.99 | ***29.28*** | 08/05/18-08/11/18 | 21.47 | 17.43 | ***19.45*** |
| 08/13/17-08/19/17 | 26.96 | 30.02 | ***28.49*** | 08/12/18-08/18/18 | 21.46 | 14.21 | ***17.84*** |
| 08/20/17-08/26/17 | 26.42 | 29.04 | ***27.73*** | 08/19/18-08/25/18 | 20.46 | 12.28 | ***16.37*** |
| 08/27/17-09/02/17 | 25.88 | 26.98 | ***26.43*** | 08/26/18-09/01/18 | 19.63 | 11.49 | ***15.56*** |
| 09/03/17-09/09/17 | 18.76 | 10.07 | ***14.41*** | 09/02/18-09/08/18 | 20.61 | 10.97 | ***15.79*** |
| 09/10/17-09/16/17 | 17.82 | 10.78 | ***14.30*** | 09/09/18-09/15/18 | 20.47 | 10.73 | ***15.60*** |
| 09/17/17-09/23/17 | 18.33 | 11.55 | ***14.94*** | 09/16/18-09/22/18 | 20.50 | 10.69 | ***15.60*** |
| 09/24/17-09/30/17 | 18.74 | 11.82 | ***15.28*** | 09/23/18-09/29/18 | 20.53 | 10.68 | ***15.61*** |
| 10/01/17-10/07/17 | 18.35 | 11.98 | ***15.16*** | 09/30/18-10/06/18 | 20.65 | 10.74 | ***15.70*** |
| 10/08/17-10/14/17 | 18.04 | 12.08 | ***15.06*** | 10/07/18-10/13/18 | 20.87 | 10.85 | ***15.86*** |
| 10/15/17-10/21/17 | 18.62 | 12.74 | ***15.68*** | 10/14/18-10/20/18 | 20.89 | 10.86 | ***15.87*** |

Table 4.5. Miranda Cabin Meadow (MC) and the Control Meadow (CM1) SMC (%) metrics from periods with overlapping data (mid-July to mid-October of 2017 and 2018).

| ***Year*** | ***2017*** | | ***2018*** | |
|---|---|---|---|---|
| *Meadow* | **MC** | **CM1** | **MC** | **CM1** |
| *Average* | 23.00 | 21.17 | 21.27 | 13.97 |
| *Maximum* | 29.33 | 33.77 | 24.33 | 22.88 |
| *Minimum* | 17.82 | 10.07 | 19.63 | 10.68 |

## 4.2. Marian Meadow

Hydrologic monitoring of the Chester meadow sites began in the fall of 2013, with meadow restoration work ending in the summer of 2015. Data collected at these sites has been utilized in three previous graduate thesis projects whose goals were to determine the effectiveness of the meadow restoration through the determination of annual water budgets. During the period of this research, August 2016- June 2019, data continued to be collected to augment the long-term monitoring of these sites. Due to instrument complications and poor diurnal water table fluctuations observed at the ARH meadow sites, data from Marian Meadow was utilized to investigate three different methods for calculating daily evapotranspiration (ET). The three methods utilized for daily ET estimation were based upon 1) diurnal groundwater table fluctuation, 2) diurnal groundwater table fluctuation modelling, and 3) soil moisture content.

Data utilized for the evapotranspiration calculation analysis was obtained from well piezometers and soil moisture sensors located in Marian Meadow (MM) during the fall of 2018. Due to the requirements of each calculation methodology and data availability, calculations were performed for as many overlapping days as possible during August and September 2018 to allow for comparison of methods.

### 4.2.1. Evapotranspiration Analysis

#### *4.2.1.1. Diurnal Water Table Fluctuations*

ET estimates based upon diurnal water table fluctuation were calculated using the White method (White, 1932). Groundwater table depth data for these calculations was collected during August and September of 2018 at a one-hour recording interval. Due to the characteristics of the hydrographs produced from this data diurnal water table fluctuations a modified recharge period, of 15:00-21:00, was utilized (Figure 4.3).

The average daily ET for the months of August and September 2018 was 11.8 mm and 9.1 mm. During the month of August, the maximum daily ET calculated was 26.6 mm, the minimum was 4.2 mm, and the range was 22.4 mm. For the month of September, the maximum was 17.7 mm, the minimum was 0.9 mm, and the range was 16.7 mm.

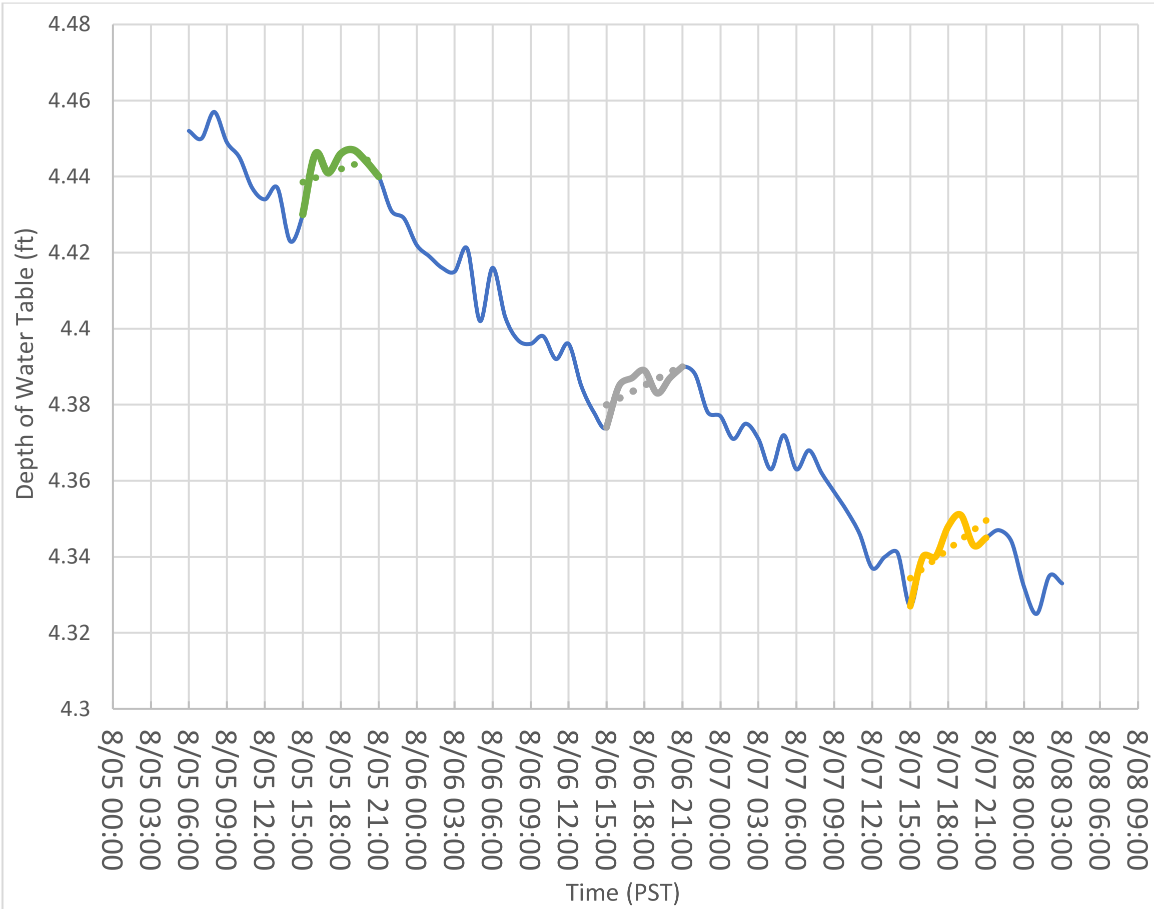


Figure 4.3. Example of the modified recharge time period (15:00-21:00) utilized for the White ET calculation method. Originally this method specifies 00:00-04:00 as the recharge (R) period, however the characteristics of the Marian Meadow water table require a modified time period to be utilized. The colored sections of hydrograph depict the modified recharge period for 8/6/2018 to 8/8/2018, while the matching colored trendlines depict the recharge rate obtained from each respective R period.

Table 4.6. White daily ET estimation metrics for August and September 2018. Metrics were calculated with the omission. Metrics for September were calculated with the omission of negative daily ET estimates produced by the White method.

| Month | Max (mm) | Min (mm) | Range (mm) | Average (mm) |
|---|---|---|---|---|
| August | 26.6 | 4.2 | 22.4 | 11.8 |
| September | 17.7 | 0.9 | 16.7 | 9.1 |

*4.2.1.3. Diurnal Groundwater Fluctuation Modelling*

Daily ET was calculated for two 14-day periods in August and September 2018 utilizing the groundwater modelling MATLAB script provided by Malama & Johhnson (2009), which utilizes a semi-infinite lateral boundary (Table 4.9). Modelling inputs include observed well hydrograph data from MM and aquifer parameters. Initially the aquifer parameters associated with soil conditions were selected using a clay-loam texture, based on the particle size distribution analysis (Table 3.4). However, these parameters did not create a good model fit. Alternatively a sandy-clay-loam texture is specified for MM in the soil survey (Natural Resource Conservation Service, 2019) The aquifer parameters for the sandy-clay-loam texture provided better model fit to measured data. Aquifer thickness was determined from ERT surveys conducted at MM and a nearby control site. Due to the intermittent nature of Marian Creek, which runs through MM, a value of 0.0001 m was used for the river head value. In addition, the distance to the watercourse was considered as the distance to the Marian Creek outlet at the downslope end of the meadow.

ET estimates for August 2018 ranged from 3 to 5 mm, with an average of 3 mm per day (Table 4.8). Figure 4.4 depicts the modelled groundwater fluctuations produced from the calculated daily ET rates (red hydrograph), in comparison to observed groundwater fluctuations in MM (blue hydrograph). Daily ET estimates for September 2018 ranged from 2 to 4 mm, with an average of 3 mm per day (Table 4.8). The hydrograph produced from these ET estimates for September 2018 is depicted in Figure 4.5 (red hydrograph), with the observed MM hydrograph (blue hydrograph) for comparison.

Table 4.7. ET estimate metrics for daily ET estimates from August and September 2018 calculated with the semi-infinite lateral extent solution provided by Malama & Johnson (2009).

| Month | Average ET (mm) | Max (mm) | Min (mm) |
|---|---|---|---|
| August | 4.2 | 5 | 3 |
| September | 3 | 4 | 2 |

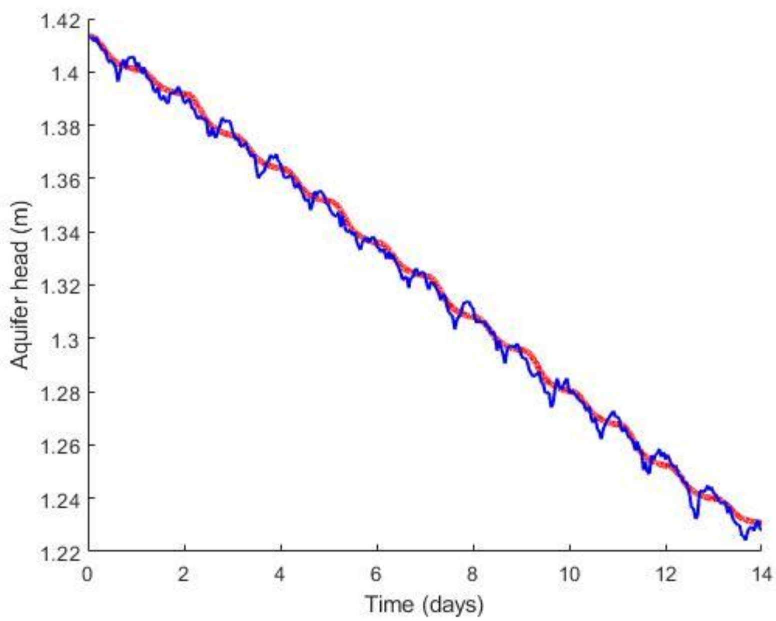


Figure 4.4. Comparison of Malama & Johnson (2009) model ET estimates (red) to observed groundwater table fluctuations at the upper Marian Meadow well (blue) from August 1-14, 2018.

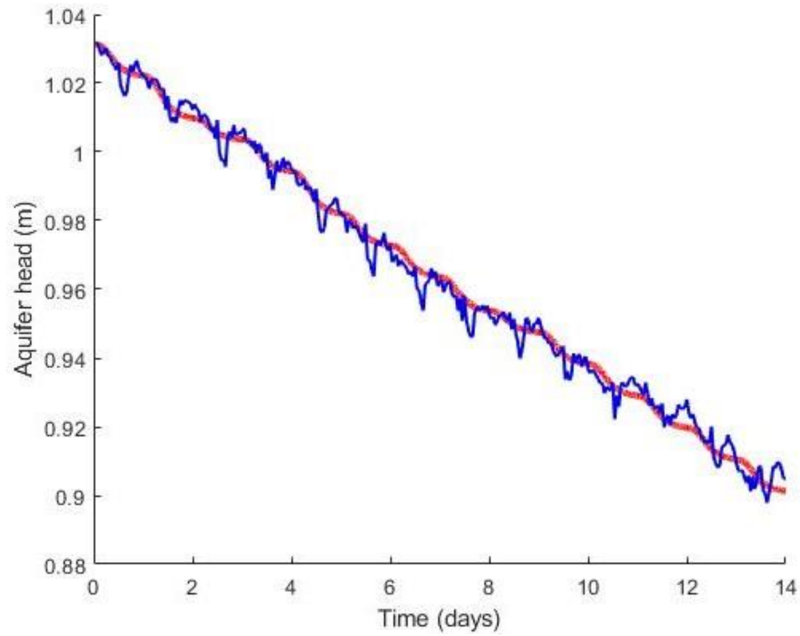


Figure 4.5. Comparison of Malama & Johnson (2009) model ET estimates (red) to observed groundwater table fluctuations at the upper Marian Meadow well (blue) from September 1-14, 2018.

#### *4.2.1.2. Soil Moisture Content*

Daily ET estimates based upon SMC were calculated for the month of August 2018 using two methods, single-step multi-layer (ssml) and multi-step multi-layer (msml) (Table 4.9). Daily ET estimates derived using ssml for August averaged 0.9 mm, while the daily average obtained using msml was 1.2 mm (Table 4.8). The maximum daily ET calculated using ssml was 1.7 mm, the minimum was 0.4 mm, and the range was 1.3 mm. In comparison, the maximum daily ET calculated using msml was 2.3 mm, the minimum was 0.1 mm, and the range was 2.2 mm.

Table 4.8. SMC ET calculation metrics for August 2018 for both multi-step multi-layer (msml) and single-step single-layer (ssml) methods.

| Method | Max (mm) | Min (mm) | Range (mm) | Average (mm) |
|---|---|---|---|---|
| SSML | 1.7 | 0.4 | 1.3 | 0.9 |
| MSML | 2.3 | 0.1 | 2.2 | 1.2 |

Table 4.9. Daily ET calculations for August 2018 using diurnal groundwater fluctuation, groundwater fluctuation modelling and soil moisture-based methodologies. Groundwater fluctuation modelling (Malama & Johnson, 2009) was utilized to obtain ET values for the first 14 days of the month.

| Date | White (mm) | Malama & Johnson (2009) Model (mm) | SSML (mm) | MSML (mm) |
|---|---|---|---|---|
| 1-Aug | 18.6 | 4 | 1.7 | 2.1 |
| 2-Aug | 9.5 | 3 | 1.5 | 0.2 |
| 3-Aug | 8.4 | 5 | 1.3 | 2.3 |
| 4-Aug | 11.5 | 4 | 1.3 | 0.2 |
| 5-Aug | 10.7 | 3 | 1.1 | 2.3 |
| 6-Aug | 4.2 | 4 | 1.1 | 1.5 |
| 7-Aug | 6.3 | 2 | 1.4 | 0.1 |
| 8-Aug | 9.4 | 3 | 1.2 | 0.3 |
| 9-Aug | 15.6 | 3 | 1.2 | 0.3 |
| 10-Aug | 10.7 | 2 | 1.1 | 2.1 |
| 11-Aug | 9.8 | 3 | 1.2 | 0.2 |
| 12-Aug | 19.8 | 2 | 1.0 | 0.2 |
| 13-Aug | *11.5* | 3 | 0.9 | 0.1 |
| 14-Aug | 14.6 | 2 | 0.8 | 2.1 |
| 15-Aug | 11.3 | - | 0.6 | 1.8 |
| 16-Aug | 9.1 | - | 0.8 | 2.1 |
| 17-Aug | 26.6 | - | 0.8 | 1.3 |
| 18-Aug | 12.3 | - | 0.6 | 1.7 |
| 19-Aug | 6.3 | - | 0.5 | 2.0 |
| 20-Aug | 13.7 | - | 0.7 | 1.8 |
| 21-Aug | *10.3* | - | 0.6 | 1.2 |
| 22-Aug | 8.0 | - | 0.6 | 1.4 |
| 23-Aug | 10.5 | - | 0.6 | 1.5 |
| 24-Aug | 13.3 | - | 0.7 | 1.3 |
| 25-Aug | 14.2 | - | 0.5 | 1.2 |
| 26-Aug | 15.0 | - | 0.5 | 1.2 |

| | | | | |
|---|---|---|---|---|
| 27-Aug | 12.3 | - | 0.5 | 0.6 |
| 28-Aug | 11.3 | - | 0.6 | 0.9 |
| 29-Aug | 9.2 | - | 0.4 | 1.3 |
| 30-Aug | 7.0 | - | 0.4 | 0.5 |
| 31-Aug | 15.7 | - | 0.7 | 1.0 |

Table 4.10. Daily ET calculations for September 2018 using diurnal groundwater table fluctuation and diurnal groundwater table modelling based methodologies (the White method and MATLAB script provided by Malama & Johnson, 2009). ET was calculated using the modelling-based approach for the first 14 days of the month. Negative ET estimates produce by the White method have been left blank.

| Date | White (mm) | Malama & Johnson (2009) Model (mm) |
|---|---|---|
| 1-Sep | 14.493 | 3 |
| 2-Sep | 12.648 | 4 |
| 3-Sep | 10.540 | 2 |
| 4-Sep | 14.231 | 3 |
| 5-Sep | 5.146 | 4 |
| 6-Sep | 14.494 | 3 |
| 7-Sep | 14.096 | 3 |
| 8-Sep | 17.652 | 3 |
| 9-Sep | 11.459 | 2 |
| 10-Sep | 9.229 | 3 |
| 11-Sep | 3.558 | 3 |
| 12-Sep | 4.880 | 3 |
| 13-Sep | 9.361 | 3 |
| 14-Sep | 10.538 | 3 |
| 15-Sep | 13.704 | - |
| 16-Sep | - | - |
| 17-Sep | 11.595 | - |
| 18-Sep | 7.380 | - |
| 19-Sep | 4.745 | - |
| 20-Sep | 3.404 | - |
| 21-Sep | - | - |
| 22-Sep | 5.678 | - |
| 23-Sep | | - |
| 24-Sep | 3.828 | - |
| 25-Sep | - | - |

| | | |
|---|---|---|
| 26-Sep | - | - |
| 27-Sep | 0.931 | - |
| 28-Sep | - | - |
| 29-Sep | 5.801 | - |
| 30-Sep | - | - |

# 5. Discussion

## 5.1. American River Headwaters

### 5.1.1. Water Table Depth Analysis

Hydrographs of the average weekly depth to the groundwater table (WTD) in MC and CM1 shared strong similarities both before and after restoration in 2018 (Figure 4.1). The similarity in the two meadow's hydrograph patterns indicates that each of their groundwater aquifers are strongly affected by climatic conditions throughout the year. Both meadows showed rapid decrease in WTD at the beginning of each water year, when rainfall and snowfall typically begin. WTD continued to decrease throughout the wet winter season and then began an increasing trend starting in late spring and continuing through the fall. The hydrograph for CM1 includes two data gaps that occurred towards the end of the water year in both 2017 and 2018. These data gaps occurred because the well depths within CM1 were shallower than those in MC due to restrictive subsurface objects or layers.

During the 2018 growing season, prior to restoration, the average weekly WTD for MC and CM1 was 4.91 feet and 2.91 feet (Table 4.1 & 4.2). According to meadow classifications by Weixelman et al. (2011), the water table conditions in MC are indicative of a dry meadow whereas conditions in CM1 are indicative of a meadow capable of supporting obligate, facultative wetland, or facultative plant species. During the 2019 growing season, the average WTD for MC and CM1 was 3.39 and 1.81 feet. Both of these averages indicate wet meadow conditions (Weixelman et al., 2011). The 2019 water year had above average snow accumulations increasing the recharge and delaying the recession of the groundwater level.

In addition to assessing average WTD, assessing the number of days that the WTD is within 0.98 feet (0.3 meter) and 2.30 feet (0.7 meters) can also provide insight into whether or not a meadow is likely to support wet meadow species (Hammersmark, Dobrowski, Rains, & Mount, 2010). In 2018 MC and CM1 experienced 12 and 10 days where the water table was within 0.98 feet of the surface, and they experienced 34 and 27 days within 2.30 feet. For the 2019 growing season, MC and CM1 groundwater tables experienced 31 and 48 days within 0. 98 feet; and they experienced 49 and 60 days within 2.30 feet of the meadow surface. Comparing 2018 to 2019, both MC and CM1 experienced more days with the water table within both 0.98 and 2.30 feet. The increase in the number of days that the water table was within 0.98 and 2.30 feet of the surface indicates conditions more strongly favoring wetland meadow vegetation (Hammersmark et al., 2010).

Regression equations were determined for WTD pre- and post-restoration. Although calculated, the regression's predictability is limited due to the amount of data available. In order to account for serial auto-correlation, a lag of three weeks was used to ensure independence of measurements. The post-restoration regression intercept and slope increase, compared to the pre-restoration regression, indicates that depth to the groundwater table has increased post-restoration. This result contradicts the findings that indicate increased water availability during the growing season post-restoration. As noted, the regression is based on limited pre- and post-restoration data, while the metrics pertaining to the growing season utilize complete data sets from 2018 and 2019. The use of the complete growing season data sets may provide better insight into water availability in MC post-restoration.

5.1.2. Soil Moisture Content Analysis

SMC data collection experienced significant instrument failures throughout the course of this monitoring effort (Figure 3.5 & 3.6). The instrumentation design utilized for this monitoring effort has been utilized at meadows located near Chester, CA for numerous years, where there have been relatively few instrument related issues. In contrast, both MC and CM1 experienced significant failure of instruments because of fauna and extreme hydrologic conditions. Due to these failures, soil moisture sensors and data loggers were installed with reinforced equipment and at new locations (Figure 3.8 & 3.9)

Yearly average SMC for the years prior to restoration, 2016, 2017 and 2018, in MC and CM1 was 25.67% and 26.33%. Although the two meadows shared similar average pre-restoration SMC, MC experienced a much greater variance in average yearly SMC increasing during 2016 to 2018 from 17.71%, to 24.15%, and then 35.39%. It is important to note again that these yearly averages are based upon very limited data for each meadow. Also, it should be noted that SMC data collected at MC during 2018 overlapped with the completion of the restoration work in the Summer and Fall of 2018. Although the restoration work would likely impact soil moisture conditions, the time of year when the restoration took place usually experiences drier soil moisture conditions.

Throughout the study of MC and CM1, only two congruent time periods had good SMC data, from 7/16/2017-10/21/2017 and from 7/15/2018-10/20/2018. During this time period in 2017 the average weekly SMC for MC averaged 23.00%, while CM1 averaged 21.17%. During 2018 MC averaged 21.27% while CM1 averaged 13.97%. The time period utilized to compare 2017 and 2018 is beneficial as it allows for comparison of conditions during similar times of the season in different years, however this time period also occurs towards the end of the growing season and water year when conditions are driest. Although soil moisture conditions during late July and August may influence the occurrence of meadow vegetation, it is more likely that soil moisture conditions earlier in the growing season would have a greater influence on the establishment of wet meadow species.

## 5.2. Marian Meadow

### 5.2.1. Evapotranspiration Analysis

#### *5.2.1.1. Diurnal Groundwater Fluctuation*

Daily ET estimates were derived using observed diurnal groundwater table fluctuation data and the White calculation method for the months of August and September 2018 (Table 4.9 & 4.10). The average daily ET for August was 11.83 mm, while the average for September was 9.10 mm (Table 4.6). Daily ET estimates for August and September had a range of 22.38 mm and 16.72 mm, however the range for September was influenced by the omission of negative ET calculations.

Daily ET estimates calculated with the White method exceed estimates found in previous research on Sierra Nevada meadows (Table 5.1), Loheide and Gorelick (2005) and Lucas (2016), and produced negative ET estimates for 7 days during September. One difficulty experienced when attempting to utilize this method was the shape of the hydrograph obtained from MM. Data collected at the ‘Upper Deep Well’ in MM had a recording interval of one hour which produced a relatively coarse hydrograph. In addition, the hydrograph obtained from the site in MM consistently displayed recharge occurring multiple hours before it typically assumed to occur. The White method uses the assumption that ET is negligible at night, thus a recharge rate is typically calculated for the time period of 0:00-04:00. However, when this original assumption regarding recharge timing was used it typically produced a negative recharge rate on most days which results in a negative estimation of daily ET. Based on the character of the hydrograph produced from MM, a recharge period of 15:00-21:00 was chosen (Figure 4.2).

Although the White ET method is easily implementable, its usefulness in producing accurate daily ET estimates relies upon the quality and character of the hydrograph being utilized. When collecting water table data to produce the hydrograph for this analysis it is important that quality instruments and proper recording intervals are utilized. It is recommended that high quality pressure transducers are utilized to determine smaller changes in water table level; and that a high recording interval be used, such as 15 or 30 minutes. If high quality pressure transducers and a high recording interval are utilized it will allow for a more descriptive hydrograph to be created that in turn could allow for a better utilization of the White method.

*5.2.1.2. Diurnal Groundwater Fluctuation Modelling*

A groundwater fluctuation model created by Malama & Johnson (2009), was used to produce daily ET estimates for two 14-day periods, August 1-14 and September 1-14, 2018. The average daily ET estimated for the month of August was 4.2 mm and the average for September was 3 mm a day, which are comparable to daily ET estimates found in other Sierra Nevada meadow studies, which ranged from 1.5-6.3 mm (Loheide & Gorelick, 2005; Lucas, 2016)(Table 5.1). The hydrographs produced from these ET estimates and aquifer parameters associated with a sandy clay loam soil texture strongly resembled the observed hydrographs from the upper well in MM during the two distinct time periods. Although the model performed well with the aquifer parameters associated with a sandy clay loam soil texture, it did not perform well with the original soil texture used for MM, clay loam. When a clay loam texture and its associated parameter values were utilized it was difficult to get the model to produce a hydrograph with a slope similar to that of the observed hydrograph. Using the parameter values associated with a sandy clay loam soil texture produced hydrographs with slopes more similar to observed hydrograph in MM. In addition to uncertainty surrounding the soil texture, there was also uncertainty pertaining to the aquifer thickness and the distance to the watercourse.

During the period of time ET was calculated, August and September 1-14$^{th}$, there is typically no surface flow in Marian Creek. Due to the intermittent nature of the watercourse the distance was set as the distance to the watercourse's outlet at the downslope, southern end of MM. In addition, it was difficult to produce a good result when the depth of aquifer was set to 12 m, which was found in ERT surveys conducted at MM. Thus, the aquifer depth from a nearby control meadow was utilized. With the change in aquifer depth the model was able to produce results that more strongly resembled the observed hydrograph during multiple distinct time periods. Future use of this model would benefit from further investigation of parameters pertaining to soil texture, depth of the aquifer and character of the watercourse boundary.

#### *5.2.1.3. Soil Moisture Content*

For August 2018, daily ET calculated using multi-step multi-level (msml) and single-step multi-layer (ssml) methods, both of which utilize SMC data. The average daily ET obtained using msml was 1.191 mm, and 0.868 mm using ssml. Estimates calculated using msml had a range of 2.240 mm/day, while those calculated with ssml had a range of 1.265 mm/day.

Daily ET estimates obtained using msml and ssml in conjunction with soil moisture data were much less those obtained with the White method and groundwater table fluctuation modelling. Although the values obtained with these two SMC methods were closer to previously calculated ET values, they often produced underestimations of ET compared to water table fluctuation calculations, especially when using the ssml method (Table 5.1). One potential for uncertainty with these methodologies is the quality of instrument being utilized to collect soil moisture data. SMC monitoring instruments with lower resolutions may not detect small changes in SMC and data may contain more noise. In addition, data for this ET analysis was collected during August which is towards the end of the water year and typically experiences drier hydrologic conditions, which can also increase the noisiness of data. Thus, it is important that if SMC methodologies are considered that high quality soil moisture sensors be utilized, especially if monitoring will occur during dry conditions.

Table 5.1. Comparison of daily meadow ET estimated in this study and estimates obtained in previous research of Sierra Nevada meadows by Loheide and Gorelick (2005) and Lucas (2016).

| | **ET (mm/day)** |
|---|---|
| Loheide and Gorelick (2005) | |
| *Wet Meadow* | 4 - 6 |
| *Dry Meadow* | 1.5 - 4 |
| Lucas (2016) | 2.7 - 6.3 |
| This Study | |
| *White Method* | 0.9 - 26.6 |
| *Groundwater Fluctuation Modelling (Malama & Johnson,2009)* | 2 - 5 |
| *Soil Moisture Content* | 0.1 - 2.3 |

# 6. Conclusion

Conifer removal and upland thinning are restoration practices that have been implemented in numerous meadows in the attempt of restoring historic habitat areas. Although these projects aren't uncommon and research has shown a strong relationship between meadow groundwater and plant community occurrence, there still remain questions regarding the effectiveness of these restoration techniques. The methods and analysis utilized in this report augment understanding of the effect that these restoration treatments have on water table depth (WTD) and soil moisture content (SMC). In addition, the results found in this study help to further investigate the accuracy and potential usefulness of daily evapotranspiration (ET) calculation methodologies for montane meadows.

## 6.1. American River Headwater

Analysis of WTD in MC and CM1 revealed both meadows share similar hydrologic patterns, indicating that both systems are highly dependent upon water inputs from the snowpack and precipitation. Prior to restoration, MC had an average weekly WTD of 4.85 feet, indicative of a dry meadow. Following restoration, the average WTD in MM was 2.91 feet which is indicative of wet meadow conditions (Weixelman et al., 2011). Although WTD results indicate an increase in groundwater availability at MC, the results were formulated with only partial data availability for 2019 and the difference in WTD between the two years will likely decrease. In addition to average weekly WTD, WTD during the growing season has been shown to be a strong metric associated with meadow vegetation occurrence (Hammersmark et al., 2010). In 2018, prior to restoration, MC experienced 15 days where the groundwater was within 0.98 feet of the soil surface and

34 days within 2.30 feet of the surface. Following restoration, these metrics increased to 27 and 42 days respectively. The increase in number of days with a shallow WTD indicates that MC after conifer removal and upland thinning are more conducive to wetland meadow vegetation (Hammersmark et al., 2010). As noted in the discussion, the WTD metrics for 2019 only account for part of the growing season and thus it is likely that the number of days the WTD is within 2.30 feet will increase, as the WTD at the end of the monitoring period was around this depth.

SMC analysis pre- and post-restoration was limited due to gaps in data collection, and only allowed for comparison of two equivalent time periods, from 7/16/2017-10/21/2017 and from 7/15/2018-10/20/2018. Although these time periods contributed to understanding the soil moisture patterns at MC and CM1, they only provide brief insight into the effect of conifer removal and upland thinning on SMC as restoration activities concluded during the Fall of 2018. Even with a short post-restoration data set available, it is interesting to note that SMC in MC decreased at a much slower rate compared to 2017. This decrease in loss of SMC could indicate that removal and upland thinning had increased water availability at MC and decreased rates of ET.

The use of shallow groundwater wells in this study proved to be an effective means of monitoring groundwater conditions, while more problems were associated with soil moisture sensors. It is recommended that future hydrologic analysis of meadow restoration effects on groundwater include the use of shallow wells equipped with piezometers. Although the groundwater table fell below the reach of the wells during extremely dry periods, they were successful at monitoring depths throughout the growing season, which is important determining factor of vegetation occurrence.

### 6.2. Marian Meadow

This study successfully calculated meadow daily ET using three different methodologies, 1) diurnal groundwater table fluctuation, 2) diurnal groundwater table fluctuation modelling, and 3) SMC. Although all three methods were successfully used to calculate ET there was strong variance between methods. As observed in previous research, the White method produced very high values of ET on most days and produced some negative values during September. One factor that contributed to these results was the lack of a defined recharge period from 0:00 to 4:00 and the need to utilize a modified recharge period from 15:00 to 21:00. One solution could be to utilize higher resolution piezometers to capture groundwater fluctuation data; however, it may also be that the character of the diurnal fluxes at MM is not conducive for use with the White method. In comparison, daily ET estimates determined from modelling of diurnal groundwater table fluctuations produced results that more closely matched estimates from other Sierra Nevada meadow ET research (Loheide & Gorelick, 2005; Lucas, 2016). Although the modelling approach was able to arrive at more realistic ET estimates there was some uncertainty in regards to the aquifer parameters input into the model. It is suggested that this methodology be explored further and for more research to be done in selecting aquifer parameters for specific sites. Estimates derived from soil moisture data typically produced underestimations of daily ET, however this analysis can be influenced by instrument noise.

For future research regarding the estimation of daily ET at MM or other meadow sites it is suggested that all methodologies be explored dependent upon the character of data collected and experimental design. Of the three methods, the model of groundwater fluctuation created by Malama & Johnson (2009) with a semi-infinite lateral extent produced the most realistic estimations of daily ET, even with uncertainties pertaining to aquifer parameters. If the White method or soil moisture methodologies are considered it is first important to determine that the groundwater fluctuation data exhibits clear diurnal fluctuation and works with the original White method assumptions; and it is important that soil moisture data does not exhibit too much noise. If these data sets do not exhibit characteristics conducive to their respective methodologies then it would be suggested to utilize an alternative approach to estimate daily ET.

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# APPENDICES

## A. Average Weekly Depth to Water Table ARH

### Miranda Cabin Meadow (MC)

| Date | MW-1 (ft) | MW-2 (ft) | MW-3 (ft) | MW-4 (ft) | MW-5 (ft) | MC (Avg) |
|---|---|---|---|---|---|---|
| ***2017*** | ***6.20*** | ***5.74*** | ***5.43*** | ***6.96*** | ***6.73*** | ***6.02*** |
| 07/16/17-07/22/17 | 4.81 | 3.93 | 3.62 | 5.41 | 4.54 | 4.22 |
| 07/23/17-07/29/17 | 5.15 | 4.32 | 3.99 | 5.97 | 5.15 | 4.65 |
| 07/30/17-08/05/17 | 5.66 | 4.92 | 4.57 | 6.79 | 6.03 | 5.29 |
| 08/06/17-08/12/17 | 6.11 | 5.46 | 5.10 | 7.49 | 6.79 | 5.87 |
| 08/13/17-08/19/17 | 6.53 | 5.96 | 5.61 | 8.11 | 7.46 | 6.39 |
| 08/20/17-08/26/17 | 6.86 | 6.36 | 6.02 | 9.17 | 7.97 | 6.80 |
| 08/27/17-09/02/17 | 7.19 | 6.73 | 6.39 | 8.63 | 8.35 | 7.17 |
| 09/03/17-09/09/17 | 7.39 | 7.01 | 6.68 | 8.70 | 8.64 | 7.43 |
| 09/10/17-09/16/17 | 7.47 | 7.17 | 6.86 | 8.84 | 8.87 | 7.59 |
| 09/17/17-09/23/17 | 7.55 | 7.31 | 7.02 | 9.02 | 9.10 | 7.74 |
| 09/24/17-09/30/17 | 7.66 | 7.43 | 7.14 | 9.13 | 9.30 | 7.88 |
| 10/01/17-10/07/17 | 7.81 | 7.61 | 7.33 | 9.17 | 9.49 | 8.06 |
| 10/08/17-10/14/17 | 7.92 | 7.74 | 7.46 | 9.17 | 9.54 | 8.17 |
| 10/15/17-10/21/17 | 7.96 | 7.82 | 7.56 | 9.17 | 9.54 | 8.22 |
| 10/22/17-10/28/17 | 7.98 | 7.86 | 7.59 | 9.17 | 9.55 | 8.24 |
| 10/29/17-11/04/17 | 8.03 | 7.95 | 7.70 | 9.18 | 9.55 | 8.31 |
| 11/05/17-11/11/17 | 7.35 | 7.34 | 7.07 | 9.17 | 9.55 | 7.83 |
| 11/12/17-11/18/17 | 5.25 | 5.09 | 4.81 | 7.36 | 7.81 | 5.74 |
| 11/19/17-11/25/17 | 3.85 | 3.28 | 2.98 | 3.87 | 3.54 | 3.41 |
| 11/26/17-12/02/17 | 3.47 | 2.79 | 2.53 | 2.65 | 1.95 | 2.69 |
| 12/03/17-12/09/17 | 3.75 | 2.94 | 2.69 | 2.50 | 1.56 | 2.74 |
| 12/10/17-12/16/17 | 3.95 | 3.10 | 2.81 | 2.86 | 1.79 | 2.91 |
| 12/17/17-12/23/17 | 4.16 | 3.30 | 2.94 | 3.38 | 2.12 | 3.13 |
| 12/24/17-12/30/17 | 4.28 | 3.43 | 3.05 | 3.76 | 2.43 | 3.30 |
| 12/31/17-01/06/18 | 4.36 | 3.51 | 3.13 | 3.95 | 2.62 | 3.40 |
| ***2018*** | ***5.18*** | ***4.62*** | ***5.34*** | ***5.31*** | ***5.07*** | ***5.05*** |
| 01/07/18-01/13/18 | 1.92 | 1.21 | 0.98 | 1.40 | 0.56 | 1.16 |
| 01/14/18-01/20/18 | 2.15 | 1.29 | 1.09 | 1.53 | 0.64 | 1.30 |
| 01/21/18-01/27/18 | 2.74 | 1.70 | 1.41 | 1.69 | 0.96 | 1.70 |
| 01/28/18-02/03/18 | 2.88 | 1.87 | 1.58 | 1.79 | 1.11 | 1.86 |
| 02/04/18-02/10/18 | 2.14 | 1.25 | 1.08 | 1.52 | 0.75 | 1.31 |
| 02/11/18-02/17/18 | 2.76 | 1.71 | 1.43 | 1.78 | 1.15 | 1.77 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 02/18/18-02/24/18 | 3.17 | 2.15 | 1.83 | 2.14 | 1.55 | 2.17 |
| 02/25/18-03/03/18 | 3.41 | 2.43 | 2.09 | 2.47 | 1.85 | 2.44 |
| 03/04/18-03/10/18 | 3.45 | 2.51 | 2.18 | 2.67 | 2.03 | 2.54 |
| 03/11/18-03/17/18 | 2.25 | 1.31 | 1.15 | 1.67 | 1.11 | 1.46 |
| 03/18/18-03/24/18 | 1.35 | 0.84 | 0.61 | 0.89 | 0.60 | 0.85 |
| 03/25/18-03/31/18 | 1.44 | 0.68 | 0.53 | 1.02 | 0.38 | 0.76 |
| 04/01/18-04/07/18 | 1.24 | 0.58 | 0.44 | 0.89 | 0.31 | 0.64 |
| 04/08/18-04/14/18 | 1.37 | 0.68 | 0.52 | 1.00 | 0.31 | 0.72 |
| 04/15/18-04/21/18 | 1.55 | 0.82 | 0.65 | 1.21 | 0.37 | 0.85 |
| 04/22/18-04/28/18 | 1.40 | 0.68 | 0.47 | 1.00 | 0.29 | 0.71 |
| 04/29/18-05/05/18 | 1.57 | 0.82 | 0.62 | 1.17 | 0.33 | 0.83 |
| 05/06/18-05/12/18 | 1.69 | 0.91 | 0.75 | 1.20 | 0.40 | 0.94 |
| 05/13/18-05/19/18 | 1.78 | 0.96 | 0.81 | 1.28 | 0.55 | 1.02 |
| 05/20/18-05/26/18 | 2.04 | 1.09 | 0.94 | 1.49 | 0.88 | 1.24 |
| 05/27/18-06/02/18 | 2.85 | 1.73 | 1.47 | 1.93 | 1.51 | 1.89 |
| 06/03/18-06/09/18 | 3.57 | 2.51 | 2.17 | 2.67 | 2.20 | 2.61 |
| 06/10/18-06/16/18 | 4.02 | 3.02 | 2.65 | 3.48 | 2.86 | 3.14 |
| 06/17/18-06/23/18 | 4.38 | 3.44 | 3.96 | 4.18 | 3.59 | 3.84 |
| 06/24/18-06/30/18 | 4.85 | 3.98 | 7.13 | 4.96 | 4.45 | 5.10 |
| 07/01/18-07/07/18 | 5.30 | 4.50 | 7.34 | 5.70 | 5.29 | 5.61 |
| 07/08/18-07/14/18 | 5.73 | 5.01 | 7.79 | 6.37 | 6.02 | 6.14 |
| 07/15/18-07/21/18 | 6.18 | 5.52 | 8.27 | 7.01 | 6.73 | 6.67 |
| 07/22/18-07/28/18 | 6.60 | 6.00 | 8.76 | 7.56 | 7.39 | 7.18 |
| 07/29/18-08/04/18 | 6.98 | 6.43 | 9.19 | 8.01 | 7.90 | 7.63 |
| 08/05/18-08/11/18 | 7.28 | 6.78 | 9.52 | 8.38 | 8.30 | 7.97 |
| 08/12/18-08/18/18 | 7.53 | 7.09 | 9.66 | 8.68 | 8.62 | 8.22 |
| 08/19/18-08/25/18 | 7.76 | 7.36 | 9.65 | 8.92 | 8.89 | 8.41 |
| 08/26/18-09/01/18 | 7.93 | 7.59 | 9.65 | 9.12 | 9.14 | 8.58 |
| 09/02/18-09/08/18 | 8.11 | 7.80 | 9.64 | 9.15 | 9.38 | 8.73 |
| 09/09/18-09/15/18 | 8.29 | 8.01 | 9.65 | 9.16 | 9.55 | 8.87 |
| 09/16/18-09/22/18 | 8.36 | 8.13 | 9.65 | 9.16 | 9.56 | 8.93 |
| 09/23/18-09/29/18 | 8.50 | 8.28 | 9.65 | 9.17 | 9.56 | 9.00 |
| 09/30/18-10/06/18 | 8.45 | 8.28 | 9.65 | 9.17 | 9.57 | 8.99 |
| 10/07/18-10/13/18 | 8.37 | 8.23 | 9.65 | 9.17 | 9.56 | 8.95 |
| 10/14/18-10/20/18 | 8.51 | 8.38 | 9.65 | 9.17 | 9.57 | 9.03 |
| 10/21/18-10/27/18 | 8.56 | 8.44 | 9.66 | 9.17 | 9.57 | 9.06 |
| 10/28/18-11/03/18 | 8.60 | 8.50 | 9.66 | 9.17 | 9.57 | 9.08 |
| 11/04/18-11/10/18 | 8.66 | 8.57 | 9.65 | 9.16 | 9.56 | 9.11 |
| 11/11/18-11/17/18 | 8.68 | 8.60 | 9.64 | 9.15 | 9.55 | 9.12 |
| 11/18/18-11/24/18 | 8.48 | 8.51 | 9.64 | 9.15 | 9.55 | 9.05 |
| 11/25/18-12/01/18 | 7.84 | 7.81 | 9.65 | 9.16 | 9.56 | 8.71 |
| 12/02/18-12/08/18 | 7.88 | 7.83 | 9.65 | 9.16 | 9.56 | 8.73 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 12/09/18-12/15/18 | 7.95 | 7.90 | 9.64 | 9.15 | 9.55 | 8.76 |
| 12/16/18-12/22/18 | 7.95 | 7.90 | 9.64 | 9.15 | 9.55 | 8.76 |
| 12/23/18-12/29/18 | 7.27 | 7.24 | 9.57 | 9.11 | 9.37 | 8.36 |
| 12/30/18-01/05/19 | 7.33 | 7.21 | 9.65 | 9.16 | 8.88 | 8.27 |
| ***2019*** | ***2.31*** | ***1.73*** | ***4.31*** | ***2.79*** | ***1.73*** | ***2.52*** |
| 01/06/19-01/12/19 | 7.19 | 7.03 | 9.54 | 9.05 | 8.55 | 8.08 |
| 01/13/19-01/19/19 | 6.52 | 6.30 | 8.86 | 8.29 | 7.82 | 7.38 |
| 01/20/19-01/26/19 | 4.24 | 3.82 | 6.44 | 4.68 | 4.99 | 4.87 |
| 01/27/19-02/02/19 | 4.03 | 3.43 | 6.09 | 3.58 | 3.61 | 4.29 |
| 02/03/19-02/09/19 | 3.44 | 2.69 | 5.37 | 2.30 | 1.60 | 3.28 |
| 02/10/19-02/16/19 | 2.07 | 2.08 | 4.24 | 1.03 | 0.49 | 2.22 |
| 02/17/19-02/23/19 | 1.30 | 0.58 | 3.36 | 0.78 | 0.14 | 1.35 |
| 02/24/19-03/02/19 | 1.30 | 0.43 | 3.24 | 0.64 | n/a | 1.66 |
| 03/03/19-03/09/19 | 0.77 | 0.08 | 2.80 | 0.21 | n/a | 1.22 |
| 03/10/19-03/16/19 | 0.77 | 0.09 | 2.78 | 0.24 | n/a | 1.21 |
| 03/17/19-03/23/19 | 1.31 | 0.88 | 3.31 | 0.82 | 0.27 | 1.44 |
| 03/24/19-03/30/19 | 1.70 | 0.85 | 3.69 | 1.19 | 0.27 | 1.63 |
| 03/31/19-04/06/19 | 1.56 | 0.68 | 3.51 | 0.96 | 0.28 | 1.51 |
| 04/07/19-04/13/19 | 1.43 | 0.56 | 3.39 | 0.82 | 0.23 | 1.40 |
| 04/14/19-04/20/19 | 1.47 | 0.59 | 3.40 | 0.88 | 0.23 | 1.42 |
| 04/21/19-04/27/19 | 1.31 | 0.45 | 3.35 | 0.65 | 0.21 | 1.33 |
| 04/28/19-05/04/19 | 1.38 | 0.53 | 3.36 | 0.71 | 0.21 | 1.37 |
| 05/05/19-05/11/19 | 1.33 | 0.50 | 3.35 | 0.64 | 0.20 | 1.34 |
| 05/12/19-05/18/19 | 1.39 | 0.56 | 3.38 | 0.67 | 0.20 | 1.38 |
| 05/19/19-05/25/19 | 1.62 | 0.76 | 3.57 | 0.96 | 0.21 | 1.54 |
| 05/26/19-06/01/19 | 1.44 | 0.60 | 3.40 | 0.75 | 0.19 | 1.41 |
| 06/02/19-06/08/19 | 1.29 | 0.52 | 3.36 | 0.59 | 0.17 | 1.34 |
| 06/09/19-06/15/19 | 1.41 | 0.61 | 3.39 | 0.69 | 0.18 | 1.40 |
| 06/16/19-06/22/19 | 1.66 | 0.87 | 3.79 | 0.95 | 0.23 | 1.64 |
| 06/23/19-06/29/19 | 1.97 | 1.11 | 4.12 | 1.50 | 0.65 | 1.96 |
| 06/30/19-07/06/19 | 3.42 | 2.41 | 5.07 | 2.25 | 1.84 | 3.00 |
| 07/07/19-07/13/19 | 3.95 | 2.98 | 5.55 | 3.07 | 2.43 | 3.60 |
| 07/14/19-07/20/19 | 4.35 | 3.42 | 5.96 | 3.79 | 3.07 | 4.12 |
| 07/21/19-07/27/19 | 4.71 | 3.85 | 6.36 | 4.45 | 3.81 | 4.64 |
| 07/28/19-08/03/19 | 5.13 | 4.33 | 6.81 | 5.16 | 4.58 | 5.20 |
| 08/04/19-08/10/19 | 5.54 | 4.82 | 7.26 | 5.85 | 5.31 | 5.75 |
| 08/11/19-08/17/19 | 5.93 | 5.28 | 7.69 | 6.49 | 5.95 | 6.27 |
| 08/18/19-08/24/19 | 6.32 | 5.74 | 8.14 | 7.08 | 6.59 | 6.77 |
| 08/25/19-08/31/19 | 6.69 | 6.17 | 8.57 | 7.59 | 7.18 | 7.24 |
| 09/01/19-09/07/19 | 6.90 | 6.40 | 8.80 | 7.86 | 7.49 | 7.49 |

## Control Meadow (CM1)

| Date | CW-1 (ft) | CW-2 (ft) | CW-3 (ft) | CW-4 (ft) | CW-5 (ft) | CW (Avg) |
|---|---|---|---|---|---|---|
| ***2017*** | ***1.56*** | ***5.81*** | ***2.77*** | ***1.61*** | ***1.47*** | ***2.64*** |
| 07/16/17-07/22/17 | n/a | 6.40 | 4.57 | n/a | n/a | 5.48 |
| 07/23/17-07/29/17 | n/a | 6.75 | 4.89 | n/a | n/a | 5.82 |
| 07/30/17-08/05/17 | n/a | 7.19 | 5.39 | n/a | n/a | 6.29 |
| 08/06/17-08/12/17 | n/a | 7.50 | 5.68 | n/a | n/a | 6.59 |
| 08/13/17-08/19/17 | n/a | 7.67 | 6.00 | n/a | n/a | 6.83 |
| 08/20/17-08/26/17 | n/a | 7.78 | 6.25 | n/a | n/a | 7.01 |
| 08/27/17-09/02/17 | n/a | 7.90 | n/a | n/a | n/a | 7.90 |
| 09/03/17-09/09/17 | n/a | 8.09 | n/a | n/a | n/a | 8.09 |
| 09/10/17-09/16/17 | n/a | 8.32 | n/a | n/a | n/a | 8.32 |
| 09/17/17-09/23/17 | n/a | 8.55 | n/a | n/a | n/a | 8.55 |
| 09/24/17-09/30/17 | n/a | 8.74 | n/a | n/a | n/a | 8.74 |
| 10/01/17-10/07/17 | n/a | 8.91 | n/a | n/a | n/a | 8.91 |
| 10/08/17-10/14/17 | n/a | 9.08 | n/a | n/a | n/a | 9.08 |
| 10/15/17-10/21/17 | n/a | 9.22 | n/a | n/a | n/a | 9.22 |
| 10/22/17-10/28/17 | n/a | n/a | n/a | n/a | n/a | n/a |
| 10/29/17-11/04/17 | n/a | n/a | n/a | n/a | n/a | n/a |
| 11/05/17-11/11/17 | 4.25 | 8.64 | 3.34 | 2.98 | 2.73 | 4.39 |
| 11/12/17-11/18/17 | 2.21 | 2.86 | 1.60 | 1.38 | 1.05 | 1.82 |
| 11/19/17-11/25/17 | 1.13 | 0.91 | 0.35 | 1.19 | 1.08 | 0.93 |
| 11/26/17-12/02/17 | 0.97 | 0.80 | 0.25 | 0.97 | 1.00 | 0.80 |
| 12/03/17-12/09/17 | 1.13 | 1.28 | 0.34 | 1.32 | 1.75 | 1.16 |
| 12/10/17-12/16/17 | 1.47 | 1.67 | 0.54 | 1.71 | 2.51 | 1.58 |
| 12/17/17-12/23/17 | 1.72 | 1.89 | 1.01 | 2.03 | n/a | 1.66 |
| 12/24/17-12/30/17 | 1.93 | 2.10 | 1.52 | 2.42 | n/a | 1.99 |
| 12/31/17-01/06/18 | 2.09 | 2.24 | 1.81 | 2.69 | n/a | 2.21 |
| ***2018*** | ***1.76*** | ***3.51*** | ***2.02*** | ***1.37*** | ***1.40*** | ***2.01*** |
| 01/07/18-01/13/18 | 0.65 | 0.62 | 0.10 | 0.91 | 0.96 | 0.65 |
| 01/14/18-01/20/18 | 0.91 | 0.89 | 0.14 | 1.07 | 0.98 | 0.80 |
| 01/21/18-01/27/18 | 1.20 | 1.39 | 0.25 | 1.30 | 1.70 | 1.17 |
| 01/28/18-02/03/18 | 1.58 | 1.63 | 0.59 | 1.66 | 2.08 | 1.51 |
| 02/04/18-02/10/18 | 1.76 | 1.70 | 0.87 | 1.79 | 2.12 | 1.65 |
| 02/11/18-02/17/18 | 1.99 | 1.89 | 1.31 | 2.01 | 2.64 | 1.97 |
| 02/18/18-02/24/18 | 2.24 | 2.04 | 1.64 | 2.33 | 2.71 | 2.19 |
| 02/25/18-03/03/18 | 2.65 | 2.32 | 2.11 | 2.78 | n/a | 2.46 |
| 03/04/18-03/10/18 | 2.95 | 2.50 | 2.42 | 2.94 | n/a | 2.70 |
| 03/11/18-03/17/18 | 1.64 | 1.50 | 0.88 | 1.73 | 1.96 | 1.54 |
| 03/18/18-03/24/18 | 1.03 | 0.98 | 0.42 | 1.10 | 1.61 | 1.03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 03/25/18-03/31/18 | 0.72 | 0.48 | 0.14 | 0.73 | 0.72 | 0.56 |
| 04/01/18-04/07/18 | 0.69 | 0.50 | 0.14 | 0.58 | 0.72 | 0.53 |
| 04/08/18-04/14/18 | 0.76 | 0.47 | 0.16 | 0.48 | 0.73 | 0.52 |
| 04/15/18-04/21/18 | 1.06 | 0.70 | 0.21 | 0.61 | 0.78 | 0.67 |
| 04/22/18-04/28/18 | 0.90 | 0.53 | 0.20 | 0.53 | 0.78 | 0.59 |
| 04/29/18-05/05/18 | 1.02 | 0.59 | 0.22 | 0.60 | 0.86 | 0.66 |
| 05/06/18-05/12/18 | 1.26 | 1.02 | 0.27 | 0.84 | 1.51 | 0.98 |
| 05/13/18-05/19/18 | 1.54 | 1.44 | 0.48 | 1.31 | 2.02 | 1.36 |
| 05/20/18-05/26/18 | 1.94 | 1.72 | 1.00 | 1.85 | 2.32 | 1.77 |
| 05/27/18-06/02/18 | 2.66 | 2.36 | 2.19 | 2.50 | 2.59 | 2.46 |
| 06/03/18-06/09/18 | 3.76 | 3.75 | 3.45 | n/a | n/a | 3.65 |
| 06/10/18-06/16/18 | 4.27 | 4.72 | 3.89 | n/a | n/a | 4.29 |
| 06/17/18-06/23/18 | 4.57 | 5.58 | 4.16 | n/a | n/a | 4.77 |
| 06/24/18-06/30/18 | n/a | 6.23 | 4.48 | n/a | n/a | 5.36 |
| 07/01/18-07/07/18 | n/a | 6.68 | 4.92 | n/a | n/a | 5.80 |
| 07/08/18-07/14/18 | n/a | 7.02 | 5.37 | n/a | n/a | 6.20 |
| 07/15/18-07/21/18 | n/a | 7.33 | 5.68 | n/a | n/a | 6.50 |
| 07/22/18-07/28/18 | n/a | 7.60 | 6.01 | n/a | n/a | 6.80 |
| 07/29/18-08/04/18 | n/a | 7.79 | 6.25 | n/a | n/a | 7.02 |
| 08/05/18-08/11/18 | n/a | 7.98 | n/a | n/a | n/a | 7.98 |
| 08/12/18-08/18/18 | n/a | 8.24 | n/a | n/a | n/a | 8.24 |
| 08/19/18-08/25/18 | n/a | 8.55 | n/a | n/a | n/a | 8.55 |
| 08/26/18-09/01/18 | n/a | 8.87 | n/a | n/a | n/a | 8.87 |
| 09/02/18-09/08/18 | n/a | 9.14 | n/a | n/a | n/a | 9.14 |
| 09/09/18-09/15/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 09/16/18-09/22/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 09/23/18-09/29/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 09/30/18-10/06/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 10/07/18-10/13/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 10/14/18-10/20/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 10/21/18-10/27/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 10/28/18-11/03/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 11/04/18-11/10/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 11/11/18-11/17/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 11/18/18-11/24/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 11/25/18-12/01/18 | n/a | n/a | 6.30 | 2.96 | 2.72 | 3.99 |
| 12/02/18-12/08/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 12/09/18-12/15/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 12/16/18-12/22/18 | n/a | n/a | n/a | n/a | n/a | n/a |
| 12/23/18-12/29/18 | 4.34 | 9.04 | 5.75 | 2.66 | 2.41 | 4.84 |
| 12/30/18-01/05/19 | n/a | n/a | 5.52 | n/a | n/a | 5.52 |
| ***2019*** | ***0.96*** | ***2.55*** | ***1.81*** | ***0.69*** | ***1.12*** | ***1.42*** |

| | | | | | | |
|---|---|---|---|---|---|---|
| 01/06/19-01/12/19 | n/a | 8.91 | 5.29 | n/a | n/a | 7.10 |
| 01/13/19-01/19/19 | 3.81 | 7.92 | 3.79 | 2.87 | n/a | 4.60 |
| 01/20/19-01/26/19 | 1.38 | 2.88 | 0.85 | 1.43 | 2.17 | 1.74 |
| 01/27/19-02/02/19 | 1.23 | 1.56 | 0.68 | 1.50 | 2.11 | 1.42 |
| 02/03/19-02/09/19 | 0.85 | 1.28 | 0.60 | 1.02 | 2.28 | 1.21 |
| 02/10/19-02/16/19 | 0.60 | 0.81 | 0.35 | 0.85 | 1.72 | 0.87 |
| 02/17/19-02/23/19 | 0.23 | 0.35 | 0.20 | 0.50 | 0.70 | 0.40 |
| 02/24/19-03/02/19 | 0.17 | 0.46 | 0.02 | 0.27 | 0.58 | 0.30 |
| 03/03/19-03/09/19 | 0.00 | 0.04 | 0.00 | 0.12 | 0.34 | 0.10 |
| 03/10/19-03/16/19 | 0.00 | 0.04 | 0.00 | 0.01 | 0.31 | 0.07 |
| 03/17/19-03/23/19 | 0.76 | 0.90 | 0.41 | 0.67 | 1.18 | 0.79 |
| 03/24/19-03/30/19 | 1.08 | 1.28 | 0.61 | 0.97 | 1.68 | 1.12 |
| 03/31/19-04/06/19 | 0.60 | 0.72 | 0.53 | 0.74 | 1.19 | 0.76 |
| 04/07/19-04/13/19 | 0.42 | 0.37 | 0.33 | 0.50 | 1.02 | 0.53 |
| 04/14/19-04/20/19 | 0.50 | 0.48 | 0.34 | 0.48 | 1.00 | 0.56 |
| 04/21/19-04/27/19 | 0.43 | 0.36 | 0.25 | 0.46 | 0.96 | 0.49 |
| 04/28/19-05/04/19 | 0.43 | 0.36 | 0.25 | 0.47 | 0.95 | 0.49 |
| 05/05/19-05/11/19 | 0.41 | 0.35 | 0.22 | 0.47 | 0.95 | 0.48 |
| 05/12/19-05/18/19 | 0.44 | 0.36 | 0.24 | 0.48 | 0.97 | 0.50 |
| 05/19/19-05/25/19 | 0.59 | 0.54 | 0.34 | 0.52 | 1.03 | 0.60 |
| 05/26/19-06/01/19 | 0.51 | 0.45 | 0.28 | 0.49 | 1.01 | 0.55 |
| 06/02/19-06/08/19 | 0.44 | 0.37 | 0.22 | 0.46 | 0.99 | 0.49 |
| 06/09/19-06/15/19 | 0.46 | 0.39 | 0.24 | 0.47 | 0.98 | 0.51 |
| 06/16/19-06/22/19 | 0.67 | 0.70 | 0.40 | 0.60 | 1.23 | 0.72 |
| 06/23/19-06/29/19 | 1.79 | 1.68 | 0.94 | 1.54 | 2.32 | 1.65 |
| 06/30/19-07/06/19 | 3.16 | 2.70 | 2.54 | 2.65 | n/a | 2.76 |
| 07/07/19-07/13/19 | 4.13 | 4.14 | 3.62 | n/a | n/a | 3.96 |
| 07/14/19-07/20/19 | 4.51 | 5.07 | 4.02 | n/a | n/a | 4.53 |
| 07/21/19-07/27/19 | n/a | 6.00 | 4.37 | n/a | n/a | 5.19 |
| 07/28/19-08/03/19 | n/a | 6.53 | 4.93 | n/a | n/a | 5.73 |
| 08/04/19-08/10/19 | n/a | 6.88 | 5.40 | n/a | n/a | 6.14 |
| 08/11/19-08/17/19 | n/a | 7.17 | 5.70 | n/a | n/a | 6.44 |
| 08/18/19-08/24/19 | n/a | 7.43 | 5.97 | n/a | n/a | 6.70 |
| 08/25/19-08/31/19 | n/a | 7.67 | 6.23 | n/a | n/a | 6.95 |
| 09/01/19-09/07/19 | n/a | 7.73 | n/a | n/a | 1.91 | 4.82 |