Projecting hydrological microrefugias: The impact of climate change on the hydrology of the Sagehen Drainage Basin

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ABSTRACT

As earth's surface temperatures rise and climate change intensifies, groundwater dependent ecosystems, like meadows, present themselves as a cause for conservation. In ecosystems like the Sagehen Drainage Basin, where certain areas of the meadows are saturated with water year-long, it is typically thought that geomorphological factors play a role in groundwater variability. Factors such as slope and elevation, are predictors for groundwater levels. In this study, I found that average groundwater levels can be better predicted by identifying the intersection of hydrological process zones and plant functional types. Using field observations, GPS coordinates, and QGIS, the Sagehen Drainage Basin can be characterized by three hydrological process zones (alluvial fan, riparian, and terrace) and by three plant functional types (willow trees, sedges, and mixed herbaceous species). Together, a combination of these two factors generate 9 crosses and indicated novel groundwater availability trends. There was no significant difference between mean groundwater levels across meadows on an elevation gradient ($p=0.611$), but there was a statistical difference between mean groundwater levels based on its hydrological process zones and plant functional types ($p>0.05$ for 24 of the 36 pairwise comparisons). Groundwater levels are better understood when placed in the context of understanding the hydrogeomorphology of the basin, rather than just geographic features.

KEYWORDS

Groundwater, hydrogeomorphology, LiDAR, geographic information systems, QGIS

INTRODUCTION

As a result of shifting climate and changes in hydrology, groundwater availability, which is a major factor in determining hydrologic refugia, and geological features, like elevation, must be studied. Hydrologic microrefugia are freshwater sites that can persist despite ecological disturbances and climate fluctuations (Andrew and Warrener 2017). Microrefugia are a cause for conservation because their resilient ecosystems, due in part to their microclimates, give way to different landscapes that can serve as buffers to drought. As climate change intensifies and temperatures rise, microrefugia must be conserved and the factors that allow these regions to persist must be studied because their resilience to climate change fosters biodiversity (Andrew and Warrener 2017). The hydrology of a particular landscape often takes into account factors such as evapotranspiration, hillslope groundwater, precipitation, snow melts, runoff and surface waters (Hornberger et al. 1998). Some factors, like higher elevation, is correlated to regions with less precipitation and serve as indicators for regions with a lower likelihood to serve as microrefugia (Lundquist and Loheide 2011). All aspects of hydrology and geology must be accounted for to determine where wetland persistence is viable and ideal for conservation.

To assess ecosystem viability and persistence, remote sensing technology like GIS and LiDAR are powerful tools to determine why some meadows and wetlands persist under certain ecological changes while others do not. Recent research has been focused on whether or not wetland restoration is effective in raising the water table and preserving the environment (Hausner et al. 2018; Pope et al. 2015). GIS (Geographic Information Systems) is often employed to model whether or not landscape features can predict locations for microrefugia. Remote sensing data, such as that obtained from Landsatwas used to perform pixel sampling on vegetation (Andrew and Warrener 2017). When studying the hydrology of wetlands, elevation is often a variable but remote sensing data like LiDAR can be used to create more precise digital elevation models.

These constituents of hydrology are affected by climate change, which influences the water table and the persistence meadow ecosystems. Meadows are often the focus of conservation studies because their broad surfaces serve as a flood buffer and their soils as a means of filtering the water before it leaves the basin (Lorenz 2017) and they serve as a habitat for plants and wildlife. For evapotranspiration, a process in which water returns to the atmosphere from plant transpiration and water evaporation from soil, physical factors like temperature influence evapotranspiration and consequently, the water table (Goulden et al. 2012).

In this study, I analyzed groundwater ecosystems with respect to climate change and determined how hydrological processes in the Sagehen Drainage Basin are affected by increasing temperatures. I used aerial LiDAR to create a digital elevation model (DEM) of the study area and from there, used GIS to delineate the drainage area of this basin. These digital models, along with field-collected measurements of the water table were used to determine groundwater availability in this region. Using these methods, I determined the controls on groundwater availability in wetland ecosystems and identified if elevation, hydrological processes zones, and vegetation type affect the water table level. I hypothesized that the hydrology of meadow regions is dictated by elevation and that at higher elevations, there will be a larger drainage area and thus, a higher water table.

METHODS

Study area

This study was conducted on four meadows within the Sagehen Drainage Basin in Nevada County, 11 miles north of Truckee, California. Sagehen is primarily dominated by plan species like the yellow pine, mixed conifer, red fir forests, brushfields, mountain meadows, and fens (UC Regents 2020). It is approximately 9,000 acres in size and its Mediterranean climate is marked by average summer temperatures (July) of 3 ºC to 26 ºC, average winter temperatures (January) of -10.5 ºC to 4.5 ºC, and an average precipitation of 88cm (water) and 515cm (snow) (UC Regents 2020).

The sites for my study were selected by PhD candidate Jennifer Natali from the Kondolf RiverLab at the University of California, Berkeley. They were chosen based on the presence of trees with adequate height to mount phenology cameras that monitor and record changes in vegetation over time. In general, only four meadows or large clearings are present in this drainage basin and few other options for site selection occur within the basin. The four meadows used as the study area vary in elevation so that I can take into account how the earth's geomorphology affects hydrological processes. I used QGIS to find the center of each of the four meadow polygons

(Upper, Kiln, East, and Lower) and to determine their respective coordinates (QGIS Development Team, Version 3.10.0 2019). The Upper meadow had a latitude and longitude of (39.432, -120.28), Kiln had (39.432, -120.26), East had (39.430, -120.24), and Lower had (39.440, -120.214). Similarly, I used QGIS to find the elevation of each meadow as this information is a unique characterization between the different meadows.

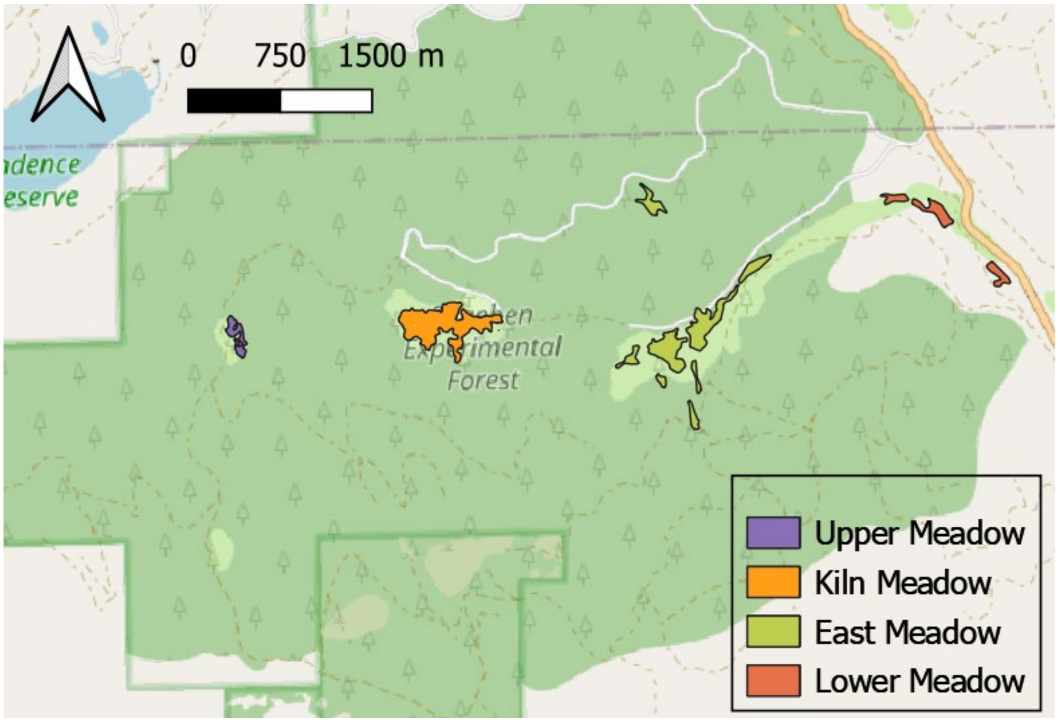

Figure 1: Study site (Sagehen Drainage Basin): Upper, Kiln, East, Lower Meadows (left to right)

Groundwater measurements

To collect groundwater measurements, I visited the Sagehen Creek Field Station. At three of the meadows, Kiln, East, and Lower, there were either pre-existing groundwater wells installed from past experiments (Allen-Diaz 1991) or new wells we installed made from PVC pipes. Jennifer Natali determined locations for where to build new groundwater wells and how to sample them based on a stratified random sampling that factored in plant functional types and hydrogeomorphic zones to help direct where to build each well. Drawing from field observations and their corresponding GPS coordinates, she used QGIS to generate polygons for the different plant functional types in Sagehen. These polygons were layered with QGIS polygons that represented the different hydrological process zones which were determined based on coordinates from a geologic map from the California Geological Society (Sylvester and Raines 2017). Then, at the center of these intersected polygons, groundwater wells were placed.

The primary hydrological process zones in the Sagehen Drainage Basin include the riparian zone, alluvial fan, and terrace. The common plant functional types observed in all four basins can be grouped into the following three categories for the purposes of this research: willow trees, mixed herbaceous species, and sedges. The geomorphology of this basin, the factors listed above, was noted to inform me on how to analyze the groundwater data.

Although some of the wells had data loggers inside of them to determine flow characteristics, a small device was still needed to measure the depth of the water table for all 33 wells from May 2018 until October 2019. The measurement apparatus was a long, bendable, meter stick with a sensor attached to the end of it. To determine the depth of the water, we lowered the measuring tool into the well and when it made contact with water, the circuit was connected and the sensor would flash a red light, indicating that the measurement can be made and that we should record the number on our meter stick as the depth of the water table. However, because this measurement also includes the height of the groundwater well, we subtracted the height of the well from this measurement to determine the actual depth of the water below ground. Since we did not have measurements for the height of the groundwater wells in the lower meadow, the groundwater level could not be calculated and I will only focus on the Kiln and East meadows.

Datasets & GIS methods

Lidar data

I used aerial LiDAR (Light Detection and Ranging) data, sourced from University of California, San Diego's OpenTopography site (REF), to perform hydrological analyses on digital elevation models. The LiDAR data I used in this project covers the Tahoe National Forest and was collected in the summer of 2014. It has a point density of 8.93 points/m^2 and was flown over an area of 3,292.14 km^2 (Guo 2017). I used this data to create catchment delineations for each of the four individual meadows. To do this, I used the "Terrain Analysis - Hydrology" toolbox in QGIS. I also used hydrological analysis tool boxes in QGIS like SAGA and GRASS to determine the topographic wetness index (TWI), absolute flow direction, and filled digital elevation model. TWI is a measure of water saturation and is calculated by including hillslope angle and drainage area (Beven 1997). These raster datasets were used to calculate the drainage areas of each meadow. I created a filled digital elevation model (filled DEM) instead of a regular digital elevation model because hydrological analysis tools require this type of DEM input (Figure 2). This is because the fill tool in GIS interpolates the cells of a raster dataset so that there is a continuous drainage network rather than sinks and peaks from errors in data resolution (Esri 2020).

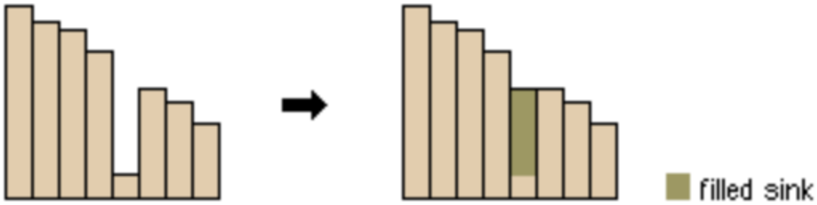

Figure 2. Filled DEM Visual Aid. This is a profile view of a sink in the dataset, pre- and post- running the Fill tool in GIS (Esri 2020).

Analysis of groundwater levels

I analyzed the groundwater field-collected measurements and related the groundwater elevations to spatial features, such as DEM elevation and drainage area, using R. One-way ANOVA, followed by a Tukey Honestly Significant Difference (Tukey HSD) test evaluated groundwater data to determine if there was a statistically significant difference in mean groundwater levels across the Kiln and East meadows. The Tukey HSD determined if there was a statistically significant difference in mean groundwater levels using pairwise comparisons of the nine different combinations of hydrological process zones and plant functional types. I also ran a two-way ANOVA in R to see if the combined effect from multiple factors (meadow location and year) had an effect on mean groundwater levels.

RESULTS

GIS

Based on the filled digital elevation model, the four meadows (listed from west to east) are generally located on an elevation gradient with the Upper Meadow having an elevation range of 2057.11m to 2073.93m, Kiln having an elevation of 1968.56m to 2018.3m, East having an elevation of 1913.31m to 2038.28m, and the Lower Meadow having an elevation of 1875.27 to 18794.25m (Figure 3). The maximum elevation in this entire basin is 2656.17m above sea level and the minimum elevation is 1869.1m.

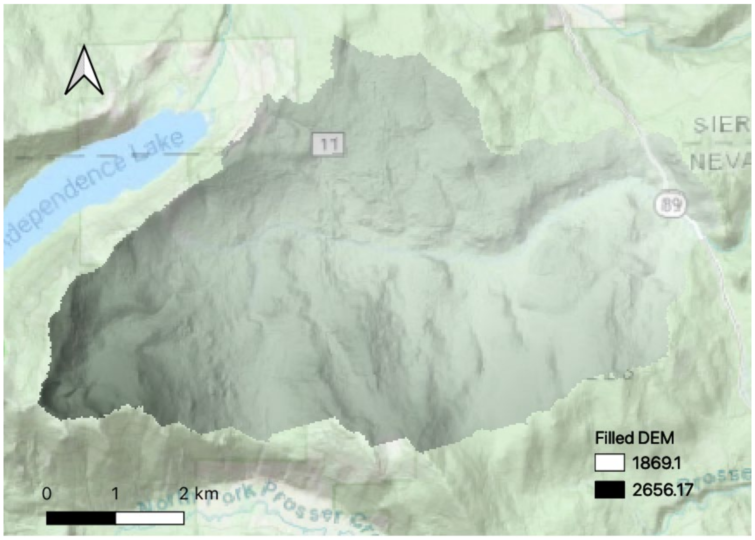

Figure 3. Filled DEM. This filled digital elevation model was used to determine the elevation for each meadow as well as to run additional hydrological analysis tools.

This digital elevation model was then used to generate the absolute flow direction model (Figure 2) which is an input to delineate the drainage area of each meadow as well as the drainage area of the entire basin (Figure 3). The four meadows (from west to east) have differences in drainage areas. Upper meadow has a drainage area of 4,609,886.156 m^2, Kiln has an area of 19,280,031.804 m^2, East has an area of 31,1390,67.391m^2, and the Lower Meadow having an area of 34,059,371.525 m^2.

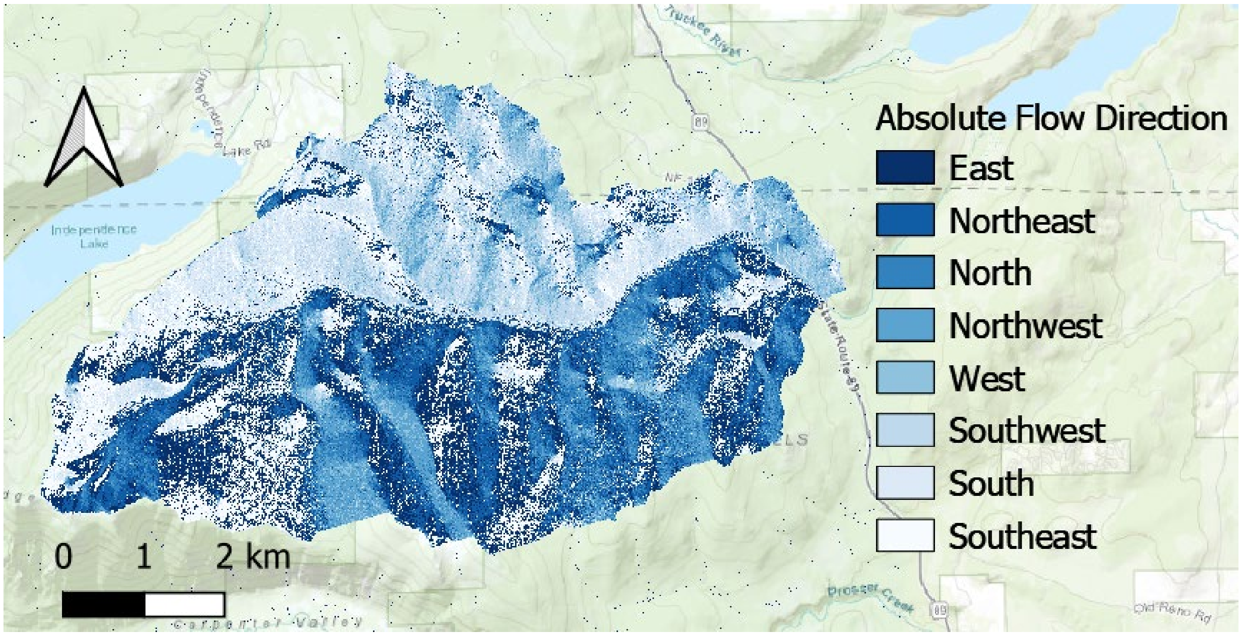

Figure 4. Absolute Flow Direction Model. This model is used to determine how the basin and meadow drainage areas are delineated.

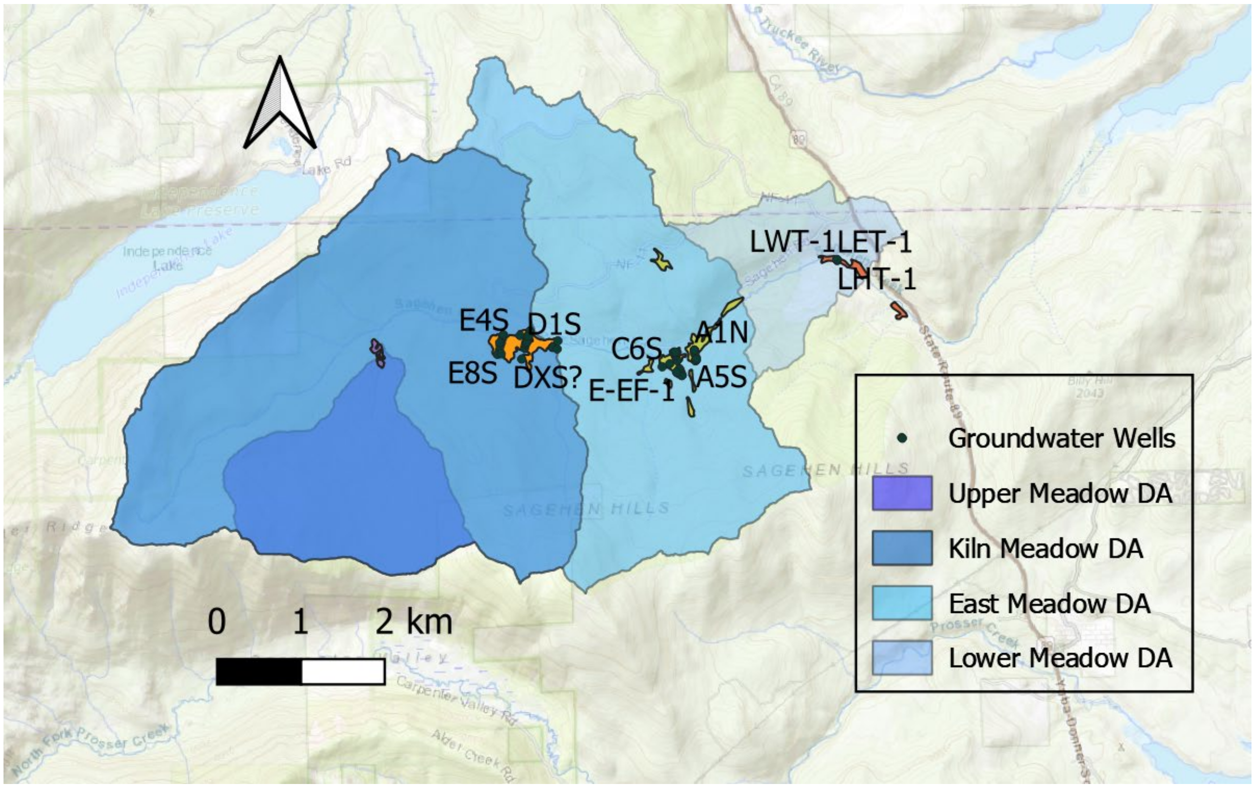

Figure 5. Drainage Area of the Sagehen Drainage Basin. A map of the whole-basin catchment delineation along with the drainage area delineations of all four meadows.

Overview of groundwater data

All 9 instances of hydrological process zones and plant functional type crosses were present in both the Kiln and East meadows. There were 20 wells in the Kiln meadow and 13 wells in the East meadow. In general, the East meadow had a lower water table with a mean groundwater level of -40.4815 cm and Kiln had a mean groundwater level of -28.77009 cm. In both meadows, the dominant plant functional type was mixed herbaceous and the dominant hydrological process zone was the riparian zone.

Table 1. Groundwater Well Characteristics for the East Meadow. This table contains all 9 hydrological process zone and plant functional type crosses, indicates the number of wells in each cross, and notes the average groundwater level below the ground.

Hydro_Plant <fctr>	n <int>	gw_avg <dbl>
Fan.Sedge	1	-13.54913
Riparian.Willow	2	-23.47747
Fan.Mixed_Herbaceous	1	-25.03406
Riparian.Sedge	1	-31.52701
Fan.Willow	1	-31.67902
Terrace.Mixed_Herbaceous	3	-47.03762
Riparian.Mixed_Herbaceous	2	-54.04527
Terrace.Sedge	1	-60.02199
Terrace.Willow	1	-68.28994

Table 2. Groundwater Well Characteristics for the Kiln Meadow. This table contains all 9 hydrological process zone and plant functional type crosses, indicates the number of wells in each cross, and notes the average groundwater level below the ground.

Hydro_Plant <fctr>	n <int>	gw_avg <dbl>
Fan.Sedge	1	-7.277041
Riparian.Sedge	3	-7.849351
Fan.Mixed_Herbaceous	3	-14.694428
Riparian.Mixed_Herbaceous	4	-27.104010
Riparian.Willow	2	-34.813317
Terrace.Willow	1	-39.034616
Terrace.Mixed_Herbaceous	5	-46.841005
Fan.Willow	1	-49.211109

Differences in Groundwater levels

When running a one-way ANOVA to compare the average groundwater levels across the Kiln and East meadows, there was no statistically significant difference amongst the measurements (p=0.611) – which were high above the significance level of 0.05 (Figure 6, Rstudio Team 2019). However, a one-way ANOVA test revealed a significant p-value of < 2e-16 when comparing the average groundwater levels across all 9 hydrological process zones and plant functional type crosses. This comparison was over aggregated data from both meadows with measurements from 2018 and 2019. I generated a boxplot in R to visually compare the mean groundwater levels across these 9 groups (Figure 6).

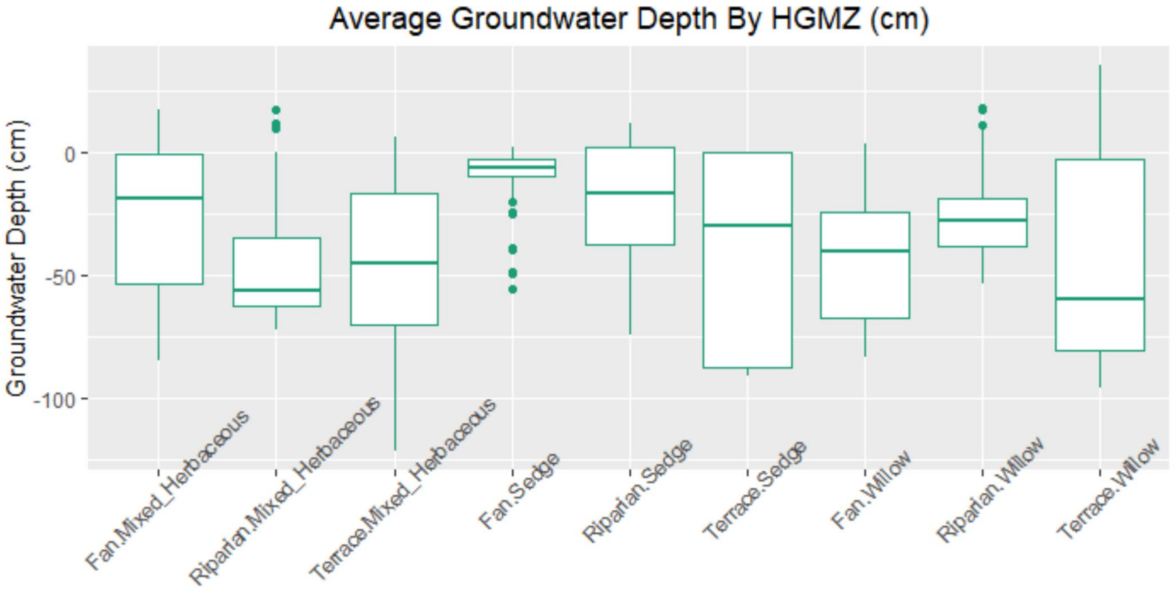

Figure 6. Average Groundwater Depth By Hydrological Process Zone and Plant Functional Type. This boxplot shows the spread and average groundwater level in the Kiln and East meadows of the Sagehen Drainage Basin for all 9 crosses.

A Tukey HSD test with pairwise comparisons of the average groundwater levels across hydrological process zones and plant functional types indicated significant differences in 24 of 36 comparisons since this yielded p-values of < 0.05 (Appendix A2). When comparing the average groundwater levels and factoring in both meadow type (Kiln or East) as well as the year (2018 or 2019), there was no significant difference (p=0.592, Appendix A3). To visualize this data and compare the annual average groundwater levels between the Kiln and East meadows, I generated a boxplot in R (Figure 7).

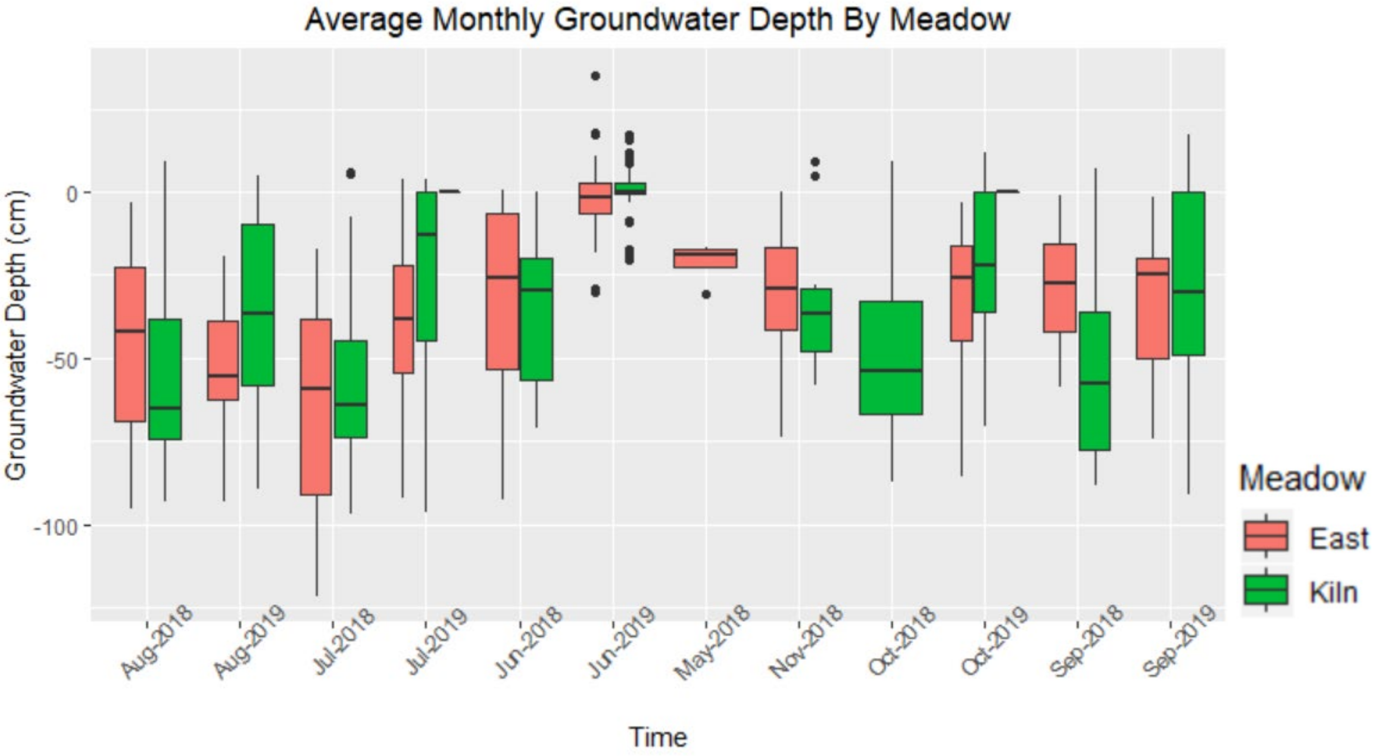

Figure 7. Monthly Groundwater Level by Meadow. A boxplot that depicts the average and spread of groundwater levels from May 2018 to September 2019.

DISCUSSION

The overall goal of this entire study was to understand the hydrology of the Sagehen Drainage Basin. To do that, I used QGIS to look into possible geographic variables that controlled water availability and hypothesized that elevation differs amongst my meadows and resulted in differing groundwater levels. I analyzed my groundwater dataset to determine if there was a relationship between the hydrogeomorphology of Sagehen and the groundwater levels. To assess that, I looked at the intersection of hydrological process zones and plant functional types to compare the groundwater levels of these 9 different combinations, or “crosses.”

Based on my qGIS data, I saw that it was correct to hypothesize that the meadows were situated on an elevation gradient from west to east with the Upper meadow having the highest minimum elevation followed by Kiln, East, and Lower. While all four meadows were generally located on an elevation gradient, Kiln actually had a maximum elevation of 2018.11 m and East had a higher elevation of 2038.28 m. This was probably due to the natural peaks and sinks in elevation because overall, East had a lower minimum elevation (1913.31m) than Kiln (1968.56) that contributed to its greater drainage area of 31,1390,67.391m^2 as opposed to Kiln's 19,280,031.804 m^2.

Given this information, I wanted to see if the differences in the meadows, which I primarily characterized by drainage area and its corresponding elevation, affected groundwater levels. I also wanted to study the interaction between the hydrological process zone and plant functional type crosses on groundwater avaliability. My groundwater data analysis in R determined that there was a significant difference in mean groundwater levels ($p< 2e-16$) based on hydrogeomorphic zone and plant functional type parameters but not so when making a comparison across the two meadows ($p=0.611$). From these one-way ANOVA tests, I concluded that hydrological process zones and plant functional types are better determinants of predicting groundwater availability, and thus, regions of microrefugia, than simply studying meadows in the context of their geographic features like elevation and drainage area.

Possible sources of error include the error in our instrumentation. The groundwater field data was collected over a span of approximately 2 years. Since equipment wore down due to its temperature sensitivity, we went through a total of 4 different sensors between May 2018 to October 2019. Functionally, these sensors all performed the same action it lit up upon making contact with water, but we still needed to normalize our data. One member of my lab, Laura Murtagh, calculated the difference in each sensor's offset, or placement, on the meter stick. This was noted down in the field by Jennifer Natali and factored into the groundwater reading levels used in my data analyses (Appendix B1).

In the future, I hope to analyze the groundwater level data for the Lower meadow, the last meadow in this study that has groundwater wells. Once the COVID-19 shelter-in-place restrictions are lifted, Jennifer Natali will revisit Sagehen to measure the height of the groundwater wells in order to calculate the rest of the groundwater depths for the lower meadow (we currently only have the measurement of the total distance from the top of the well to the water level below the ground).

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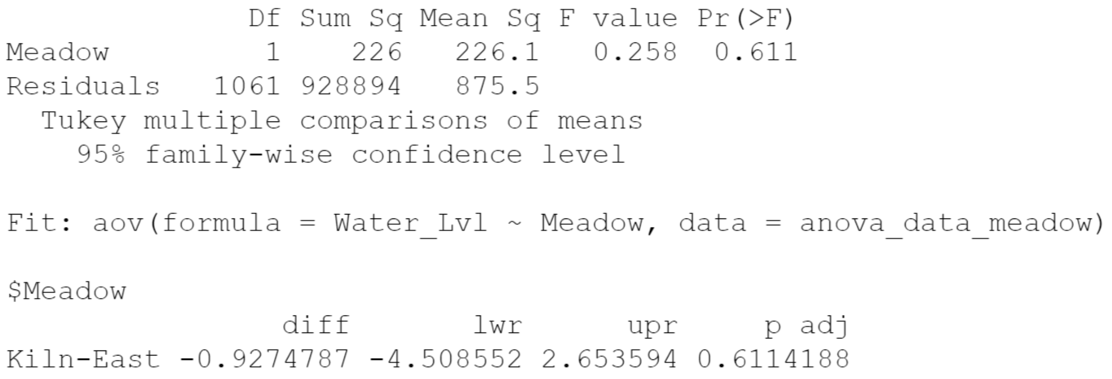
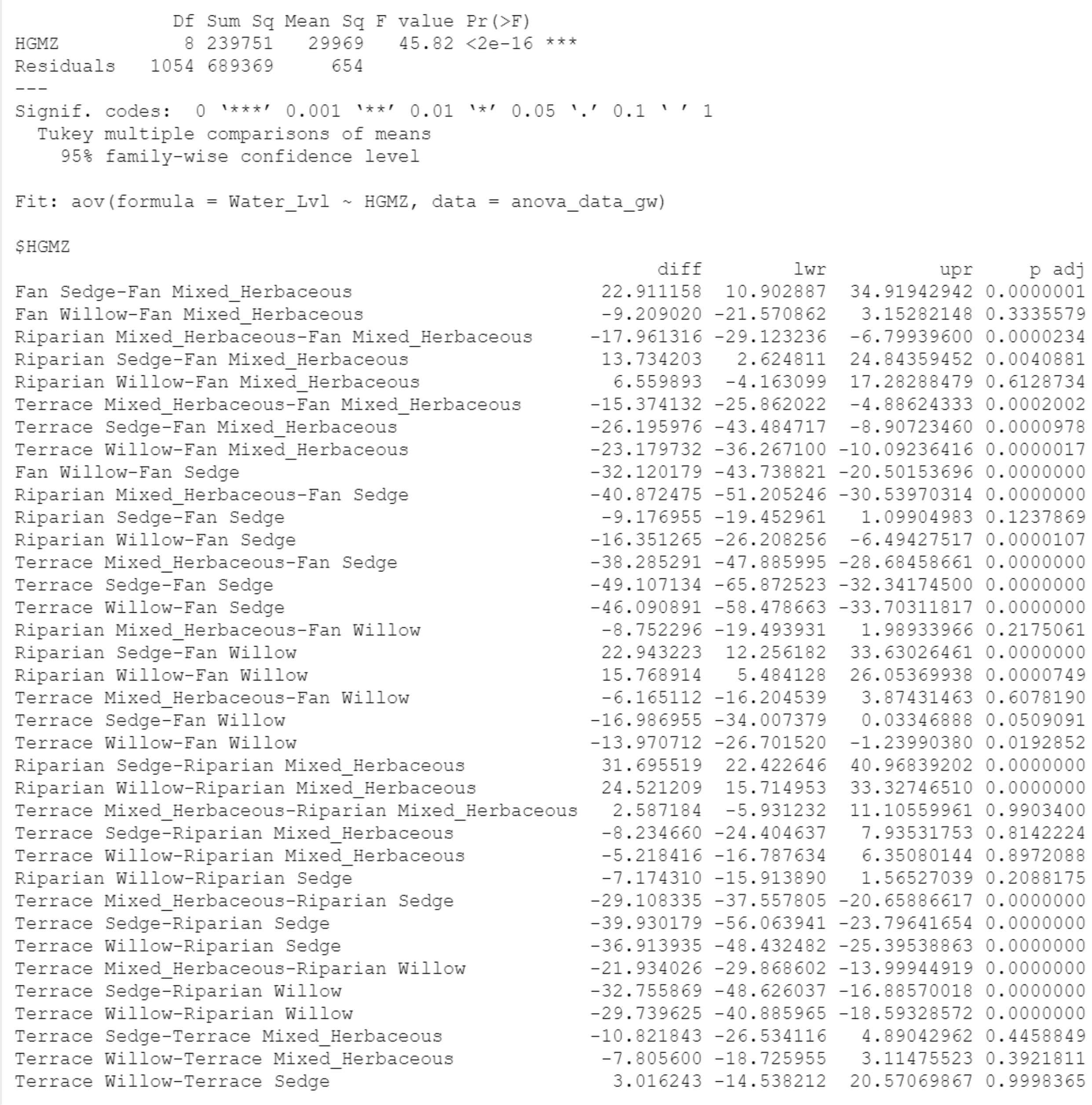
APPENDIX A: One and two-way ANOVA tests



```
              Df Sum Sq Mean Sq F value Pr(>F)
Meadow         1    226   226.1   0.258  0.611
Residuals   1061 928894   875.5
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Water_Lvl ~ Meadow, data = anova_data_meadow)

$Meadow
                diff       lwr      upr     p adj
Kiln-East -0.9274787 -4.508552 2.653594 0.6114188
```

Appendix A1. One-way ANOVA test + Tukey HSD (meadows). This is a test of statistical significance for average groundwater levels across the Kiln and East meadows.



```
             Df Sum Sq Mean Sq F value Pr(>F)    
HGMZ          8 239751   29969   45.82 <2e-16 ***
Residuals  1054 689369     654                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Water_Lvl ~ HGMZ, data = anova_data_gw)

$HGMZ
                                                         diff        lwr          upr     p adj
Fan Sedge-Fan Mixed_Herbaceous                      22.911158  10.902887  34.91942942 0.0000001
Fan Willow-Fan Mixed_Herbaceous                     -9.209020 -21.570862   3.15282148 0.3335579
Riparian Mixed_Herbaceous-Fan Mixed_Herbaceous     -17.961316 -29.123236  -6.79939600 0.0000234
Riparian Sedge-Fan Mixed_Herbaceous                 13.734203   2.624811  24.84359452 0.0040881
Riparian Willow-Fan Mixed_Herbaceous                 6.559893  -4.163099  17.28288479 0.6128734
Terrace Mixed_Herbaceous-Fan Mixed_Herbaceous      -15.374132 -25.862022  -4.88624333 0.0002002
Terrace Sedge-Fan Mixed_Herbaceous                 -26.195976 -43.484717  -8.90723460 0.0000978
Terrace Willow-Fan Mixed_Herbaceous                -23.179732 -36.267100 -10.09236416 0.0000017
Fan Willow-Fan Sedge                               -32.120179 -43.738821 -20.50153696 0.0000000
Riparian Mixed_Herbaceous-Fan Sedge                -40.872475 -51.205246 -30.53970314 0.0000000
Riparian Sedge-Fan Sedge                            -9.176955 -19.452961   1.09904983 0.1237869
Riparian Willow-Fan Sedge                          -16.351265 -26.208256  -6.49427517 0.0000107
Terrace Mixed_Herbaceous-Fan Sedge                 -38.285291 -47.885995 -28.68458661 0.0000000
Terrace Sedge-Fan Sedge                            -49.107134 -65.872523 -32.34174500 0.0000000
Terrace Willow-Fan Sedge                           -46.090891 -58.478663 -33.70311817 0.0000000
Riparian Mixed_Herbaceous-Fan Willow                -8.752296 -19.493931   1.98933966 0.2175061
Riparian Sedge-Fan Willow                           22.943223  12.256182  33.63026461 0.0000000
Riparian Willow-Fan Willow                          15.768914   5.484128  26.05369938 0.0000749
Terrace Mixed_Herbaceous-Fan Willow                 -6.165112 -16.204539   3.87431463 0.6078190
Terrace Sedge-Fan Willow                           -16.986955 -34.007379   0.03346888 0.0509091
Terrace Willow-Fan Willow                          -13.970712 -26.701520  -1.23990380 0.0192852
Riparian Sedge-Riparian Mixed_Herbaceous            31.695519  22.422646  40.96839202 0.0000000
Riparian Willow-Riparian Mixed_Herbaceous           24.521209  15.714953  33.32746510 0.0000000
Terrace Mixed_Herbaceous-Riparian Mixed_Herbaceous   2.587184  -5.931232  11.10559961 0.9903400
Terrace Sedge-Riparian Mixed_Herbaceous             -8.234660 -24.404637   7.93531753 0.8142224
Terrace Willow-Riparian Mixed_Herbaceous            -5.218416 -16.787634   6.35080144 0.8972088
Riparian Willow-Riparian Sedge                      -7.174310 -15.913890   1.56527039 0.2088175
Terrace Mixed_Herbaceous-Riparian Sedge            -29.108335 -37.557805 -20.65886617 0.0000000
Terrace Sedge-Riparian Sedge                       -39.930179 -56.063941 -23.79641654 0.0000000
Terrace Willow-Riparian Sedge                      -36.913935 -48.432482 -25.39538863 0.0000000
Terrace Mixed_Herbaceous-Riparian Willow           -21.934026 -29.868602 -13.99944919 0.0000000
Terrace Sedge-Riparian Willow                      -32.755869 -48.626037 -16.88570018 0.0000000
Terrace Willow-Riparian Willow                     -29.739625 -40.885965 -18.59328572 0.0000000
Terrace Sedge-Terrace Mixed_Herbaceous             -10.821843 -26.534116   4.89042962 0.4458849
Terrace Willow-Terrace Mixed_Herbaceous             -7.805600 -18.725955   3.11475523 0.3921811
Terrace Willow-Terrace Sedge                         3.016243 -14.538212  20.57069867 0.9998365
```

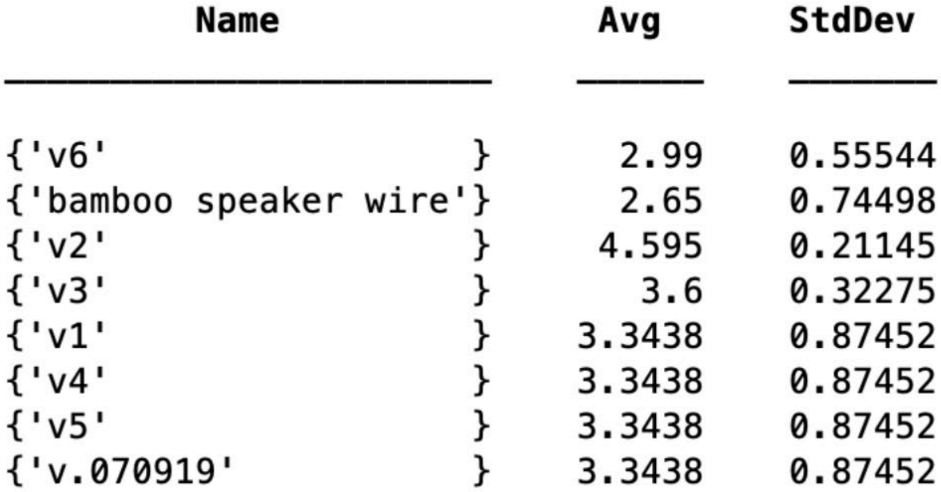
Appendix A2. One-way ANOVA test + Tukey HSD (hydrological process zones/plant functional types). This is a test of statistical significance for the average groundwater levels between each of the 9 hydrological process zone and plant functional type crosses in both Kiln and East meadows.

```
              Df Sum Sq Mean Sq F value Pr(>F)
Meadow         1    226     226   0.287  0.592
Year           1  94488   94488 120.034 <2e-16 ***
Residuals   1060 834406     787
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Water_Lvl ~ Meadow + Year, data = anova_data_twanova)

$Meadow
                diff       lwr     upr     p adj
Kiln-East -0.9274787 -4.323138 2.46818 0.5921056

$Year
              diff      lwr      upr p adj
2019-2018 18.85665 15.47902 22.23429     0
```

Appendix A3. Two-way ANOVA test + Tukey HSD (meadow and year). This is a test of statistical significance for the average groundwater levels based on two factors, meadow and year.

APPENDIX B: Instrumentation data

Appendix B1. Groundwater meter offset data table. This is a table of the offset values used to normalize the groundwater level column in my groundwater dataset across the 8 different groundwater sensors we used in the field.



```
         Name                  Avg     StdDev
_____________________________  ______  _______

{'v6'                    }       2.99  0.55544
{'bamboo speaker wire'}          2.65  0.74498
{'v2'                    }      4.595  0.21145
{'v3'                    }        3.6  0.32275
{'v1'                    }     3.3438  0.87452
{'v4'                    }     3.3438  0.87452
{'v5'                    }     3.3438  0.87452
{'v.070919'              }     3.3438  0.87452
```