Soil and water quality: an assessment of New Mexico meadow jumping mouse habitat

Robert B. Prather Jr.

Directorate Fellows Program, US Fish & Wildlife

August 5, 2022

Abstract

The New Mexico meadow jumping mouse (*Zapus hudsonius luteus;* hereafter jumping mouse) is a critically endangered habitat specialist that lives in isolated populations within New Mexico, eastern Arizona, and southern Colorado. Despite extensive management, many known populations are thought to be extirpated and all extant populations exist within patches of suitable habitat that are too small to support resilient and robust jumping mouse populations. Currently, Bosque del Apache National Wildlife Refuge hosts the only known remaining Rio Grande River Valley jumping mouse population. To further enhance management of this population, I assessed soil and water quality across the refuge and within jumping mouse habitat. I measured soil moisture hourly using 15-20 probes located within jumping mouse habitat within one unit, 18A4, during the jumping mouse's active season during 2020 through 2022. The findings reveal that the water control structures and management actions maintained saturated soils at levels needed to sustain jumping mouse habitat. Soil electrical conductivity (EC) across all the jumping mouse managed habitat was variable, with 85.6% of readings falling within optimal levels (between 0.15 and 1.25 mS/cm). Desired jumping mouse plant species were rarely found at high (EC >2 mS/cm) soil salinity levels. A cumulative link mixed model revealed a significant relationship between soil EC and plant community suitability ($p < 0.0001$). Before and after sampling of soil EC in units treated by flooding revealed a significant reduction ($p < 0.0001$) in soil EC following treatment. However, these flooding events were not conducted in jumping mouse managed habitat. I also found significant variation in water quality parameters across refuge water sources. Specific conductance values of water from the Riverside and Socorro canals were in the permissible range for plant health and growth (means between 0.84 and 0.90 mS/cm), however, they were slightly above the optimal range for irrigation water (below 0.75 mS/cm). The specific conductance of groundwater sources was extremely variable, ranging from extremely poor for plant health and growth (2.05 mS/cm, well 2) to good (0.61 mS/cm, well 7). Dissolved oxygen and pH of all refuge water sources were within acceptable ranges. Further assessment and monitoring of soil salinity (via electrical conductance) is recommended to determine where soil salinity exceeds acceptable values for desired jumping mouse plant species and to help evaluate the effectiveness of management actions such as flooding to reduce soil salinity to acceptable levels.

Introduction

The New Mexico meadow jumping mouse (*Zapus hudsonius luteus*, hereafter NMMJM or jumping mouse) is a rare subspecies of the meadow jumping mouse (*Zapus hudsonius*) that occurs in small and isolated populations across eastern Arizona, southern Colorado, and central and northern New Mexico (Harris 1963, Morrison 1990, USFWS 2020). Between 2005 and 2104, only 29 populations were documented and approximately 70 historic populations were thought to be extirpated (USFWS 2014). Of the 29 extant populations, over half were substantially compromised due to water shortages, grazing, wildfires, and postfire floods (Frey and Malaney 2009, USFWS 2014). The NMMJM was listed as an endangered species in 2014 because of the past declines and status of the extant populations (USFWS 2014). Since 2014, 39 new populations have been documented because of more expansive surveying efforts (USFWS

2020). Despite this, nearly all the extant populations exist in patches of habitat that are extremely isolated and currently too small to support robust jumping mouse populations (USFWS 2020). Informed and extensive management of extant populations is necessary to prevent the extinction of this species.

The NMMJM is a habitat specialist that relies heavily upon a diverse and thriving herbaceous riparian plant community (Morrison 1990, Frey and Malaney 2009). The best indicators of high-quality jumping mouse habitat include tall, dense riparian herbaceous vegetation, saturated soils, and proximity to flowing water (Morrison 1990, USFWS 2020, Lehnen et al. 2021). In addition to the strict habitat requirements, the NMMJM also has a uniquely challenging life history. This species hibernates for approximately 8-9 months, and as such, it only has 3-4 months to mate, gestate, raise young, and store sufficient fat reserves for the following hibernation period (Morrison 1990). This short active period makes access to abundant food resources vital for survival and the maintenance of positive population growth rates.

Almost all extant NMMJM populations are found in montane riparian habitats, however, one population still exists within the Middle Rio Grande River Valley (USFWS 2020, Lehnen et. al. 2021). This remaining population is found at Bosque del Apache National Wildlife Refuge along 2 km (1.2 miles) of the Riverside canal. This population is unique in the fact that it exists alongside canals and managed moist soil units rather than natural creeks or streams. Furthermore, this habitat lacks the sedge species (*Carex* spp.) which are often associated with jumping mouse habitat in the montane locations; instead, New Mexico jumping mouse habitat at Bosque del Apache NWR is dominated by many plants species that are uncommon or absent from the montane locations (Frey and Wright 2012, USFWS 2014). This population was still present at Bosque del Apache NWR as of 2022 and was the 6th largest population (by estimated habitat size) across the entirety of the species range when the initial species status assessment was published (USFWS 2014, B. Baker unpublished observation 2022). Estimates of the total area of suitable habitat from 2014 through 2020 show an increasing trend towards more suitable habitat, however, all years still fall below the minimum recommended size outlined by the 2020 Species Status Assessment (Figure 1, USFWS 2014, Lehnen et. al. 2021). An especially rainy year, 2019, came within an acre of meeting the minimum recommended size, however, years such as 2019 are infrequent and may become scarcer under the effects of climate change.

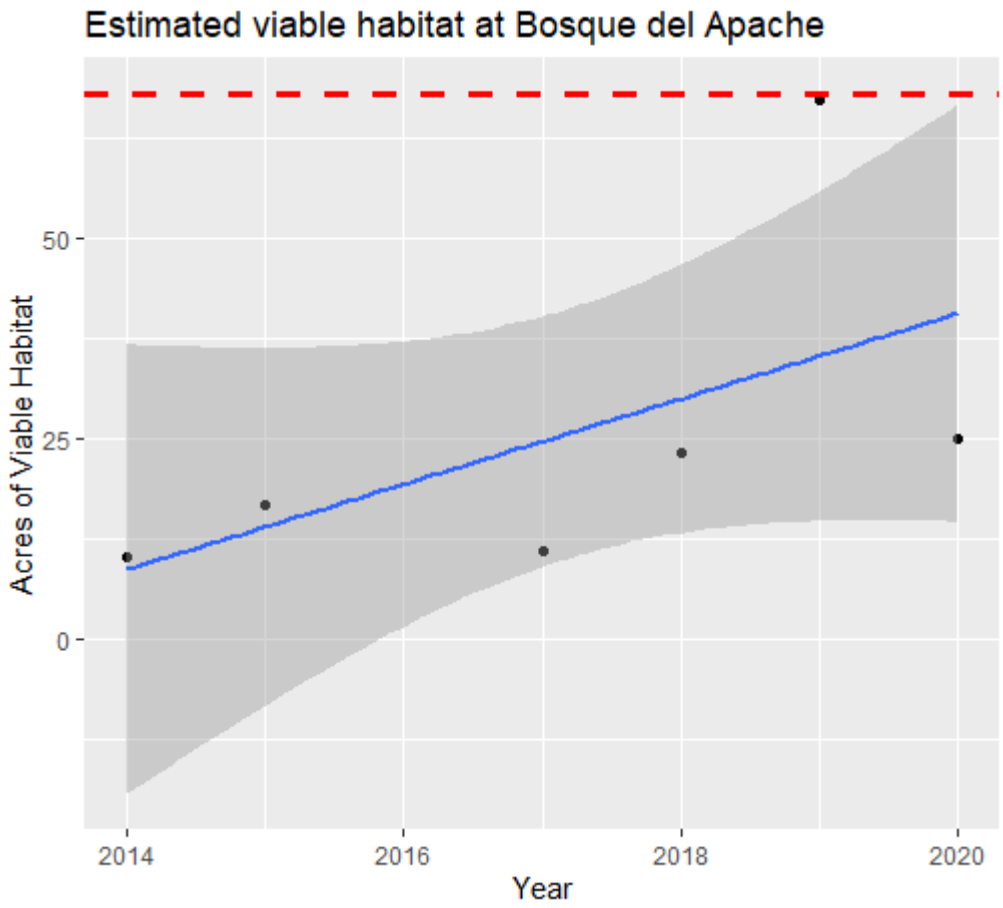


Figure 1. Estimated viable habitat at Bosque Del Apache NWR from 2014 to 2020. The 2014 estimate is from the 2014 USFWS Species Status Assessment, the 2015 and 2017 estimates are from Species Distribution Models, and 2018-2020 estimates were produced with habitat mapping that combined vegetation surveys and remote sensing. The shaded gray region represents the standard error and the horizontal red line represents the minimum size needed to satisfy the 2014 USFWS Species Status Assessment recommendations.

The positive trend observed in Figure 1 is likely due to management, restoration activities, and an especially rainy year in 2019, however, the trend would remain positive if the 2019 data was removed entirely. Bosque del Apache NWR Staff have steadily increased their focus on habitat creation in areas adjacent to suitable mouse habitat. Ongoing management procedures include installation of water control structures and an additional Langemann gate, mechanical and chemical removal of undesirable species, and rotational disturbance regimes. Despite these measures, a more extensive knowledge of the ecology of this unique system and increasingly sophisticated management protocols will be required to meet the minimum recommended habitat size, especially under decreasing water resources and increasing effects of climate change.

Water resources in the Middle Rio Grande Valley are diminishing, thus, effective water management will be critical to the ongoing rehabilitation and management of the jumping mouse habitat (Samimi et al. 2022). To further enhance management of NMMJM habitat, I aimed to assess the soil and water quality at Bosque del Apache. Saturated, productive soils and water are the most fundamental components of a high-quality jumping mouse habitat as these abiotic

characteristics are needed to create the desired vegetative community; however, limited quantitative assessment of these parameters has occurred outside of soil moisture monitoring. It is especially relevant here given the differences in climate, water resources, management regime, and plant community composition relative to all other extant jumping mouse populations. Here, I aim to assess three primary components: soil moisture, soil quality, and water quality.

Soil moisture is arguably the most important abiotic component associated with high-quality jumping mouse habitat. Constantly saturated soils are required for these plant communities to produce enough resources to support stable and robust jumping mouse populations (USFWS 2014, USFWS 2020).

Soil salinity is an additional factor that might inhibit growth of riparian plant communities. Saline and sodic soils can interfere with root processes like water and nutrient uptake, which slows growth and decreases overall productivity. Extreme salt accumulation might prevent growth entirely. This is because plants rely on a greater salt concentration in their roots relative to the soil to extract water. When salt levels exceed those in the roots, the plants will fail to extract water and will die. An accumulation of salts might also promote the growth of undesirable species which are more resilient to high soil salinity. An example is Kochia (*Bassia scoparia*), which thrives in saline soils and can quickly outcompete other species and form a monoculture. The hydrology of these managed units is significantly different from natural jumping mouse environments, and these differences may facilitate the accumulation of salts and other compounds. In fact, a buildup of salt can be seen in various units at Bosque del Apache, including those which support the jumping mouse (Figure 2). Moreover, the water resources within the Rio Grande valley are decreasing and users may have to adapt to more saline water sources (Samimi et al. 2022). Thus, it is imperative that soil salinity is monitored and managed to further enhance the growth of high-quality jumping mouse habitat. Management activities such as flooding and flushing a unit may have positive impacts on soil quality if soil salinity is beyond the ideal conditions for healthy riparian plant communities. Halophytic plants and chemical treatments are also possible avenues for restoring saline soils (Fipps 2003, Hasanuzzaman et. al. 2014, Saddhe et. al. 2020, Jiaping and Wenjaun 2021). However, these actions might not be feasible or effective within jumping mouse units.

Figure 2. A white crust atop the soil in unit 18A5. This crust is indicative of an excessive salt accumulation. Note that the herbaceous riparian plant community that supports the NMMJM is largely absent from this area. Furthermore, undesirable species such as *Phragmites australis* dominate the areas adjacent to the salt accumulation.

Despite extensive water management at Bosque del Apache, little attention has been given to the quality of the available water resources. Poor water quality can have a plethora of negative effects, such as decreased plant growth and production. Bosque del Apache currently has multiple sources of water for the jumping mouse habitat, including inflow from the Rio Grande via the Riverside canal and multiple groundwater wells. In addition to these sources, future infrastructure between the Socorro and Riverside canals may allow refuge staff to supplement jumping mouse habitat with water from the Socorro canal. Before this study, it was unknown whether water quality among these sources varied or how it fluctuated temporally. Awareness of how water quality varies among these sources will allow refuge staff to choose to supplement jumping mouse habitat with lower salinity water sources. A more thorough knowledge of the quality of refuge water resources will also benefit conservation projects outside the work with the jumping mouse.

Overall, the goals for this assessment are to answer the following questions: (1) How does soil moisture within jumping mouse habitat within one moist soil unit vary at a fine temporal scale across the active period and in response to water availability in the Riverside canal? (2) How

does soil salinity vary across mouse habitats and is it reduced after a flooding treatment? (3) Are water quality parameters within acceptable levels and is there a significant difference among the potential water sources for jumping mouse habitat (Riverside, Socorro, Groundwater)?

The answers to these questions will further enhance the management of the New Mexico meadow jumping mouse at Bosque del Apache National Wildlife Refuge. Upon completion of the assessment, I developed a protocol for refuge staff to further monitor water and soil parameters across jumping mouse habitat.

Materials and Methods

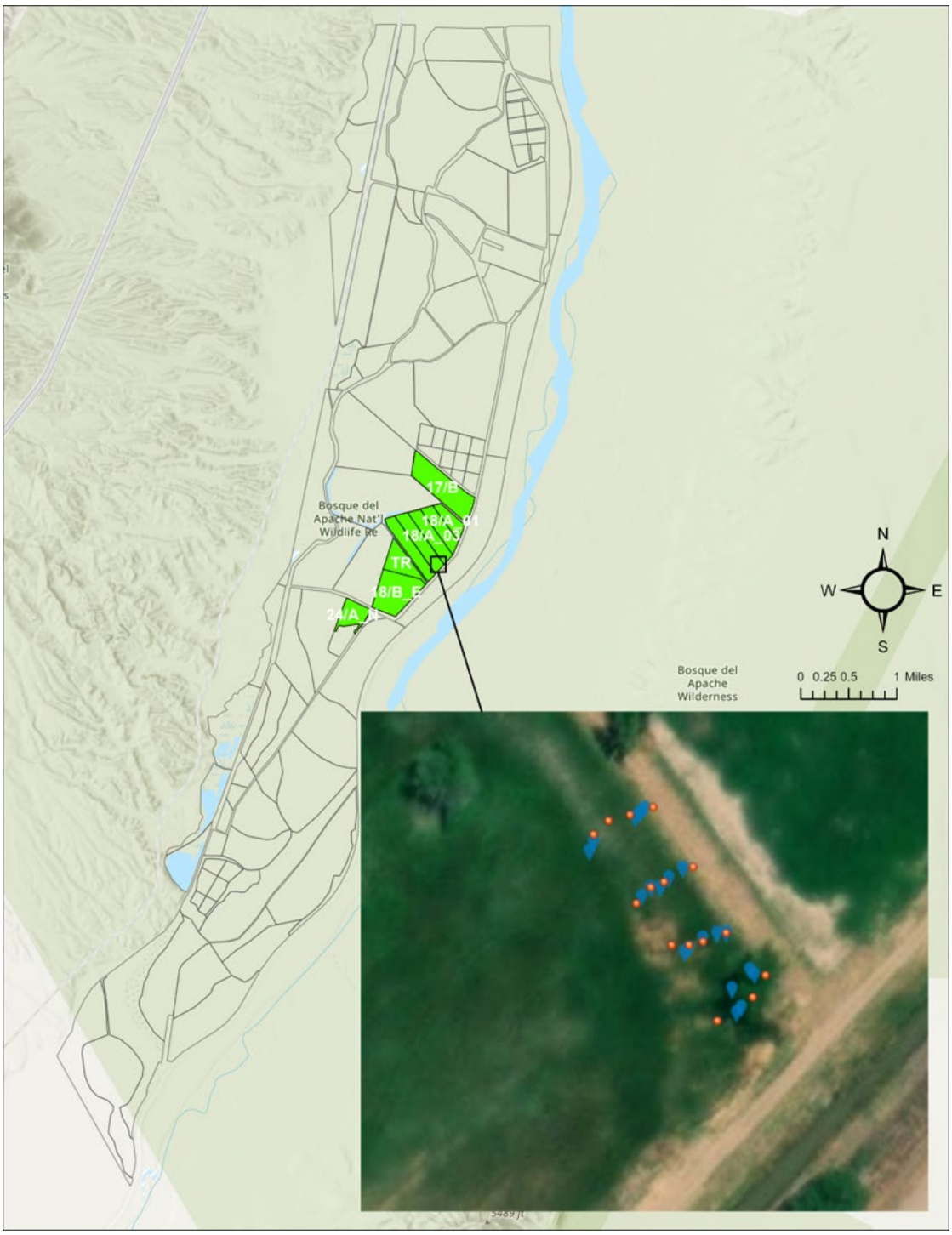
Soil Moisture

Decagon© EM50 data loggers and soil moisture probes were used to assess soil moisture levels across unit 184A. This unit hosts high quality mouse habitat and photo trapping has documented the presence of the NMMJM in this unit across multiple years (Lehnen et. al. 2021). The probes were installed at 4 cm (1.57 inches) deep across transects that were 10, 20, 30, and 40 meters (32.8, 65.6, 98.4, and 131.2 feet) from the inflow of water to the unit (Figure 3). The loggers were set to collect a reading every hour and were installed during the jumping mouse active periods of 2020, 2021, and 2022 (See table 3 for exact dates). One of the loggers malfunctioned in 2021, so the 2022 data collection consists of 15 probe readings rather than the 20 that were recorded during 2020 and 2021. Despite this, I retained adequate coverage of the 4 transects. The loggers were checked several times throughout the season to ensure the probes were properly collecting data.

Variation in soil moisture data might be explained by three sources of available data: water management activities, water availability in the Riverside canal, and precipitation. Water management personnel record their management activities in logbooks. Water levels in the Riverside canal are automatically recorded every 15 minutes in the Langemann adjacent to unit 9 (upstream of the mouse habitat) and readings from the Langemann gates adjacent to mouse units are recorded by management personnel several times per week. Precipitation readings are taken every 24 hours by visitor services personnel. The combination of these sources allows for a thorough assessment of how soil moisture responds to variation in water management activities, water availability, and climatic events.

For the analysis, I deemed volumetric water content (VWC) readings of 50% or greater to be fully saturated soils and ideal for full plant growth potential. I considered 38.3% to be the minimum for needed to sustain high-quality jumping mouse habitat (Lehnen et. al. 2021). Sometimes probes may malfunction or produce erroneous readings. This can be a result of wildlife landing on and slightly dislodging the probe cables or through processes such as corrosion and device fatigue. The data were cleaned, and obvious erroneous readings were removed by comparing the maximum VWC and relative change in VWC between faulty probes and consistent probes. Finally, I assumed the jumping mouse active period was from 1 June through the 15th of October and only used readings from this period for the analysis.

Figure 3. Soil moisture probe locations for the 2021 (blue points) and 2022 season (red points) within unit 18A4.



Soil Salinity

Sampling was performed by surveying points along transects that extend through available jumping mouse habitat. A Hanna Instruments© Soil Conductivity meter was used to assess soil electrical conductivity (EC) across jumping mouse habitats. Measuring soil electrical

conductivity is one of the most common and efficient ways of assessing soil salinity. The soil EC probe was calibrated before sampling with a 1413 µS/cm conductivity standard. I utilized a 2:1 ratio of distilled water to soil to produce soil slurries from which samples were taken. When sampling the soil, any live, dead, or decaying plant matter was pushed aside, and samples were taken approximately two inches below the surface of the soil. I used a 5mL scoop to take the soil samples. After, I tamped down the soil in the scoop until it was level with the measurement line and added them to a glass test tube with 2 scoops of distilled water. The test tube was shaken vigorously until it was fully mixed, and then the sample was allowed to settle for approximately 15 minutes, as recommended by Hanna Instruments. After the sample had settled, the probe was inserted, and a reading was taken once the device indicated the reading was stable.

At each sampling point I recorded the overall suitability (scale of 1 to 5) of the plant community to support the jumping mouse. The procedure to estimate plant community suitability for jumping mice involved estimating the relative abundance of high-, medium-, and low-quality jumping mouse habitat plant species, and then ranking the sampling point based on the relative abundance of different plant species (5=High quality, 1=Poor quality, see Lehnen et. al. 2021). I also recorded which plant species were present at each sampling point.

I also assessed soil EC in units that were treated for cocklebur (*Xanthium* spp.). Treatment of cocklebur involves flooding a unit for several days until the cocklebur dies. This procedure may reduce soil salinity by pushing salts down below the root zone. I sampled 20 points per unit pre- and post-flooding, once all the water had drained or evaporated off the surface of the soil.

Guidelines from the University of Georgia's Agricultural and Environmental Soil Testing Laboratory were adopted for interpreting EC data from 2:1 soil slurry extract (Table 1, Sonon et. al. 2012). Readings in the low or medium categories (0.16 to 1.25 mS/cm) were considered optimal for maximum plant growth and productivity.

A CLMM (Cumulative Link Mixed Model, 'clmm2' function from 'ordinal' package, version 2019.12.10, Christensen 2019) was used to investigate whether variation in plant community suitability is explained by soil EC. I included unit as a random effect and fit the model with the Laplace approximation. I compared models fit with a linear and quadratic relationships based on AIC criterion, with decreases of more than 2 AIC points confirming a better model fit. GLMM's (Generalized Linear Mixed Models, 'glmer' function from lme4 package, version 1.1.27.1, Bates et. al. 2015) were used to assess whether soil EC explained variation in plant species presence/absence. Unit was included as a random effect and a logit link function was used for the binomial response (species presence or absence). For both mixed models, the presence of sizable variation confirmed that it was appropriate to include the random effect. A one-way analysis of variance (ANOVA) was used to assess the differences amongst pre- and post-flooding EC soil levels. Estimated Bayesian Kriging was used to produce a map of soil EC across the mouse habitats. Statistical analyses were performed in R (Version 4.2.1, R Core Team 2022) and maps were created in ArcGIS Pro (Version 2.9.2, ArcGIS Pro 2021).

Table 1. Electrical conductance interpretation guide for a 2:1 water to soil method. Adopted from the University of Georgia (Sonon et. al. 2012).

Electrical conductivity (mS/cm)	Rating	Interpretation
0 - 0.15	Very low	Plants may be starved of nutrients.
0.16 - 0.50	Low	Poor if soil lacks organic matter. Satisfactory if soil is high in organic matter.
0.51 - 1.25	Medium	Okay range for established plants.
1.26 - 1.75	High	Okay for most established plants. Too high for seedlings or cuttings.
1.76 - 2.00	Very high	Plants usually stunted or chlorotic.
> 2.00	Excessively high	Plants severely dwarfed; seedlings and rooted cuttings frequently killed.

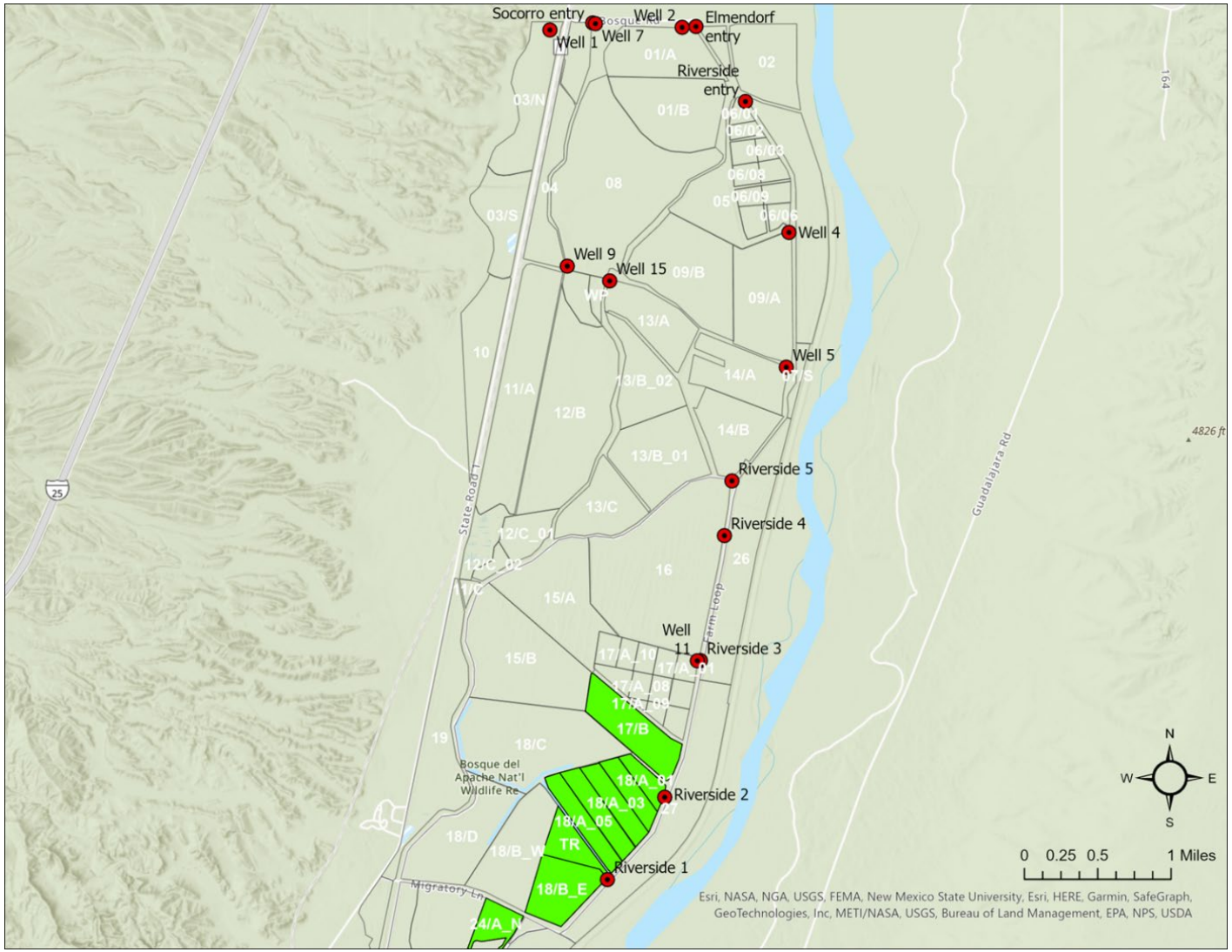
Water quality

A YSI Pro2030 handheld multiparameter meter was used to assess dissolved oxygen, conductivity, and salinity levels of different water sources. An additional YSI professional plus was used to assess pH, however, these readings were only taken once. Each device was calibrated prior to each sampling event with a 1413 µS/cm conductivity standard and appropriate pH calibration solutions. Dissolved oxygen sensors were calibrated prior to each sampling event and the membranes were replaced every 2-3 weeks. I followed all other maintenance and sampling protocol specified by YSI.

I sampled the Riverside, Socorro, and Elmendorf canals at their entrance to the refuge, the Riverside canal between each Langemann gate leading up to the mouse units, and the Riverside and Socorro/Interior before and after they have merged and are exiting the refuge (Figure 4). I also sampled each active groundwater well on the refuge (Figure 4). Sampling of every refuge water resource occurred at least once, sampling of mouse-specific groundwater sources (wells 2, 4, 5, & 11) occurred at least three times, and sampling of water within the Riverside and Socorro canals took place at least once a week for 8 weeks.

Langemann gates, culverts, catwalks, and other structures allowed for adequate and thorough sampling across the water column within the canals. For groundwater sampling, the column water volume was purged a minimum of three times from each well prior to collecting readings (USGS 2006). A summary of the well information and calculations used to estimate purge volume/time is available below (Supplementary table 1).

Figure 4. Water sampling locations across the Bosque del Apache National Wildlife Refuge. Riverside 1 & 2 correspond with points directly adjacent to jumping mouse habitats. Riverside 3 – 5 are points between water control structures leading up to the mouse habitats. Wells 11, 5, and 4 are the nearest wells that could be used to supplement jumping mouse habitat with water. The Riverside, Socorro, and Elmendorf entry locations are the locations near to where these canals first enter the refuge. The bright green regions are jumping mouse units. Well 22 is not visible on this map.



The pH data was compared to data collected from directly upstream of the refuge in both irrigation canals and the Rio Grande (from San Acacia Diversion Dam to San Antonio, Rehder 2013) and other data from more widespread sampling of the middle Rio Grande (Bland et. al. 2005, BEMP Data 2009). These sources indicate that water resources from the middle Rio Grande are typically alkaline, and most pH readings range from about 7.7 to 8.6. Dissolved oxygen levels for irrigation water are considered healthy if they are above 5mg/L (Horiba 2019). Finally, I adopted the permissible limits for specific conductance from Texas A&M (Fipps 2017, Table 2).

A one-way ANOVA was used to assess whether there were statistically significant differences amongst possible sources of water for the jumping mouse units. The sampling locations along the riverside and adjacent to the mouse units were lumped into one single group because of their proximity and nearly identical values. After, I applied a post-hoc pairwise multiple comparison to identify which specific groups were different. The post-hoc pairwise comparison was performed with t-tests and pooled standard deviations, and the Bonferroni adjustment method was used because of differences in sample size amongst groups. Both analyses were performed in R.

Table 2. Electrical conductivity interpretation guide for irrigation water. Adopted from Texas A&M AgriLife Extension, Fipps 2017.

Electrical conductivity (mS/cm)	Rating
0 - 0.250	Excellent
0.251 - .750	Good
0.751 - 2.00	Permissible
2.01 - 3.00	Poor / Doubtful
> 3.00	Unsuitable

Results

Soil Moisture

The 2020 data shows that the soils across all four transects were saturated for the duration of the sampling, with 93.1% of probe readings surpassing the 50% threshold (Table 3, Figure 5). Furthermore, 100% of readings during the active period surpassed the 38.3% minimum threshold. There were no precipitation events or significant management activities which would have influenced these moisture readings. The waters levels in the Riverside canal were relatively

consistent across this period and averaged at 2.83 feet (0.86 meters), while flow averaged at 32.69 cfs.

Table 3. Summary of soil moisture monitoring from 2020 through 2022. I deemed volumetric water content (VWC) readings of 50% or greater to be fully saturated soils and ideal for full growth potential. I considered 38.3% to be the minimum for continued survival of high-quality jumping mouse habitat (Lehnen et. al. 2021).

Year	Transect	Monitoring dates	Readings > 38.3% VWC	Readings > 50% VWC
2020	10m	9/24 - 10/15	2242 / 2242 **(100%)**	2223 / 2242 **(99.6%)**
	20m	9/24 - 10/15	2482 / 2482 **(100%)**	1858 / 2482 **(74.9%)**
	30m	9/24 - 10/15	2484 / 2484 **(100%)**	2484 / 2484 **(100%)**
	40m	9/24 - 10/15	2505 / 2505 **(100%)**	2476 / 2476 **(98.8%)**
	SEASON TOTAL		9713 / 9713 **(100%)**	9041 / 9713 **(93.1%)**
2021	10m	7/12 - 7/20	721 / 721 **(91.4%)**	659 / 721 **(91.4%)**
	20m	7/27 - 10/15	9080 / 9659 **(94.0%)**	7023 / 9659 **(72.7%)**
	30m	7/27 - 10/10	6357 / 6791 **(93.6%)**	5902 / 6791 **(86.9%)**
	40m	7/27 - 10/15	8632 / 8990 **(96.0%)**	7378 / 8990 **(82.1%)**
	SEASON TOTAL		24790 / 26161 **(94.8%)**	20,962 / 26161 **(80.1%)**
2022	10m	6/9 - 7/29	2319 / 2319 **(100%)**	2319 / 2319 **(100%)**
	20m	6/9 - 7/29	2871 / 2871 **(100%)**	2871 / 2871 **(100%)**
	30m	6/9 - 7/29	4602 / 4602 **(100%)**	4602 / 4602 **(100%)**
	40m	6/9 - 7/29	3553 / 3553 **(100%)**	3553 / 3553 **(100%)**
	SEASON TOTAL		13346 / 13346 **(100%)**	13346 / 13346 **(100%)**

The 2021 data reveals that the soils across all four transects were saturated for the duration of the sampling, with 80.1% of probe readings surpassing the 50% threshold (Table 3, Figure 6). Furthermore, 94.8% of readings during the active period surpassed the 38.3% minimum threshold. The waters levels in the Riverside canal varied slightly across this period and averaged at 3.84 feet (1.17 meters), while flow averaged at 40.80 cfs.

The 2022 data shows that the soils across all four transects remained saturated for the entirety of the sampling period, with 100% of probe readings surpassing the both the 38.3% and 50% thresholds (Table 3, Figure 7). The water levels in the Riverside canal varied slightly across this period and averaged at 3.31 feet, while flow averaged at 44.37 cfs.

Figure 5. Soil moisture across unit 18A4 and water availability in the Riverside canal for a portion of the Fall 2020 season. The panels are specific to each transect.

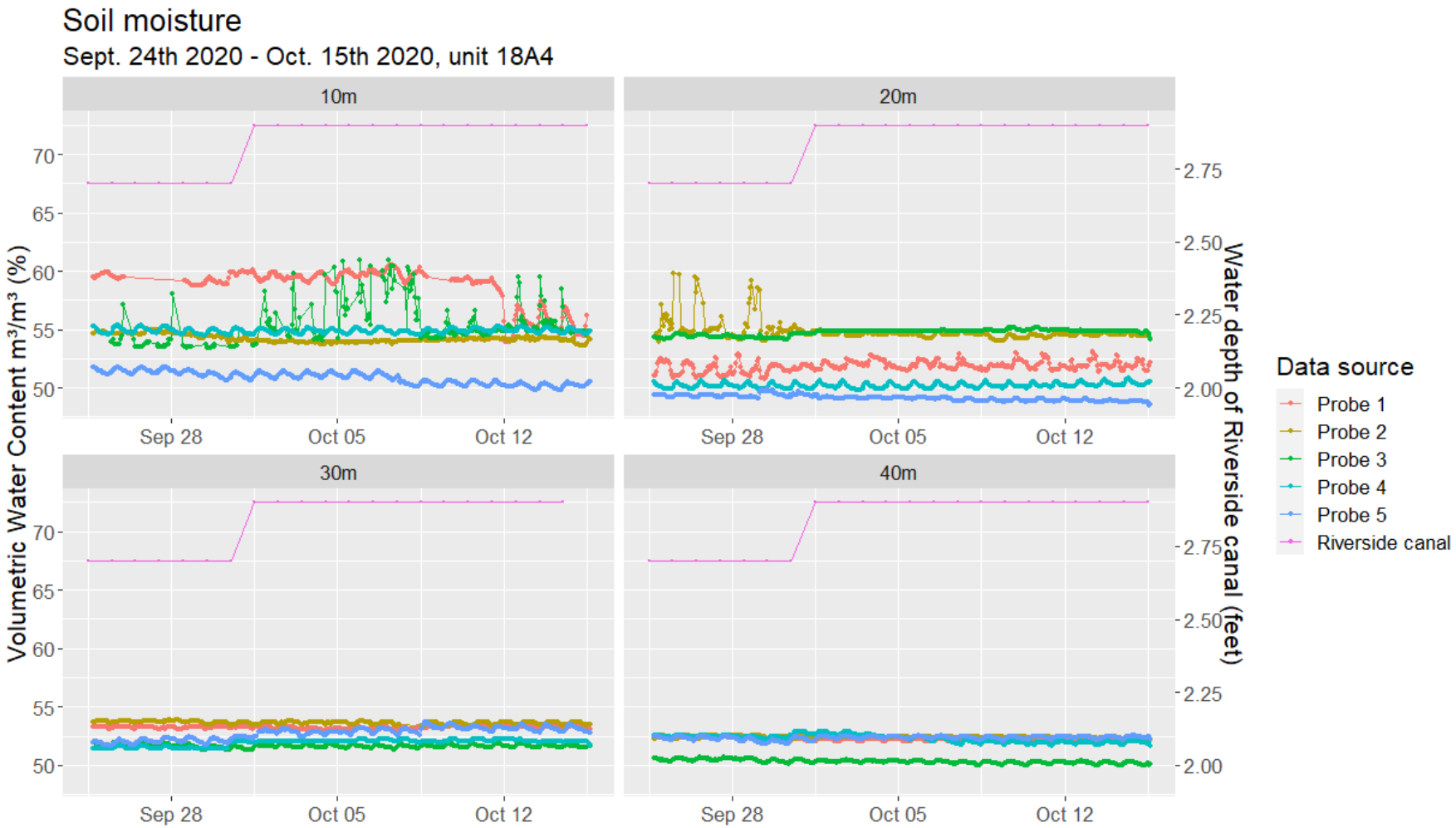
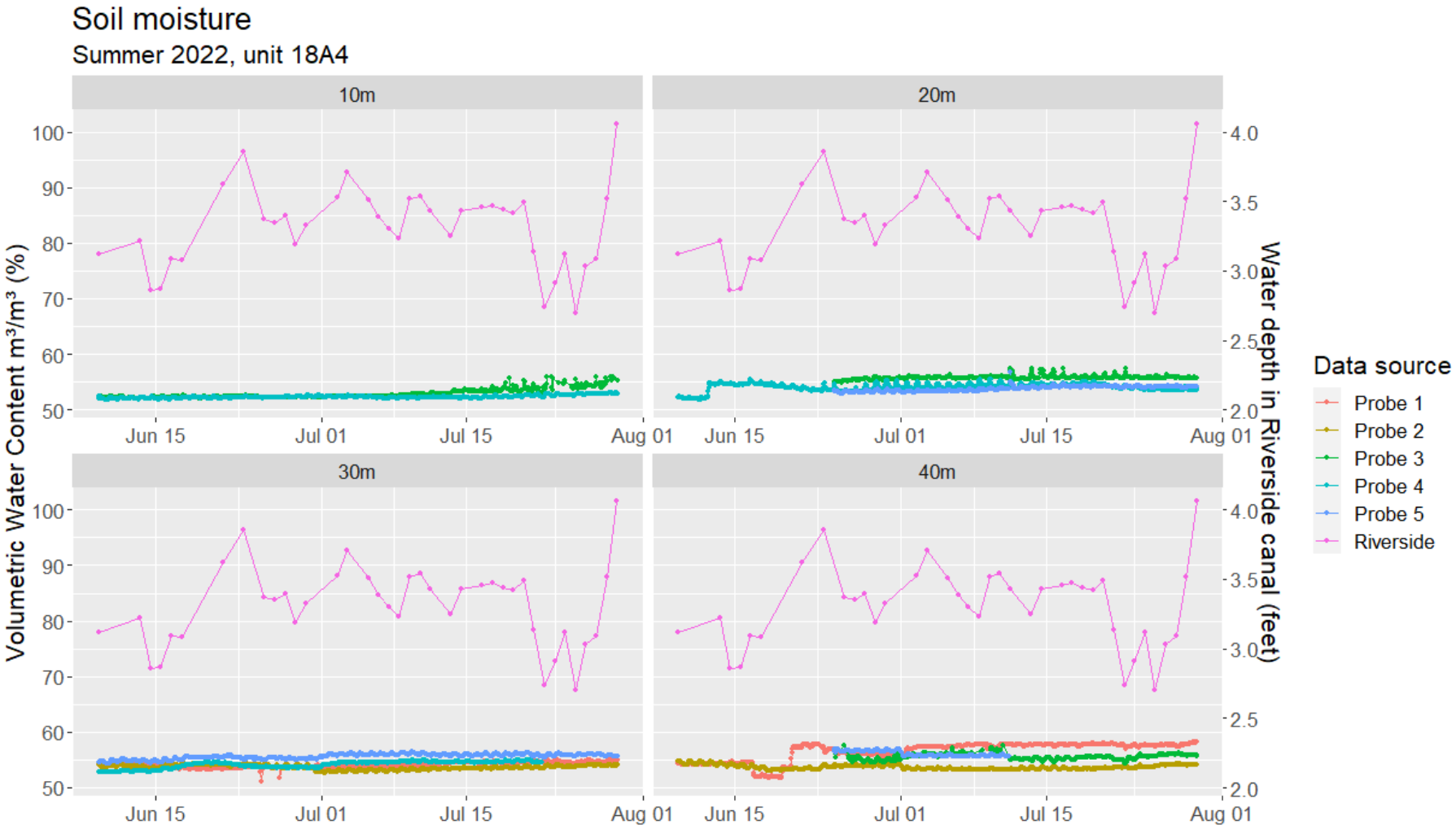


Figure 6. Soil moisture across unit 18A4 and water availability in the Riverside canal for Fall 2021. The panels are specific to each transect.

Figure 7. Soil moisture across unit 18A4 and water availability in the Riverside canal for Summer 2022. The panels are specific to each transect.



Soil Salinity

The soil electrical conductance survey resulted in 360 readings across the entirety of the jumping mouse habitat. Of these 360 readings, 52 (14.44%) were above the optimal range (Figure 8). No readings fell below the minimum threshold. Furthermore, I only detected a single point in which the plant community suitability ranked 4 or 5 and the soil EC exceeded the threshold for optimal growth (Figure 9).

Figure 8. Distribution of soil EC readings across jumping mouse units. The two red dashed line represents the lower and upper thresholds for optimal soil EC levels. The spike at 4.0 is because that is the upper limit for the Hanna Instruments soil EC probe used. Bin width on plot was set to 0.04.

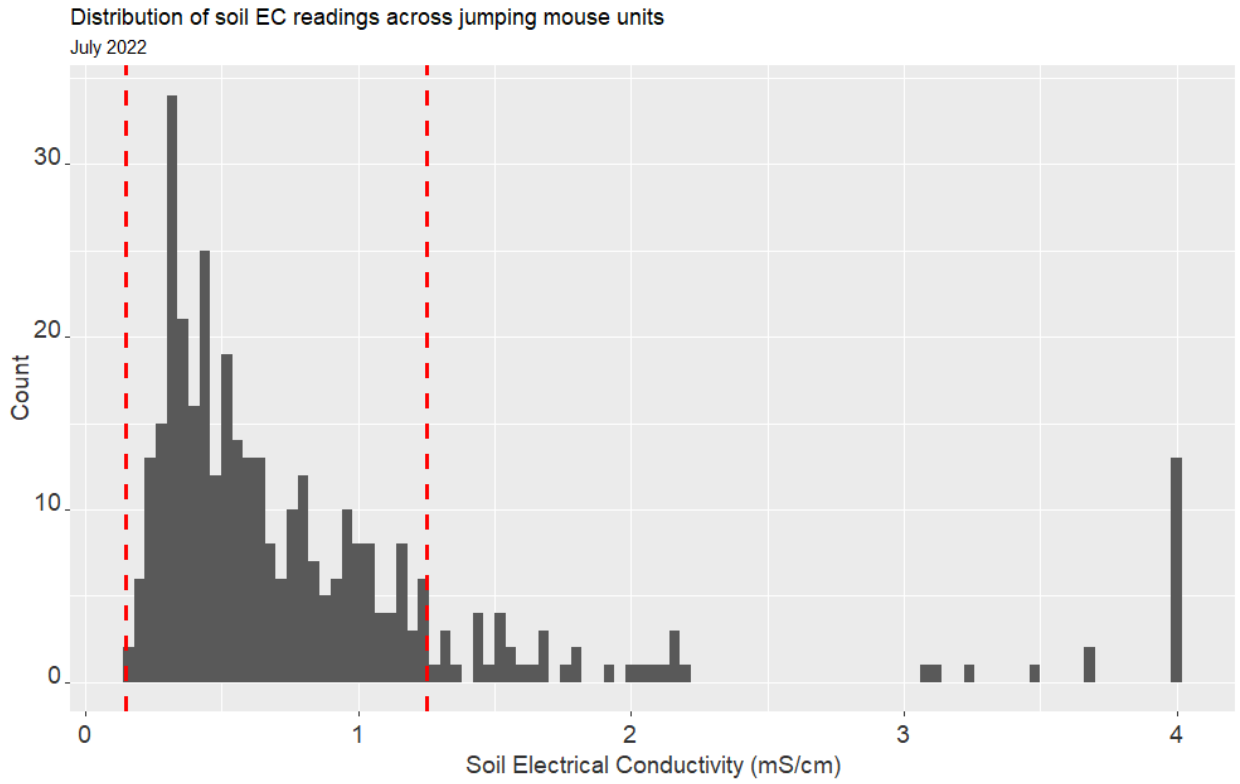
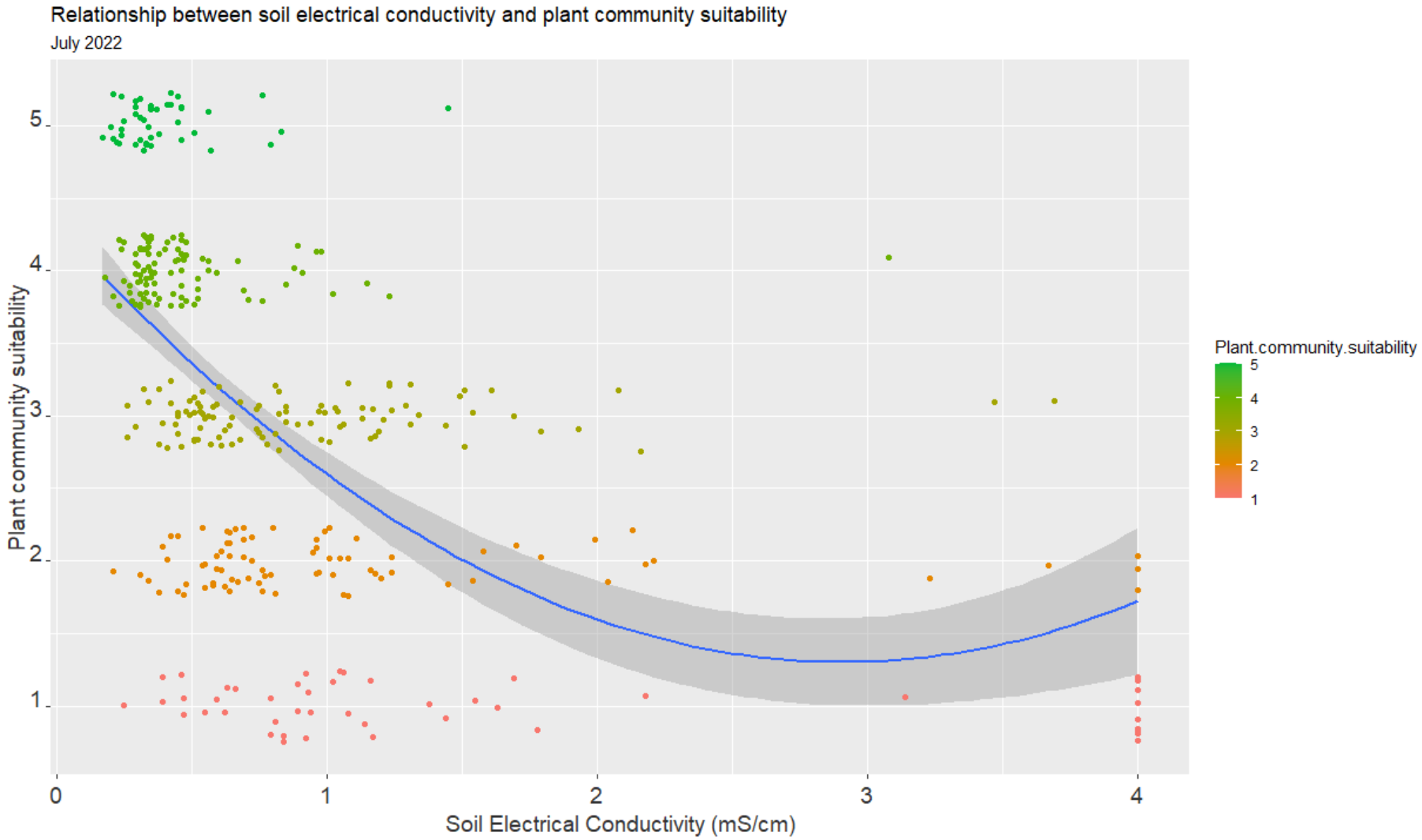


Figure 9. A quadratic relationship between Soil EC and plant community suitability across jumping mouse units.



Fitting the cumulative link mixed model with a quadratic relationship significantly improved the model fit (Δ AIC = -40.4). The model results suggest that soil EC has a significant correlation with the suitability of the vegetation community for jumping mice ($z = -8.3717$, $p < 0.0001$, Table 4). Overall, the influence of soil EC is strong, and the precision with this model is high. Furthermore, relatively large variance amongst units was accounted for, as seen in the random effect output (Table 4).

The GLMM models revealed a significant correlation between soil EC and presence/absence for 12 of the 20 species I investigated (fixed effects summarized in Table 5). The variation of the random effect term for each model was far from zero, indicating that it was appropriate to include in the model. The soil EC data was also categorized and summarized by plant species, plant rating, and unit (Tables 5-7, Figures 10-12).

Table 4. Model output table for the Cumulative Link Mixed Model.

Call: clmm2(PlantCommunitySuitability ~ SoilEC + I(Soil EC^2), random = Unit, data=soilsurvey, Hess=true)				
Fixed effects	**Estimate**	**SE**	**Z**	**p**
Soil EC	-4.575	0.514	-8.907	< 0.0001
Soil EC^2	0.773	0.119	6.475	< 0.0001
Random effect (Unit)	**Var**	**Std. Dev**		
Unit	1.704	1.305		

Table 5. Soil electrical conductivity summary for each species with more than 8 recorded observations. The 4 columns on the far right correspond to the fixed effect outputs from GLMM's that were produced to investigate whether soil EC explained variation in species presence or absence.

Species	**Status**	**Habitat Ranking**	**n (count)**	**mean**	**sd**	**median**	**IQR**	**Estimate**	**SE**	**Z**	**p**
Common three-square (*Schoenoplectus pungens*)	Native	Very good	108	0.532	0.382	0.405	0.285	-1.961	0.370	-5.293	< 0.0001
Frogfruit (*Phyla nodiflora*)	Native	Very good	70	0.548	0.33	0.445	0.375	-1.960	0.435	-4.512	< 0.0001
Rabbitsfoot (*Polypogon monspeliensis*)	Naturalized	Very good	51	0.672	0.439	0.49	0.535	-0.544	0.233	-2.330	0.020
Dogbane (*Apocynum cannabinum*)	Native	Very good	40	0.724	0.432	0.51	0.587	-0.720	0.308	-2.337	0.019
Slender wheatgrass (*Elymus trachycaulus*)	Native	Very good	9	0.696	0.501	0.54	0.16	-0.272	0.660	-0.411	0.681
Japanese Brome (*Bromus japonicas*)	Naturalized	Very good	10	0.76	0.544	0.63	0.225	-0.022	0.525	-0.041	0.967
Ribwort plaintain (*Plantago lanceolata*)	Naturalized	Very good	36	0.95	0.891	0.645	0.542	0.149	0.220	0.677	0.498
Foxtail Barley (*Hordeum jubatum*)	Native	Very good	27	0.9	0.74	0.64	0.565	-0.055	0.263	-0.210	0.834
Knotgrass (*Paspalum distichum*)	Native	Good	83	0.515	0.264	0.41	0.37	-3.020	0.548	-5.510	< 0.0001
Cattail (*Typha spp.*)	Native	Good	26	0.501	0.303	0.4	0.223	-0.984	0.474	-2.075	0.038
Spike rush (*Eleocharis spp.*)	Native	Good	84	0.545	0.295	0.425	0.443	-1.675	0.444	-3.777	< 0.001
Baltic rush (*Juncus balticus*)	Native	Good	37	0.61	0.423	0.45	0.48	-0.775	0.364	-2.130	0.033
Curly dock (*Rumex crispus*)	Naturalized	Good	19	0.604	0.44	0.46	0.22	-1.084	0.549	-1.976	0.048
Willows (*Salix spp.*)	Native	Good	64	0.839	0.776	0.58	0.635	-0.205	0.185	-1.104	0.270
Cottonwood (*Populus deltoides wislezenii*)	Native	Neutral	10	0.678	0.398	0.54	0.675	-0.521	0.654	-0.797	0.425
Saltgrass (*Distichlis spicata*)	Native	Neutral	61	0.937	0.617	0.75	0.5	0.226	0.166	1.363	0.173
Alkali Sacaton (*Sporobolus airoides*)	Native	Poor	20	0.994	1.09	0.57	0.388	0.225	0.272	0.828	0.408
Rough Cocklebur (*Xanthium strumarium*)	Native	Poor	23	1.33	0.942	0.89	0.92	0.263	0.002	117.300	< 0.0001
Phragmites australis	Invasive	Poor	41	1.5	1.27	1.01	0.99	0.797	0.172	4.623	< 0.0001
Kochia (*Bassia scopariaa*)	Invasive	Poor	30	2.1	1.36	1.66	2.92	1.360	0.249	5.456	< 0.0001

Figure 10. The observed range of soil EC values for 20 common jumping mouse habitat plant species. Species with eight or less observations were not included in this figure. Species were categorized by their rating, which is effectively how beneficial that specific species is for the overall quality of jumping mouse habitats (Lehnen et. al. 2020).

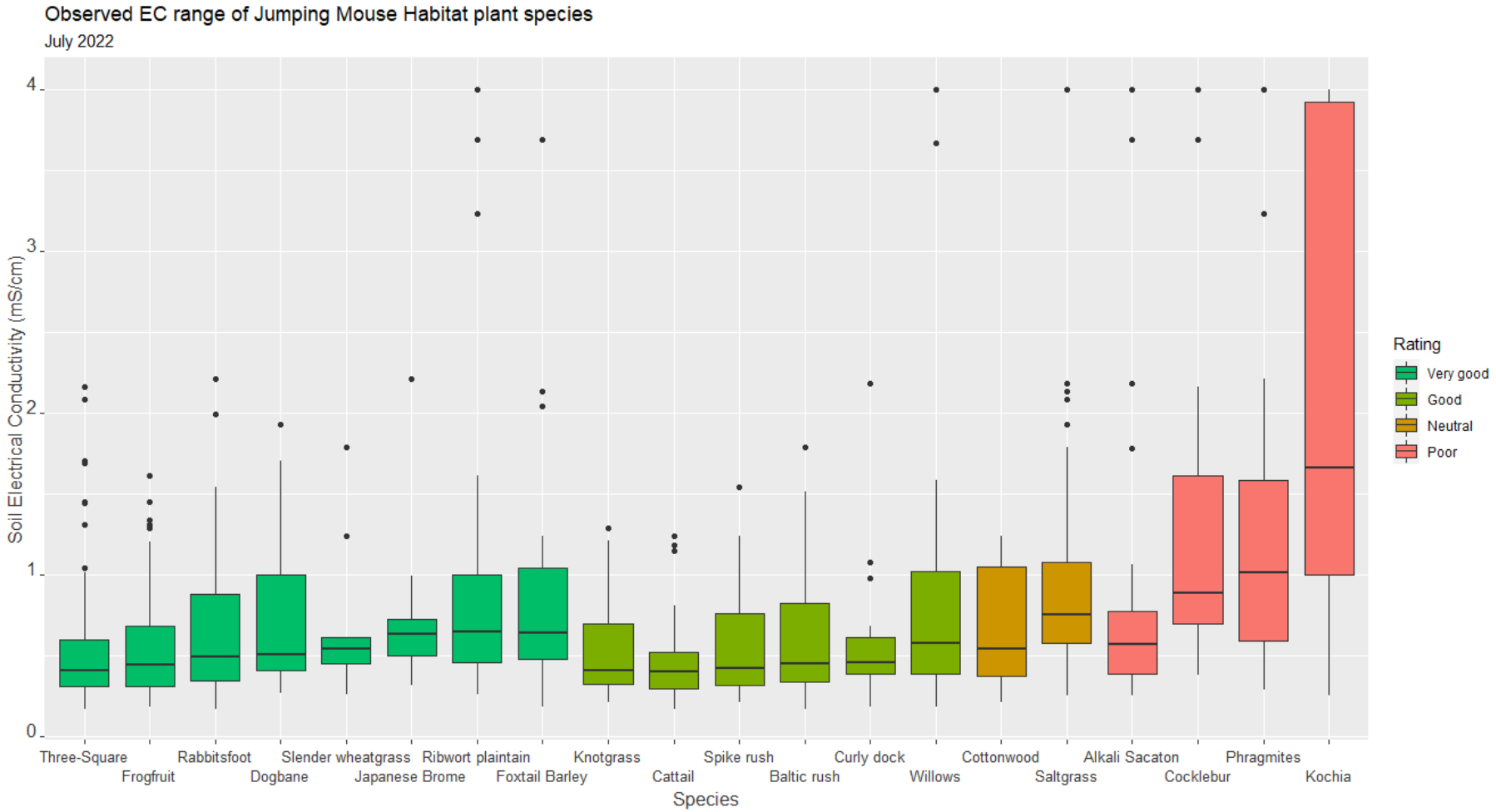


Figure 11. The range of soil EC values for all species within each rating category.

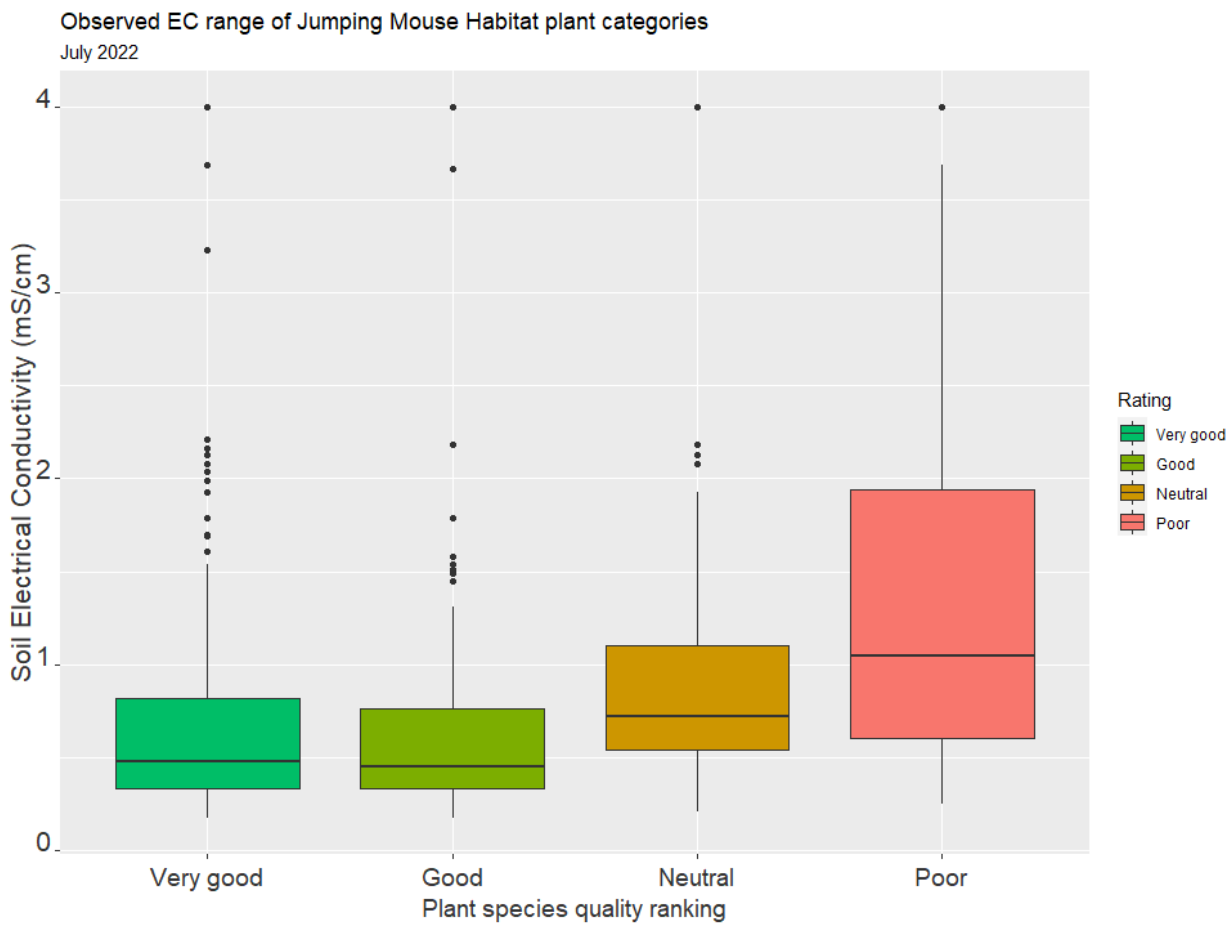


Table 6. Soil EC summaries for each plant rating category.

Rating	n (count)	mean	sd	median	IQR
Very good	351	0.659	0.519	0.48	0.485
Good	313	0.605	0.467	0.45	0.43
Neutral	71	0.9	0.596	0.72	0.565
Poor	114	1.53	1.25	1.04	1.34

Figure 12. The range of soil EC values observed in each of the jumping mouse units. The entirety of the area between the roadside and the Riverside canal were collapsed into a single unit called “Riverside”.

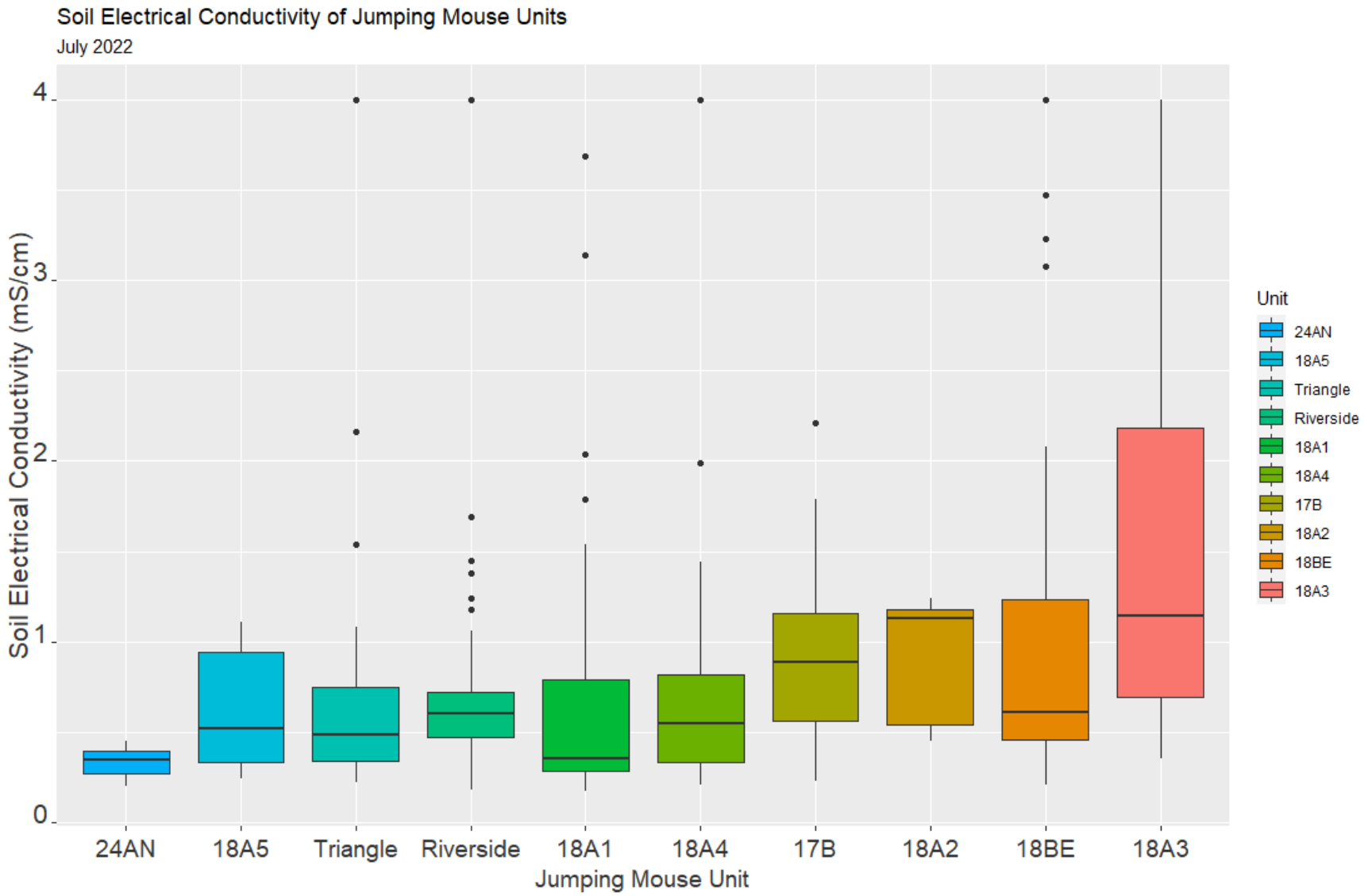


Table 7. Soil EC summaries for each jumping mouse unit.

Unit	n (count)	mean	sd	median	IQR
17B	38	0.912	0.417	0.89	0.577
18A1	37	0.702	0.803	0.35	0.51
18A2	6	0.945	0.352	1.13	0.48
18A3	29	1.67	1.29	1.14	1.49
18A4	33	0.718	0.704	0.55	0.49
18A5	22	0.609	0.297	0.52	0.585
18BE	77	1.07	1.02	0.61	0.77
24AN	8	0.332	0.0962	0.345	0.125
Riverside	72	0.687	0.488	0.6	0.248
Triangle	38	0.674	0.67	0.485	0.403

Mapping of soil EC and plant community suitability via Bayesian estimated kriging revealed a high degree of variation of both parameters across the available jumping mouse habitat (Figures 13 & 14).

Figure 13. A map of plant community suitability across available jumping mouse habitat. The map was produced via estimated Bayesian kriging.

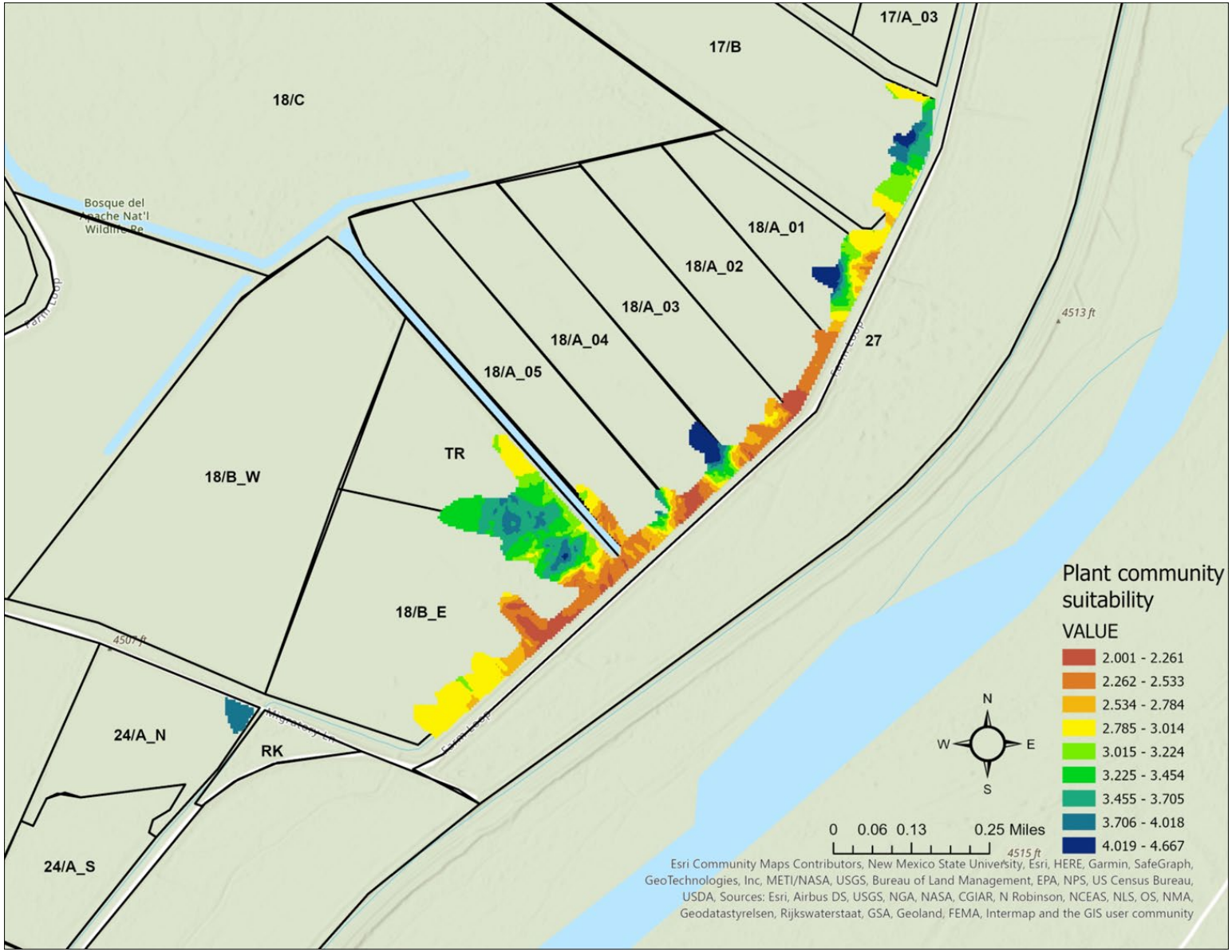
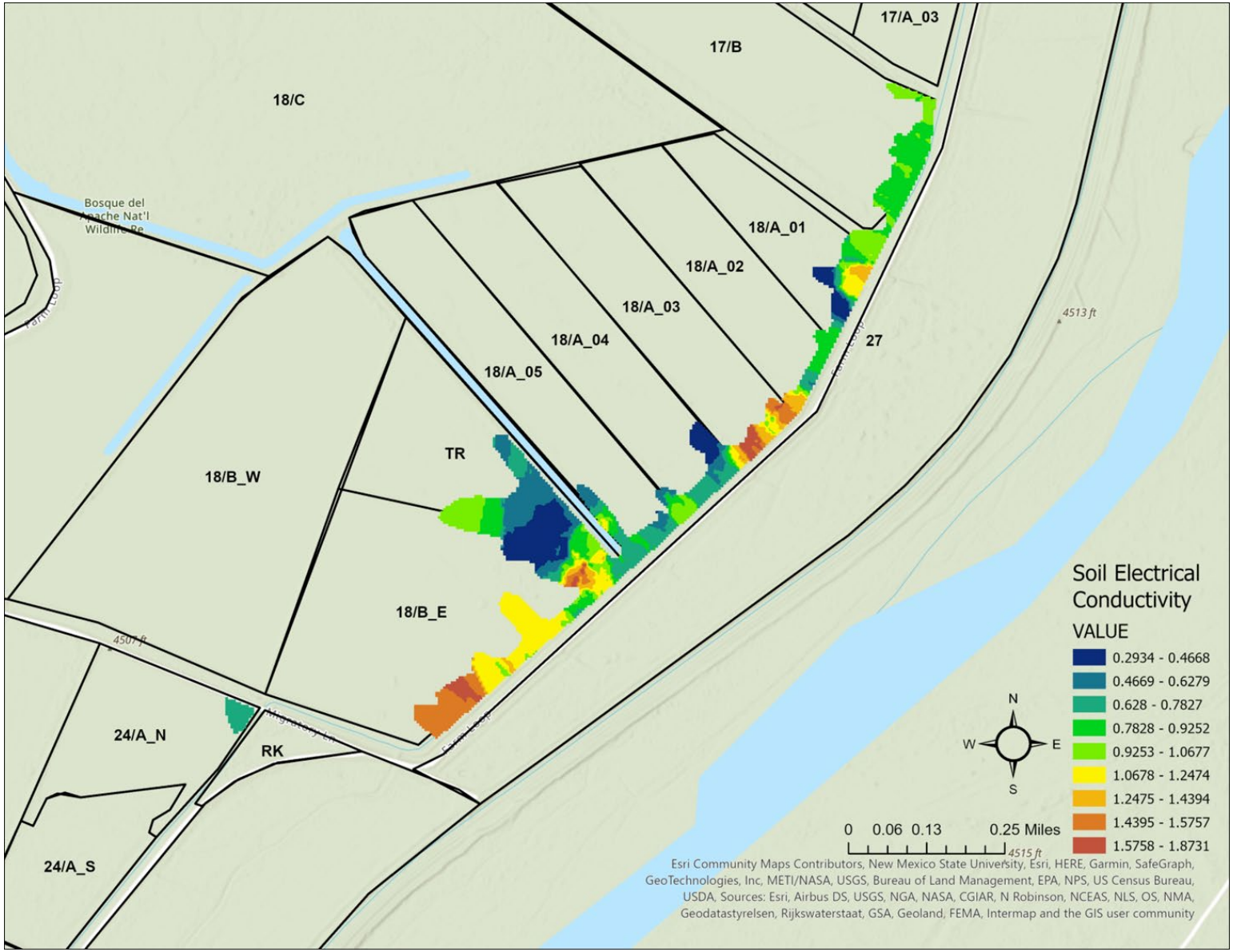
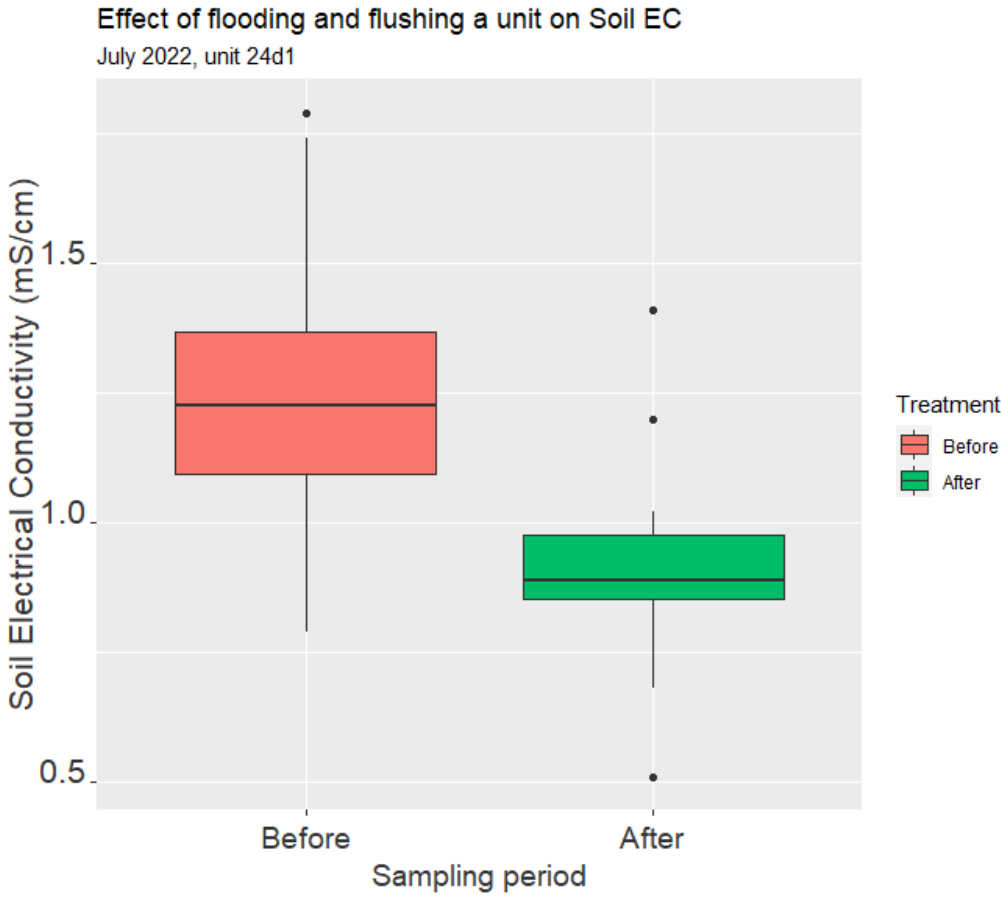


Figure 14. A map of soil EC across available jumping mouse habitat. The map was produced via estimated Bayesian kriging.



I observed a positive effect of the flooding and flushing treatment on the soil EC of unit 24d1 (Figure 15). This unit experienced a 26.18% reduction in soil EC levels (mean before: 1.232 mS/cm, after: 0.910 mS/cm). A one-way analysis of variance (ANOVA) confirmed that this was a statistically significant reduction in soil EC levels ($f = 20.969$, $p < 0.0001$).

Figure 15. The effect of a flooding and flushing treatment on the soil EC of unit 24d1.



Water Quality

I conducted 110 independent evaluations of water quality across the refuge water sources. I observed pH and dissolved oxygen values that were within acceptable levels. For pH, all sources ranged between 7.5 and 8.5 (Figure 16) and were within the ranges observed in previous, nearby assessments of water quality (Rehder 2013). Canal readings for dissolved oxygen, on average, were above 6.0 and did not significantly vary amongst canals (Figure 17). The dissolved oxygen of groundwater was on average much lower than that of the canal water, however, that is to be expected (Figure 17).

In contrast to DO and pH, I observed specific conductance and salinity levels that were extremely variable and beyond the optimal threshold for some sources. Wells 4, 5, and 7 all averaged in the “good” range and Well 22 averaged in the “poor” range. All other sources, both canal and groundwater, fell into the “permissible category” (Figures 18 & 19).

Figure 16. pH across Bosque del Apache water sources that could be utilized for jumping mouse habitat. “Riverside @ JM” is all sampling locations in the Riverside canal that are adjacent to or directly upstream of jumping mouse habitat.

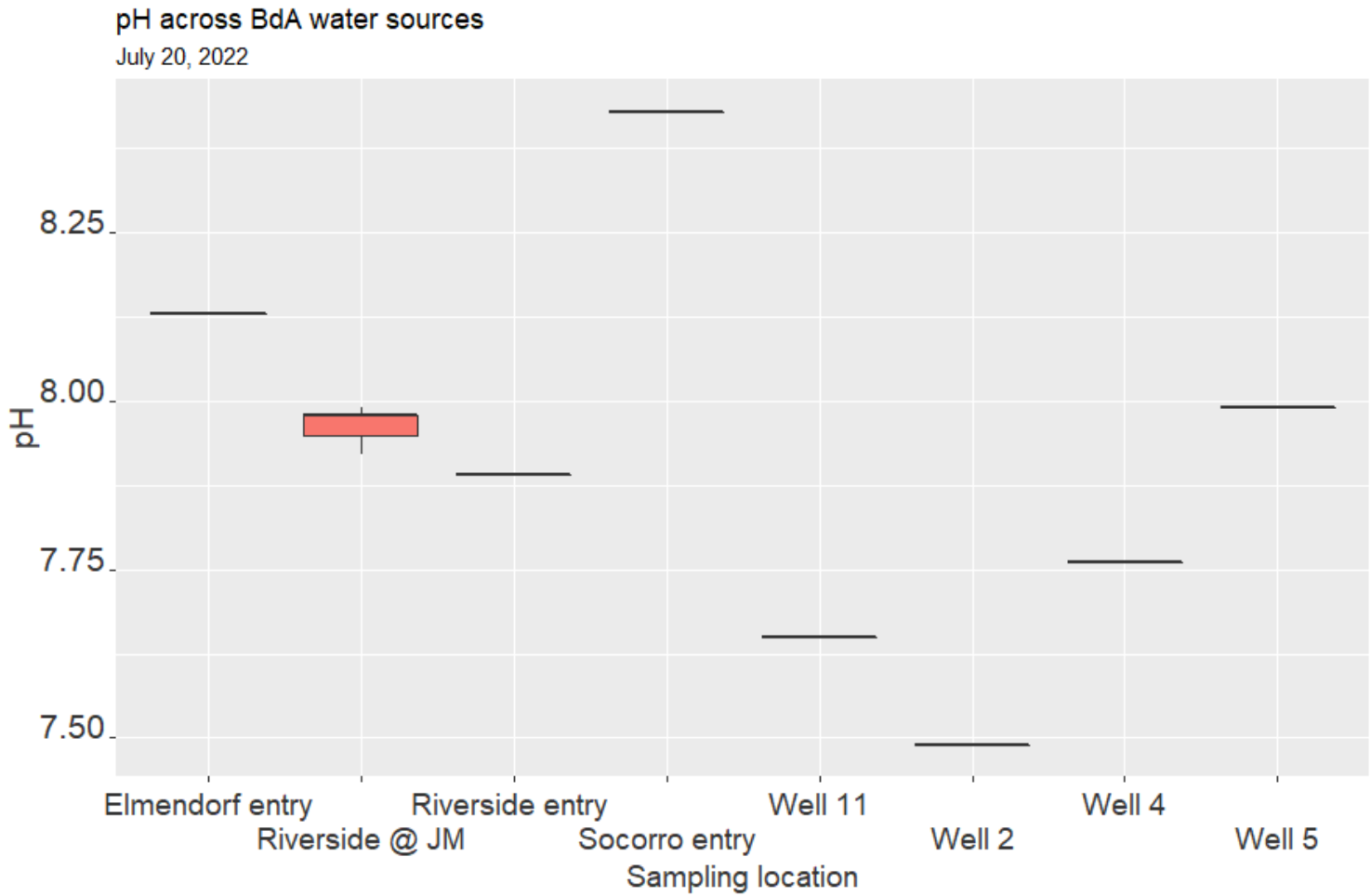


Figure 17. Dissolved oxygen across Bosque del Apache NWR water sources. “Riverside @ JM” is all sampling locations in the Riverside canal that are adjacent to or directly upstream of jumping mouse habitat.

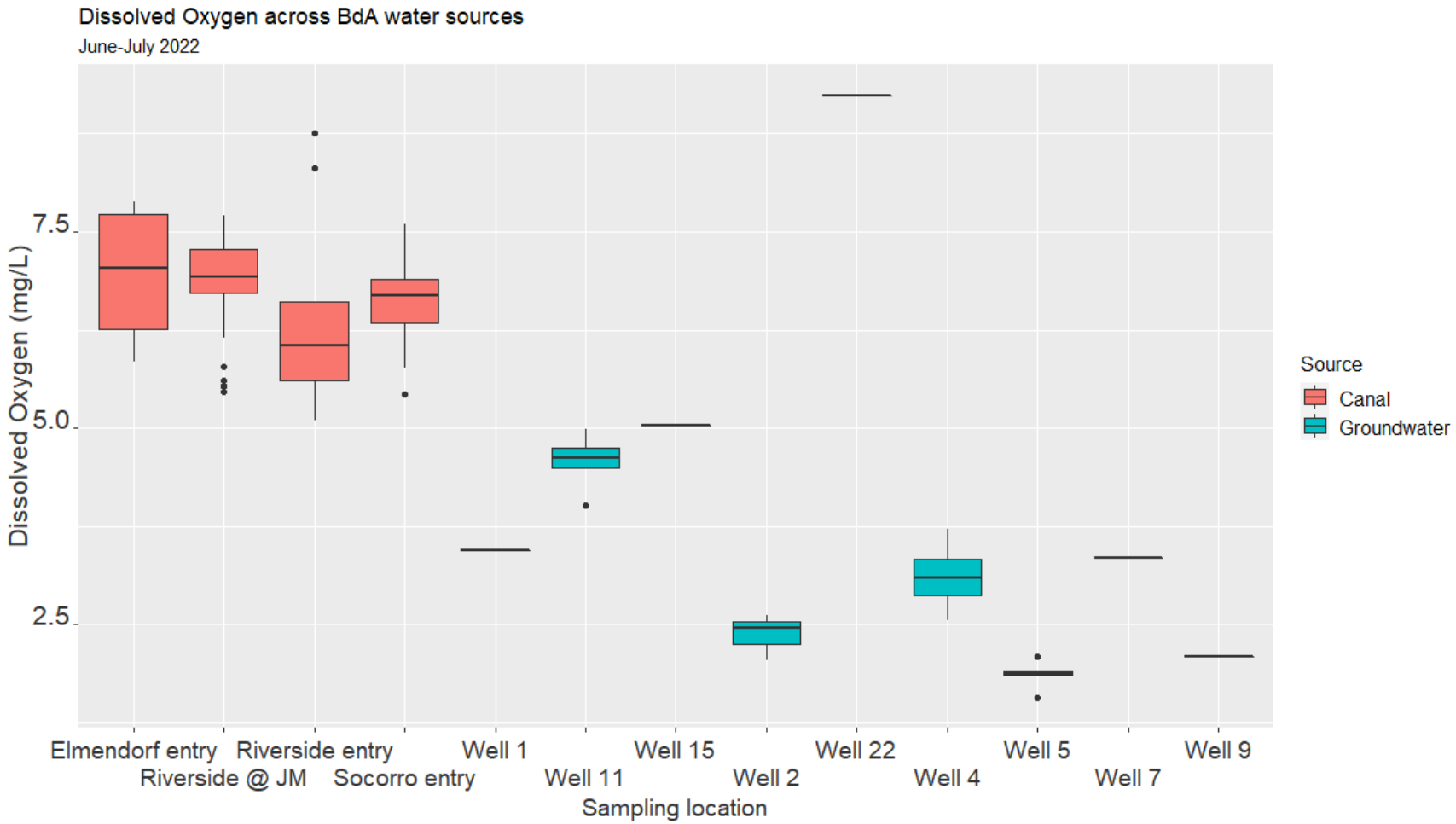


Figure 18. Specific conductance across Bosque del Apache NWR water sources. "Riverside @ JM" is all sampling locations in the Riverside canal that are adjacent to or directly upstream of jumping mouse habitat.

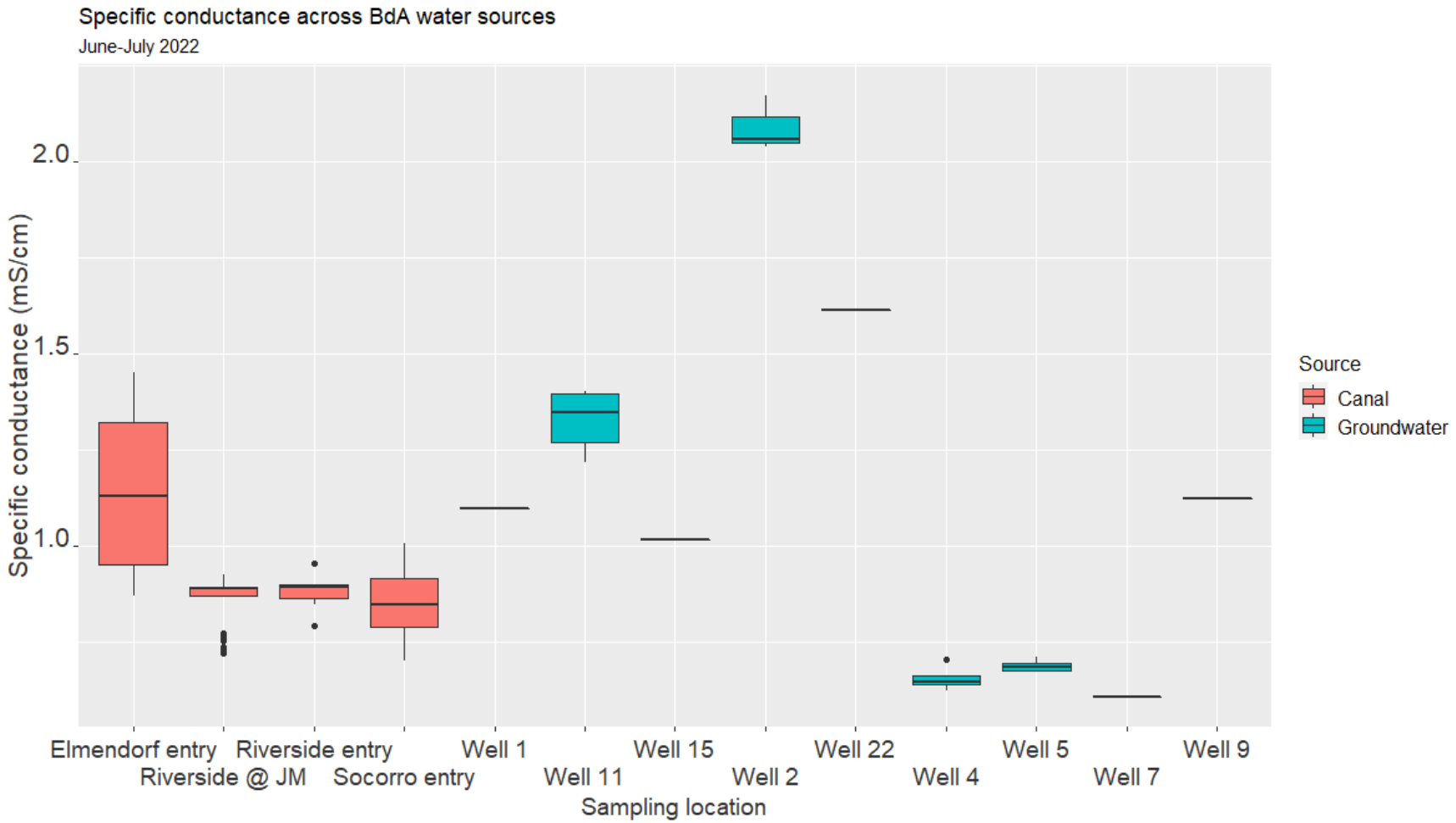
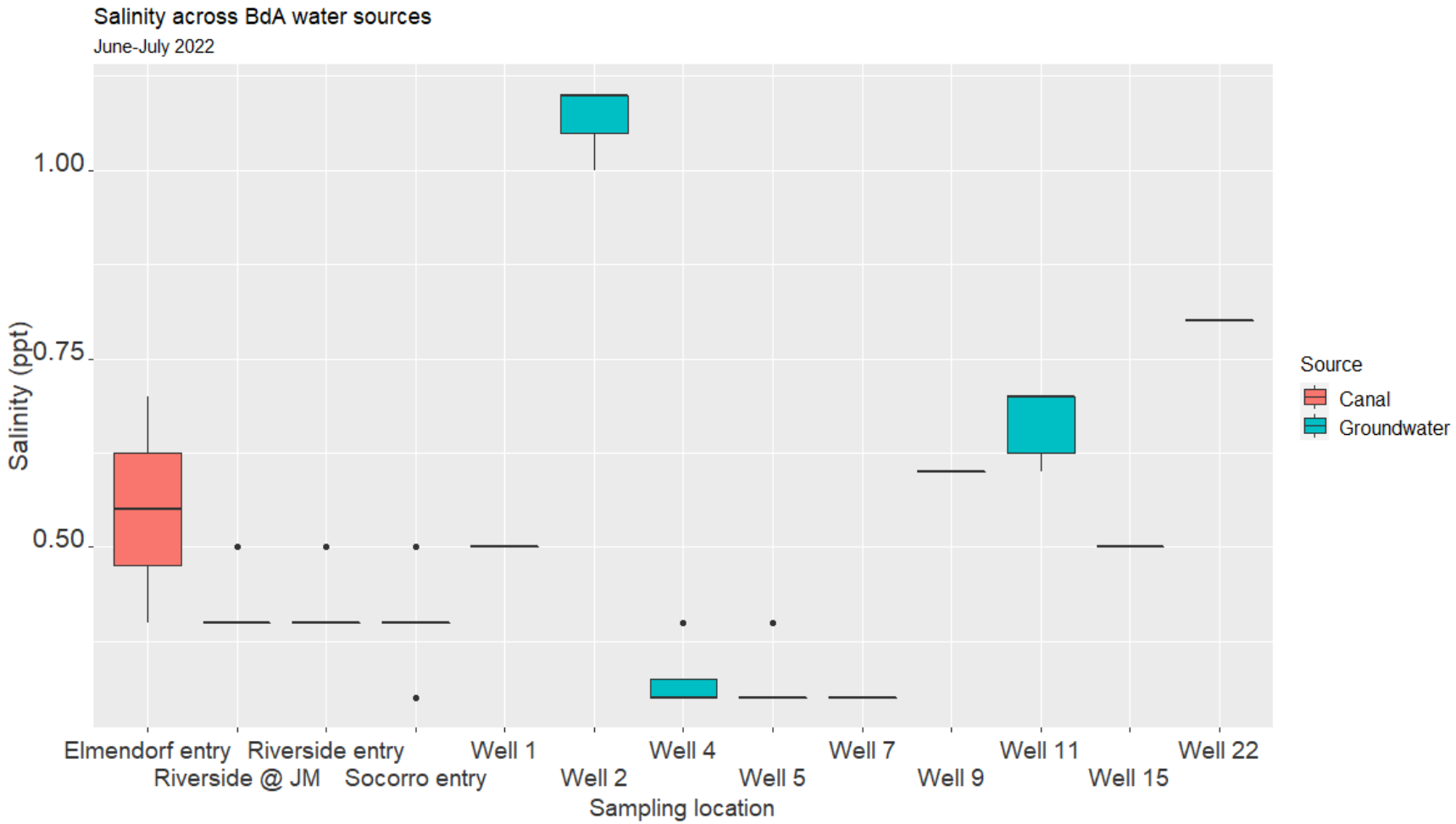


Figure 19. Salinity across Bosque del Apache NWR water sources. "Riverside @ JM" is all sampling locations in the Riverside canal that are adjacent to or directly upstream of jumping mouse habitat.



Our analysis of specific conductance among jumping mouse specific sources revealed significant differences amongst water resources (Table 8). The post-hoc pairwise comparison revealed that there was no statistical difference between the Riverside and Socorro canals and wells 4 & 5 ($p > 0.05$), however, all other mouse-specific sources varied significantly ($p < 0.0001$, table 9).

Table 8. ANOVA table for the analysis of specific conductance across mouse-specific water resources.

Analysis of Variance Table, Response: Specific conductance					
	Df	Sum Sq	Mean Sq	F	p
Treatment	5	5.936	1.187	311.86	< 0.0001
Residuals	82	0.312			

Table 9. Multiple pairwise comparisons of specific conductance amongst mouse-specific water resources, performed with t-tests and pooled standard deviations. The Bonferroni adjustment method was applied.

Post-hoc pairwise comparisons via Bonferroni method					
	Riverside	Socorro	Well 11	Well 2	Well 4
Socorro	$p > 0.05$	-	-	-	-
Well 11	$p < 0.0001$	$p < 0.0001$	-	-	-
Well 2	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	-	-
Well 4	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	-
Well 5	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p > 0.05$

Discussion

Soil Moisture

The results from the hourly soil moisture sampling revealed that soil moisture in jumping mouse habitat within unit 18A4 remained saturated for most of each sampling period during 2020 through 2022. During the limited monitoring of 2020 there were no significant dips or spikes in the moisture readings, and water flow of approximately 30 cfs in the Riverside canal was adequate for maintaining water levels in the canal, and thus saturated soils. The 2021 sampling period began with a significant decline in moisture levels. During this period refuge staff increased water flow to unit 18A4 on July 29, 2021, and this had no noticeable effect on the decreasing soil moisture trend. Another supplementation of water on August 9, 2021, had a large positive effect on moisture, causing it to rapidly rise to saturated levels. From this date until September 30, 2021, the soils remained saturated, even during brief periods where the Riverside canal was receiving as little water as 25 cfs. On September 30, 2021, a Langemann needed maintenance and flow to the Riverside was completely shut off for 24 hours. During this period, the mean soil moisture level decreased by 6.5%, but quickly rose back to saturated levels once flow was restored. A small precipitation event during this period may have helped the soils quickly rise back to saturated levels. In October, moisture levels steadily decline until the units were re-flooded for migratory waterfowl on December 9, 2021. The steady decline is due to

management cutting water off to the units. The jumping mouse is likely hibernating by this time, and the units need to dry prior to the flood-up so that management can utilize machinery to maintain these habitats. Although the water may be cut off to the 18A4, it appears to maintain volumetric water content levels above 38.3% until late October 2021. There were no significant dips or spikes in the moisture readings throughout the 2022 sampling period, and all readings surpassed 50% VWC. Flow within the riverside was variable during this period (averaged at about 44 cfs) and was higher than the 2020 and 2021 sampling periods.

Generally, these results suggest that soil moisture should not be a limiting factor for this plant community throughout the jumping mouse active season. However, this assessment was only performed on one unit and at most 40 meters (131.2 feet) from the water source to the unit. The periods of lower cfs were usually brief and later in the season, and it is impossible to know how soil moisture might respond to these low levels during periods of higher evapotranspiration. The refuge has invested heavily in infrastructure that enables them to control water levels in the portion of the Riverside Drain adjacent to jumping mouse management units. During periods of low cfs the refuge can still maintain the water levels necessary for appropriate soil moisture. However, the refuge has management obligations to provide habitat for other endangered species, including the Southwest Willow Flycatcher and the Yellow Billed Cuckoo, in addition to provide sufficient food resources for migratory waterfowl. During periods of low flow, maintaining sufficient water levels in the Riverside Drain for NMMJM will likely come at the expense of these other management obligations. Thus, these findings should be interpreted carefully, and more information about the status of the habitat should be considered before making assumptions across the entirety of the jumping mouse units.

Soil Salinity

The results from the soil EC sampling suggest that soil salinity may be limiting desirable plant communities within some of the jumping mouse units. Although only 14.4% of the readings fell outside of the optimal range for soil EC, the model revealed an extremely strong effect of soil EC (Figure 9, Table 4) on plant community suitability. Sites with high soil EC were nearly all located in plant communities that were unsuitable for jumping mice. Moreover, I only recorded a single observation of high-quality habitat (Plant community suitability score of 4 or 5) existing at soil EC levels beyond the ideal range (0.16 to 1.25 mS/cm). Poor-quality plant species were observed across a wider soil EC range than the very good and good groups (Table 5, Figures 10 & 11). As soil EC rises it may be increasingly likely that poor-quality invasive species, such as Kochia or *Phragmites australis*, become dominant and outcompete the more desirable species. Further monitoring may assist in identifying where soil EC is a limiting factor for desirable plant communities.

Going forward, refuge staff should focus on restoring soils within units that have large areas of salt accumulation, such as 18BE and 18A3 (See Figures 12 & 14). Both units had numerous excessive readings (EC > 2 mS/cm), and poor-quality plant species were beginning to become dominant across the high EC areas. Some parts of these units, such as the southern end of 18BE, are crucial habitat as they serve as a corridor between adjacent areas of available habitat. Continued management of soil salinity will be required to maintain maximum productivity and

health of the plant community across the jumping mouse habitats, in addition to enhancing the continued expansion of jumping mouse habitat.

The combination of an arid climate with semi-saline water resources is likely the cause of salt accumulations within jumping mouse units. This occurs gradually, irrigation water that contain salts are constantly applied to the habitat, and these salts accumulate as the water evaporates, is used by plants, or passes through to the water table. Given the constant application of water to these units, it is likely that the water table is shallow, and this may allow salts to move throughout the root zone via capillary action. The negative effects of these processes might be mitigated through the flooding (commonly referred to as "leaching", Supplementary table 2). The excess water can collect and carry a significant portion of the accumulated salts below the root zone. The amount of water applied, and the timing of the treatment will both play a role in how effective the treatment is. Seedlings and early vegetative stages are generally the most sensitive to salinity, thus, leaching treatments that occur just before the growing season begins are likely to be the most beneficial.

This flooding of unit24d1 had a significant positive effect on the soil EC ($p < 0.0001$). Soil EC levels across the unit dropped by 26.18%, which effectively moved the unit from a high to medium salinity rating. However, this trial was performed outside of jumping mouse managed habitat. Further investigation is needed to assess the effectiveness of this treatment within jumping mouse units.

Other avenues may also exist for mitigating the effect of saline soil conditions. Certain plant species, known as halophytes, are extremely salt-tolerant plants that may reduce soil salinity levels by removing the salts from the soil and storing them in their tissues or excreting them on the surface of their leaves. Recent work has demonstrated the viability of numerous plant species for soil desalination (Saddhe et. al. 2020). Interestingly, several species described in this review already occur within jumping mouse habitats (*Phragmites australis*, *Typha spp*., and *Distichlis spicata*). Unfortunately, none of these are high-quality species for jumping mouse habitats. It is possible that careful management of these species could allow for some desalination while minimizing the negative effect on jumping mouse habitat quality, however, a more thorough and detailed analysis should occur prior to the utilization of this technique.

Chemical treatments may also be used to restore sodic (soils with high levels of exchangeable sodium) soils. A great example is the application of gypsum, which is a common and viable approach for restoring sodic soils (Hanay et. al., 2004). However, there are a wide variety of salts within irrigation waters (Supplementary table 3), and viable chemical amendments may not exist for all kinds of saline conditions. Furthermore, these treatments may have complex side effects on other soil parameters which should be thoroughly investigated before considering their usage.

Water Quality

The results from the water quality surveys revealed that the dissolved oxygen and pH of refuge water sources were within acceptable ranges and followed expected patterns. pH of across all sampled sources ranged from about 7.5 to 8.5, which is slightly above what is typically expected of irrigation water, however, it is not a surprising result given that the Rio Grande is typically

alkaline (Bland et. al. 2005, BEMP 2009, Rehder 2013). Dissolved oxygen levels for all canal water averaged above 6.0, which is acceptable, especially given its relatively minimal impact on the health of jumping mouse habitat. Dissolved oxygen of the groundwater sources was lower than the canal sources, as expected. One well (number 22) did have a high dissolved oxygen reading, however, this is likely due to the way that water is released from that specific pump.

In contrast, there were relatively large differences in specific conductance and salinity amongst refuge water sources. These measures are directly correlated (see figures 18 & 19), so I predominately focused on specific conductance for this assessment. Specific conductance varied widely; some groundwater wells had relatively low readings and are good sources while some wells have relatively high readings and are unsuitable for use in the jumping mouse habitat. All canal sources and most groundwater wells fall into the "permissible" range and are generally suitable for use within the mouse units. However, sources in this range are beyond ideal, and soil leaching may be required with the usage of these sources (Fipps 2003).

Going forward, refuge management should primarily utilize canal sources when water is available, however, if water is scarce and groundwater is needed to supplement what is available in the riverside, then the 4 and 5 wells should be utilized before the number 11 well. The number 2 well should never be used to for jumping mouse habitat. All other refuge wells lack the appropriate infrastructure to deliver water to the jumping mouse. Another factor to consider when using groundwater resources is the efficiency of the well and pump. Most wells at Bosque del Apache costs approximately the same to run (diesel wells excluded), however, their outputs vary widely, from 200 gph to 2000 gph (Supplementary table 1). Decisions will need to be made regarding whether the benefits of these higher quality sources are worth their increased costs.

Further assessment of refuge water sources may also be warranted if plant growth and productivity is not at expected levels, especially if all other possible causes are accounted for. Some parameters that may be worth investigating under these circumstances include fertilizer runoff in the form of macronutrients (N and P), pollutants (pesticides and herbicides), and heavy metals. These parameters, when found above certain concentrations, may produce toxic effects on plants, such as decreased growth, chlorosis, reduced nutrient assimilation, low biomass accumulation, distorted water balance (resulting in wilting), or even plant death (Singh et. al. 2016, Kulkarni et. al. 2019).

Overall, the soils within jumping mouse units and water resources across the refuge were mostly within acceptable levels and can support high-quality jumping mouse habitat. However, results suggest that there are minor issues associated with water and soil salinity, that if ameliorated and managed, will enhance the continued expansion of jumping mouse habitat and populations.

Acknowledgements

I'm extremely grateful to Dr. Sarah Lehnen for her support and supervision during my completion of this project. I've learned so much from working with her, and every interaction along the way has been pleasant and enjoyable. I would also like to extend my gratitude to many of the fantastic individuals from water resources (Dr. Stephanie Siemek, Darrell Kundargi, Maximiliano Trujillo, Peter Burck) who met with me weekly and did everything they could to help me complete this project. I'm grateful for the help from the Bosque Environmental Monitoring Project. Ben Sinclair, Matt Leister, and others lent me sampling equipment and engaged in fruitful discussions about the development of my project and water resources across the Middle Rio Grande. I also would like to express my deepest appreciation to all the staff here at Bosque del Apache NWR. Gerad Montoya explained all things water management to me, gave me tours of the refuge, showed me how to operate the groundwater wells, and overall was an invaluable resource. Bryden Baker showed me how to assess plant suitability, assisted in the installation of the soil moisture loggers, and was an amazing resource for all things jumping mouse. Deb Williams and Bernard Lujan both made sure I had everything I needed throughout my time here. I want to thank everyone else here at Bosque del Apache for any contributions they have made to this project and for making this an enjoyable environment to live and work. Finally, I want to thank everyone at the National Conservation Training Center and the Hispanic Access Foundation for organizing this opportunity. This has been a phenomenal experience and I am looking forward to a potential future with the US Fish and Wildlife Service.

References

ArcGIS Pro (Version 2.5). (2021). Esri Inc. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Bates D, Mächler M, Bolker B, Walker S (2015). "Fitting Linear Mixed-Effects Models Using lme4." Journal of Statistical Software, **67**(1), 1–48. doi:10.18637/jss.v067.i01.

Bland, C. S., Ireland, J. M., Lozano, E., Alvarez, M. E., & Primm, T. P. (2005). Mycobacterial ecology of the Rio Grande. Applied and environmental microbiology, *71*(10), 5719–5727. https://doi.org/10.1128/AEM.71.10.5719-5727.2005

Chapter A4. Collection of water samples (Report No. 09-A4; Techniques of Water-Resources Investigations, p. 231). (2006). USGS Publications Warehouse.

Christensen R. H. B. (2019). "ordinal—Regression Models for Ordinal Data." R package version 2019.12-10. https://CRAN.R-project.org/package=ordinal.

Fipps, G. (2003). Irrigation Water Quality Standards and Salinity Management. Texas A&M Agriculture and Life Sciences, B-1667, 4-03.

Flynn, R., & Ulery, A. (2011). An Introduction to Soil Salinity and Sodium Issues in New Mexico. New Mexico State University Circulars, 656. https://pubs.nmsu.edu/_circulars/CR656/index.html

Frey, J. K., and J. L. Malaney. (2009). Decline of the meadow jumping mouse (Zapus hudsonius luteus) in two mountain ranges in New Mexico. The Southwestern Naturalist 54:31–44.

Frey, J.K., and G.D. Wright. (2012). Multiple scale habitat selection by a small mammal habitat specialist (Zapus hudsonius luteus) in a managed floodplain landscape. Department of Fish Wildlife and Conservation Ecology, New Mexico State University, Las Cruces, NM, 152 pp.

Harris, A.H. (1963). Ecological distribution of some vertebrates in the San Juan Basin, New Mexico. Museum of New Mexico Press, Papers in Anthropology, No. 8, 63 pp.

Horiba. (2019). Dissolved Oxygen in the Greenhouse. Application note. Rev. 0.

Jiaping, L., Wenjuan, S. (2021). Cotton/halophytes intercropping decreases salt accumulation and improves soil physicochemical properties and crop productivity in saline-alkali soils under mulched drip irrigation: A three-year field experiment. Field Crops Research. 262: 108027. doi:10.1016/j.fcr.2020.108027. S2CID 230576810

Kulkarni, Sunil and Kulkarni, Sunil and Goswami, Ajaygiri, Effect of Excess Fertilizers and Nutrients: A Review on Impact on Plants and Human Population (February 23, 2019). Proceedings of International Conference on Sustainable Computing in Science, Technology and Management (SUSCOM), Amity University Rajasthan

Lehnen, S., Sanchez, J., Wilder, D., Goyette, M. (2021). The New Mexico Meadow Jumping Mouse at Bosque del Apache National Wildlife Refuge: 2016-2020. FWS Servcat, Internal report.

Hasanuzzaman, M., Nahar, K., Alam, M., Bhowmik, P., Hossain, A., Rahman, M., Prasad, M., Ozturk, M., Fujita, M. (2014). Potential Use of Halophytes to Remediate Saline Soils. BioMed Research International, vol. 2014, Article ID 589341. https://doi.org/10.1155/2014/589341.

Morrison, J. L. (1990). The meadow jumping mouse in New Mexico: habitat preferences and management recommendations. Pp. 136-141, in Proceedings of the symposium on managing wildlife in the Southwest (P.R. Krausman and N. S, Smith, eds). Arizona Chapter, the Wildlife Society, Phoenix, AZ, USA.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rehder, B. T. (2013). Salinity of the lower middle Rio Grande, Socorro County, New Mexico. University of New Mexico Digital Repository.

Saddhe, A. A., Manuka, R., Nikalje, G. C., & Penna, S. (2020). Halophytes as a Potential Resource for Phytodesalination. Handbook of Halophytes, 1–21. https://doi.org/10.1007/978-3-030-17854-3_92-1

Samimi, M., Mirchi, A., Townsend, N., Gutzler, D., Daggubati, D., Ahn, S., Sheng Z., Moriasi, D., Granados-Olivas, A., Alian, S., Mayer, A., Hargrove, W. (2022). Climate Change Impacts on Agricultural Water Availability in the Middle Rio Grande Basin. Journal of the American Water Resources Association. Vol. 52, No. 2.

Singh S, Parihar P, Singh R, Singh VP and Prasad SM (2016) Heavy Metal Tolerance in Plants: Role of Transcriptomics, Proteomics, Metabolomics, and Ionomics. Front. Plant Sci. 6:1143. doi: 10.3389/fpls.2015.01143

Sonon, L., Saha, U., Kissel, D. (2012). Soil Salinity Testing, Data Interpretation and Recommendations. Agricultural and Environmental Services Laboratories, University of Georgia Extension. Circular 1019.

USFWS, Listing Review Team. (2014). Species status assessment report: New Mexico meadow jumping mouse (Zapus hudsonius luteus).

USFWS, Listing Review Team. (2020). Species status assessment report: New Mexico meadow jumping mouse (Zapus hudsonius luteus), 1st Revision; https://www.fws.gov/southwest/es/NewMexico/documents/20200130_NMMJM_Revised_SSA_Report_final.pdf

Supplementary Information

Supplementary table 1. Well information for Bosque del Apache wells. All wells in this list are either currently active or have been active in the last 10 years. Purge volume is estimated by multiplying the well depth by the gallons of water per foot of casing, and then multiplying by three. Purge time in seconds is calculated by dividing the purge volume by the pump speed, and then multiplying by 60. Note that the pump speed values may change across time. These values represent the speeds the pumps were operating at when sampling was performed. Pump speed should be assessed during future sampling events, and purge time will need to be recalculated if they vary from the values listed here.

Well Number	Casing Diameter (inches)	Depth (feet)	Gallons / foot	Pump Speed (gpm)	Total Purge Volume	Minimum Purge Time (seconds)
1	10	180	4.08	900	2203.2	146.9
2	10	180	4.08	200	2203.2	661.0
4	8	180	2.61	900	1409.4	94.0
5	8	180	2.61	1000	1409.4	84.6
7	10	180	4.08	900	2203.2	146.9
8	10	180	4.08	800	2203.2	165.2
9	10	180	4.08	3200	2203.2	41.3
10	10	180	4.08	950	2203.2	139.1
11	10	180	4.08	2000	2203.2	66.1
14	10	180	4.08	800	2203.2	165.2
15	10	180	4.08	3000	2203.2	44.1
22	10	90	4.08	500	1101.6	132.2

Supplementary table 2. Estimated leaching requirements for the reduction of salt content in soils.

Estimated leaching requirements to remove salts	
Volume of salt-free water	**Reduction of salt content**
6 inches	50%
12 inches	80%
24 inches	90%

Supplementary table 3. Salts typically found in irrigation waters. (Fipps 2003)

Chemical name	**Chemical symbol**	**Approximate proportion of total salt content**
Sodium chloride	NaCl	Moderate to large
Sodium sulfate	Na_2SO_4	Moderate to large
Calcium chloride	$CaCl_2$	Moderate
Calcium sulfate (gypsum)	$CaSO_4\,2H_2O$	Moderate to small
Magnesium chloride	$MgCl_2$	Moderate
Magnesium sulfate	$MgSO_4$	Moderate to small
Potassium chloride	KCL	Small
Potassium sulfate	K_2SO_4	Small
Sodium bicarbonate	$NaHCO_3$	Small
Calcium carbonate	$CaCO_3$	Very Small
Sodium carbonate	Na_2CO_3	Trace to none
Borates	BO^{-3}	Trace to none
Nitrates	NO^{-3}	Small to none

Water and Soil quality monitoring procedure

Future recommendations

Soil moisture is assessed by measuring the volumetric water content (VWC) of the soil; high soil moisture is necessary to promote jumping mouse habitat. This report assessed how high temporal resolution soil moisture data within one jumping mouse management unit varied with water and flow levels in the Riverside canal. Based on this assessment, water levels over the last 3 years of monitoring were sufficient to maintain targeted soil moisture levels. In the future, if there is a change to the system that causes additional variation in water levels within the Riverside canal, further monitoring of soil moisture using high resolution temporal probes may be warranted and the methods used in this report can be reinitiated.

Soil Electrical conductivity (EC) can be measured in the field using handheld devices and is a great measure of overall soil health and salinity levels. Additional parameters worth considering for future monitoring include Total Soluble Salts (TSS), Sodium Adsorption Ratio (SAR) or Exchangeable Sodium Percentage (ESP), Metals, Macronutrients (Nitrogen and Phosphorus), and suspected pollutants (Herbicides or Pesticides). Some of these parameters are important for fully understanding the complexities and implications of soil salinity at the refuge (such as SAR or ESP), while others are important as they may negatively impact plant health at higher concentrations (such as macronutrients, metals, and pollutants). Several labs that provide these tests offer combination packages, where an entire series of parameters can be tested for each sample provided, at a lower cost. A great example is the Basic Soil Salinity Test (#S36) from the University of Georgia Agricultural & Environmental Services Laboratory. The S36 test provides an analysis of SAR, TSS, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, pH, and electrical conductivity (EC), all for a cost that is lower than if these tests were ordered independently ($35.00 per sample, plus preparation fees). This specific test would be valuable for further evaluation of parameters that contribute to overall soil quality, identification of the salts that are responsible for the observed soil EC patterns, and validation of the ability to properly measure soil EC with a handheld meter. The utility of measuring these parameters should be measured against the cost and the management implications of the possible results.

Water quality parameters can be measured via a combination of field and laboratory testing. A multiparameter device, such as a YSI probe, can measure dissolved oxygen, pH, salinity, nitrates, phosphorus, specific conductance, and much more depending on the specifics of the device. Parameters that are likely to require a laboratory test include metals, total organic carbon and suspected pollutants (Herbicides or Pesticides). Some of these parameters may be measurable in the field with more sophisticated multiparameter probes. The refuge has no control over the water that enters. However, a lift station may be installed at a future date that would allow the refuge to move water between the Socorro drain and the riverside canal. It may be worth monitoring water at the entry points to determine if one water source is more suitable.

Monitoring locations

1. High temporal resolution soil moisture – Jumping mouse habitat, distributed along transects at increasing distances (e.g., 10m, 20m, 30m, 40m) from the inflow of water to the unit.
2. Soil electrical conductivity – Across available habitat in jumping mouse units and adjacent areas which might allow for jumping mouse habitat/population expansion.
3. Water quality (see figure 4):
    - Riverside and Socorro canals at their entrance to the refuge and/or adjacent to points of interest.
    - Groundwater wells.

Sampling frequency

1. High temporal resolution soil moisture - (i.e., hourly monitoring via data loggers and soil probes) - Sampling not currently needed. If sampling is needed in the future, a decision should be made for how long and for what purpose.
2. Soil Electrical Connectivity (EC) – For three years, soil EC should be assessed at the beginning and end of the jumping mouse active period. This will allow for assessment of the impact of management actions of soil EC, as well as the natural variation in EC levels across seasons and years. Individual point readings are not necessary unless high-resolution data is desired: one can utilize composite sampling for a more rapid estimation of soil EC across a unit. Estimated time required: 70-90 hours for point sampling across all jumping mouse units or about 15 minutes per sample (total time depends upon sampling intensity). 6-8 hours for composite surveys of all jumping mouse units, 30-40 minutes per sample.
3. Water quality – The information provided in this assessment can be used to make decisions about the quality (pH, DO, Sp. Conductance, Salinity) of available water resources. Further sampling might be beneficial to assess temporal variation of water quality or if the refuge installs infrastructure that enables movement of water from the Socorro to the Riverside canals. The frequency of these events should be tailored to the question at hand.

Soil electrical conductivity (1:2 Method) sampling protocol

Materials needed:

1. Soil conductivity meter
2. 1413 µS/cm conductivity standard solution
3. Distilled water
4. Measuring scoop
5. Wash bottle
6. Sterile gloves
7. Vials or test tubes (greater than 3x the volume of the scoop)
8. Beaker (for composite sampling)
9. Graduated cylinder (for calibration)
10. Stake Flags (optional, for marking sampling locations)
11. Device with the ArcGIS Field Maps application (for point sampling)
12. GPS device (Bad Elf or similar, for point sampling)

Device Calibration:

Calibration procedures will vary by meter, but most will utilize the 1413 µS/cm conductivity standard. This guide is written specifically for the Hanna Instruments Soil Conductivity meter (model HI98331). The meter should be calibrated as frequently as possible, but at a minimum, once a month or after the life of a battery. For other meter, see the instruction manual for calibration procedures.

1. Put on a pair of clean, sterile gloves.
2. Clean a vessel (test tube, vial, or graduated cylinder) by rinsing thoroughly with distilled water and allow it to dry.
3. Fill the graduated cylinder with at least 3 inches of the 1413 µS/cm conductivity standard.
4. Remove the black protective cover from the meter. Turn the meter on, allow a reading to appear, and then enter calibration mode by holding the power button until “OFF” is replaced by “CAL”. Release the button. The display should now read “1.41 USE”.
5. Insert the device into the solution, making sure that the probe tip and sensors (two black bands near the tip) are submersed at least two inches and centered in the vessel. Add more conductivity standard if needed.
6. If the calibration procedure is successful, “REC” will be displayed. Wait until the calibration is complete and accepted. Once the display reads “Stor”, the procedure is complete and the meter will return to measurement mode. If the calibration procedure is unsuccessful, “WRNG” is displayed. This may occur if the calibration solution is contaminated or degraded. This may also occur if there is not enough volume of conductivity standard or the probe tip is not centered in the solution. Make sure the solution is fresh and all equipment is thoroughly cleaned with distilled water prior to calibration.
7. Remove the meter from the solution and rinse with distilled water. Turn the meter off.

Sampling procedure (point sampling):

1. Define the area that you will sample and the interval at which you will sample across the area. Make sure you have Field Maps enabled with a layer that is configured for data collection, with input fields for soil EC and all other parameters of interest. Ensure the GPS device is connected and feeding GPS data to the data collection device.
2. Put on a pair of clean, sterile gloves.
3. Take a soil sample by first gently pushing aside all live or dead plant matter. Make a small hole in the soil and use the scoop to take a sample at approximately 2 inches below the surface of the soil.
4. Tamp down the sample with a gloved finger and ensure it is level with the measurement line or rim of the scoop. Add the sample to a clean test tube or vial.
5. Add two scoops of distilled water to the test tube or vial for every one scoop of soil.
6. Shake or stir vigorously until sample is thoroughly mixed.
7. Allow the mixture to settle for 15 minutes.
8. Rinse the soil EC meter with distilled water.
9. Turn on the meter and insert it into the sample. Make sure the probe tip is inserted by at least 2 inches.
10. Wait for the reading to stabilize. This is indicated by the disappearance of the stability indicator (a small hourglass symbol).
11. Enter the value, along with other parameters of interest, to Field Maps.
12. Turn off the meter and rinse the probe with distilled water.
13. Empty the vial or test tube and rinse with distilled water.

Sampling procedure (composite sampling):

1. Define the area and interval at which you will sample across the area.
2. Put on a pair of clean, sterile gloves.
3. Take a soil sample by first gently pushing aside all live or dead plant matter. Make a small hole in the soil and use the scoop to take a sample at approximately 2 inches below the surface of the soil.
4. Tamp down the sample with a gloved finger and ensure it is level with the measurement line or rim of the scoop. Add the sample to a clean beaker.
5. Continue to the next sampling point, take a sample, and add it to the beaker with the previous sample. Keep track of how many scoops of soil were added to the beaker.
6. Continue to take soil samples until you have filled the beaker to 30% of its capacity, or until you have adequately sampled the area of interest.
7. Add two scoops of distilled water to the beaker for every scoop of soil that was added.
8. Stir vigorously until sample is thoroughly mixed.
9. Allow the mixture to settle for 15 minutes.
10. Rinse the soil EC meter with distilled water.
11. Turn on the device and insert in into the sample. Make sure the probe tip is inserted by at least 2 inches.

12. Wait for the reading to stabilize. This is indicated by the disappearance of the stability indicator (a small hourglass symbol).
13. Record the reading and other parameters of interest.
14. Turn off the device and rinse the probe with distilled water.
15. Empty the beaker and rinse with distilled water.

Water Quality sampling protocol

Materials needed:

1. Multiparameter water quality meter (with standard accessories)
2. 1413 µS/cm conductivity standard solution
3. Distilled water
4. Graduated cylinder
5. Wash bottle
6. Sterile gloves

Calibration:

Calibration procedures will vary by meter, but most will utilize the 1413 µS/cm conductivity standard. This guide is written for YSI instruments (Specifically the Pro2030). Calibrations should occur prior to each sampling session. For other meters, see the instruction manual for calibration procedures.

Barometer:

1. Calculate the true barometric pressure for your sampling site with the following equation (for meters corrected to sea level):
   (Corrected Barometric Pressure in mmHG) - (True BP = 2.5 * (Local Altitude in feet / 100)). For Bosque del Apache, the true BP is roughly 649.45.
2. Turn the meter on and use the up and down keys to highlight the barometer box on the run screen. Press enter.
3. Use the up and down arrows to enter the True BP value calculated in step 1. Press enter to save the calibration.

Specific conductance:

1. Put on a pair of clean, sterile gloves.
2. Clean the graduated cylinder with distilled water and allow it to dry.
3. Place the sensor into the graduated cylinder and add the 1413 µS/cm conductivity standard solution until the sensor is completely submerged. The sensor is located within two small holes at the top of the sensor body, near the cable.
4. Gently move the probe around to ensure any trapped air bubbles are released.
5. Turn the meter on and allow the readings to stabilize. Stabilization is indicated when the "[AS]" symbol next to each parameter stops flashing.
6. Press and hold the "Cal" key until the calibration menu appears.
7. Highlight specific conductance and press enter.
8. Select µS/cm and press enter. Use the up and down keys to set the values to 1,413. Press enter to begin the calibration.
9. "Calibration successful" will be displayed if the procedure was accepted. The meter will then return to the run screen. If the procedure is unsuccessful, an error message will be displayed. This may occur is the calibration solution is contaminated or degraded. Make sure the solution is fresh and all equipment is thoroughly cleaned with distilled water

prior to calibration. If problems still occur, refer to the troubleshooting section of the manual.

Dissolved oxygen (Quick DO):

1. Put on a pain of clean, sterile gloves.
2. Make sure the Quick DO feature is enabled in the System Setup menu.
3. Ensure the DO membrane and electrolyte solution is in good condition. These should be replaced every 2-3 weeks (see manual). Inspect for bubbles, wrinkles, tears, or other signs of damages.
4. Rinse the gray storage sleeve and sponge with distilled water. Invert it and gently shake a few times to allow any excess water to drain out. Install it over the sensor.
5. Turn the meter on and wait 5-10 minutes for the chamber to become saturated. Make sure the barometer is reading correctly.
6. Press and hold the "Cal" key until the calibration menu appears.
7. Highlight Dissolved Oxygen and press enter to begin the calibration. The calibration may take a few minutes to run.
8. "Calibration successful" will be displayed if the procedure was accepted. The meter will then return to the run screen. If the procedure is unsuccessful, an error message will be displayed. This may occur if the previous steps were not followed properly or if the DO membrane is unsuitable for use. Reperform steps 1-6. If problems still occur, replace the DO membrane and electrolyte solution. If problems still occur after that, refer to the troubleshooting section of the manual.

Canal water sampling:

1. Find or define your sampling locations. Ideal locations are catwalks, Langemann gates, culverts, or other structures that enable you to adequately sample throughout the water column. Ensure the meter was calibrated, has sufficient battery, and has enough storage for the amount of data you wish to collect.
2. Turn the meter on (wait 5-15 minutes if using polarographic sensor) and ensure the sensor guard is installed.
3. Place the sensor into the sample and allow the temperature reading to stabilize. Make sure that the water is moving 3-6 inches per second (depending on whether you have the blue or yellow membrane). If the natural flow of the stream is not sufficient, the sensor can be physically stirred throughout the water.
4. Once the readings stabilize, make sure save is highlighted and press enter. Record the data set number and your location elsewhere.

Groundwater sampling:

1. Ensure the meter has sufficient battery, was calibrated, and has enough storage for the amount of data you wish to collect.
2. Ensure the well pump is greased and all appropriate protocols are followed for the operation of each well. Operation can vary slightly among wells.

3. Calculate the purge time for each well you will sample (see Supplementary table 1).
4. Turn the well on. Observe the gauge for gallons dispensed per hour and adjust purge time as necessary.
5. After the well has ran for the entire purge time, take a bucket or other vessel large enough to completely submerge the sensor, and collect a water sample. Rinse the bucket twice before collecting the sample.
6. Turn the meter on (wait 5-15 minutes if using polarographic sensor) and ensure the sensor guard is installed.
7. Place the sensor into the sample and allow the temperature reading to stabilize. Make sure that the water is moving 3-6 inches per second (depending on whether you have the blue or yellow membrane). Physically stir the sensor throughout the water sample to achieve this.
8. Once the readings stabilize, make sure save is highlighted and press enter. Record the data set number and the well number elsewhere.

High temporal resolution soil moisture monitoring protocol

Materials needed:

1. Decagon Data Loggers
2. Soil and Media Moisture probes (5x per logger)
3. Computer with ECH2O Utility software
4. AUX to USB data transfer cable
5. T-posts (1x per logger, plus T post driver)
6. Zip ties (2x per logger)
7. 70% isopropyl alcohol wipes

Procedure:

1. Install batteries into the data logger. Inspect for corrosion or other residues.
2. Insert the AUX end of the cable into the COM port and insert the USB end into your computer.
3. Install the "ECH2O Utility" software and open the program. In the upper panel, press connect. If the device fails to connect, make sure the cable and ports are clean. You can also try pressing the reset button. It may take a few attempts for the device to connect.
4. After connecting, make sure the battery level is adequate, that the measurement interval is set to 1 hour, the time and date is correct, and that each sensor is set to "Soil and Media Moisture Probe".
5. In the top menu, select Actions, then device tools, and then select Test device firmware. This will perform a test of your firmware.
6. Data can be downloaded from the "data tab". Press disconnect and remove the cable from the COM port and from your computers USB port.
7. Collect probes and clean cable end and probes with isopropyl alcohol.
8. Bring probes, loggers, t-posts and driver, and zip ties to the area of interest. Install t-post and attach loggers with zip ties. Install probe cables in ports 1-5. Ensure the green light near the reset button is active.
9. Take the probe end of the cable and press it firmly into the soil at the desired location. Ensure the probe will not become dislodged. Record probe locations when necessary.
10. The logger should now record a measurement once per hour.