Final Report: Climate Change Refugia for Terrestrial and Aquatic Taxa in New Mexico

25 June 2025

Completed in partial fulfillment of Agreement # 23-CO-11221632-013

State Wildlife Grant # T-80-R-1

Megan Friggens, Rocky Mountain Research Station, Megan.friggens@usda.gov*

Karen Cooper Chaudhry, Rocky Mountain Research Station, Karen.CooperChaudhry@usda.gov

D. Max Smith, Rocky Mountain Research Station, David.Smith3@usda.gov

*For questions or comments

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Overview

This final report outlines the process used to assess variables important for identifying climate refugia for a wide range of vertebrate species (Morrelli et al. 2020). We use our results to compare the distribution of climate refugia across landscapes within New Mexico with respect to geographies considered in current conservation planning efforts. New Mexico's varied landscapes, from alpine peaks to desert basins, create natural laboratories for understanding how different species might persist through climate change. The goal of this 2-year project was to inform conservation strategies and protected area planning by identifying and characterizing the best set of indicators to identify both macro- and microrefugia for all vertebrate species and for aquatic ecosystems.

In Year 1, we identified variables that could measure or represent change in regional and local conditions or indicate the potential of sites to provide a buffer against change. These efforts are described in the Year 1 report, "Identifying and mapping climatically stable macro- and microrefugia in New Mexico." (Found here) In Year 2, we evaluated these indicators to identify those that are most important for identifying climate refugia among the varied vertebrate taxa and expanded our efforts to include aquatic ecosystems. This report outlines the efforts of Year 2 activities and presents the results of our analysis in two parts: 1) Terrestrial Species and 2) Aquatic Systems.

Part I of this final report focuses on terrestrial species and Part II describes analyses for aquatic resources. Each part describes the outcomes of the following objectives:1) Identify and test potential indicators of climate refugia; 2) Use selected indicators to identify micro-, macro-, and aquatic hydrorefugia within New Mexico; and 3) Evaluate the potential for Conservation Opportunity Areas in New Mexico to provide climate refugia. As a result of these findings, we generated several composite indices specific to different taxonomic and aquatic groups that also pertained to both large- and small-scale predictors of climate refugia. Parts I and II of this report are designed so that they can each be used as a stand-alone product, though Part II does reference some of the methods from Part I.

Data produced as part of this project can be accessed by contacting M. Friggens at megan.friggens@usda.gov

Acknowledgements

This analysis is part of a New Mexico Department of Game and Fish Share with Wildlife Project. We would like to thank several people that provided us with expertise and feedback during this process including Virginia Seamster, Matt Wunder, Karen H. Gaines, Rachel Loehman, Nancy Karraker, David Hawksworth, Estevan Muldavin, U.S. Forest Service R3 Water Resource group, and Chelcy Miniat.

This project was funded by the Rocky Mountain Research Station (RMRS) and through a grant awarded to RMRS by the U.S. Fish and Wildlife Service to support this Share with Wildlife Project (State Wildlife Grant T-80-R-1).

Part I. Climate Change Refugia for Terrestrial Species

Megan Friggens, Rocky Mountain Research Station, Megan.Friggens@usda.gov

Karen Cooper, Rocky Mountain Research Station, Karen.CooperChaudhry@usda.gov

1. Introduction

1.1. Background

Climate change poses an unprecedented threat to biodiversity, forcing species to adapt, migrate, or face potential extinction. As global temperatures continue to rise, identifying and protecting climate refugia - areas that maintain suitable conditions for species persistence - have become crucial for conservation planning (Cartwright 2018). These areas allow species to persist *in situ* or serve as retreat locations when surrounding conditions become uninhabitable (Keppel et al. 2012, 2015; Rojas et al. 2018). Methods for identifying climate refugia provide powerful tools for developing adaptation strategies that aim to conserve biological diversity (Morelli et al. 2020).

Because we have a limited capacity to generate information and data specific to all species existing within a landscape, climate refugia concepts provide a promising avenue for landscape-scale conservation planning, especially in the absence of species-specific data. However, the application of these concepts and the principles upon which they are based are not well defined for all systems and species. The majority of refugia studies to date involve plant species or ecosystems (Dobrowski 2011; Hegl et al. 2017; Cartwright 2018; Santoro et al. 2018; Ackerley et al. 2020; Duniway et al. 2021; Estevo et al. 2022; Haire et al. 2022; Stark and Fridley 2022; see Year 1 Report, Friggens and Chaudhry 2024). Of those studies that consider vertebrate species, some focus on specific taxa (e.g., birds [Carroll et al. 2017; Stralberg et al. 2018; Carroll and Noss 2020]; pika [Gentili et al. 2014]; mammals [Malakoutinakhah et al. 2019]), and others lump all taxa together (e.g., Dobrowski 2011; Carroll and Noss 2020; Haight and Hammill 2020).

Climate refugia can be considered at two scales. The first, macrorefugia, are areas that provide a buffer against climate extremes and offer sustained climatic suitability across broad areas and longer timeframes (Stralberg et al. 2018). The second, microrefugia, are smaller areas containing features that decouple local climates from surrounding changes, thereby buffering sites from extreme climate conditions (Ashcroft 2010; Cartwright 2018; Dobrowski et al. 2011). In general, macrorefugia are represented by metrics produced from downscaled Global Climate Model (GCM) projections (Stralberg et al. 2018) and largely reflect broad-scale gradients such as those generated by latitude, continentality, and the movement of air masses (Dobrowski et al. 2011). For terrestrial species, macrorefugia are commonly inferred based on the relationship between regional climates and the distribution of species (i.e., limiting climatic factors; Dobrowski et al. 2011) or simply as the relative change in climate conditions over time (e.g., Stralberg et al. 2018; Cartwright 2019). With respect to microrefugia, research has focused on a range of determinants of refugia quality including disturbance (Cartwright 2018), local temperature buffering (Estivo et al. 2022), moisture availability, landscape connectivity or intactness (Eigenbrod et al. 2015), or some combination of these factors (e.g., Dobrowski 2011; Haire et al. 2022; Stark and Fridley 2022). Microrefugia account for the potential for local terrain patterns to moderate regional climatic shifts (Dobrowski et al. 2011) and benefit species by either buffering local sites from extreme conditions within the landscape or maintaining more stable conditions over time (i.e., future conditions remaining relatively similar to current conditions; Hoffrén et al. 2022). Key mechanisms for this buffering effect at the local level include reduced net radiative flux through greater canopy cover or topographic features that promote cold air pools or create wind shelters (Ashcroft et al. 2009; Dobrowski 2011). Existing at finer scales, microrefugia can support isolated populations beyond their primary range boundaries and enable local dispersal and recolonization when conditions allow (McLachlan et al. 2005; Pearson 2006; Birks and Willis 2008; Provan and Bennet 2008).

We considered both macro- and microrefugia in an analysis of New Mexico habitats using data on climate, topographic, soil, vegetation and landscape heterogeneity metrics (**Supplemental 1, Tables 1.1 and 1.2**). This approach is novel; few studies have integrated analyses of both macro- and microrefugia simultaneously (but see Carroll et al. 2017; Stralberg et al. 2018; Haight and Hammill 2020). Past studies have presented information on a limited scope of species (e.g., birds, Stralberg et al. 2018) and it is unclear whether noted trends can be extrapolated to other species or locations. Although Haight and Hammill (2020) do consider a range of vertebrates, they focus on already threatened species, which are notable for their habitat specialization, a trait that may obscure landscape assessment. Therefore, we still need studies that test specific applications and suites of indicators for multiple taxonomic groups and for both common and rare taxa.

1.2. Objectives

The diversity of landscapes within New Mexico potentially offers both macro- and microrefugia for a wide range of taxa, including birds, amphibians, mammals, and reptiles, each with distinct habitat requirements and dispersal capabilities. Our objectives were to 1) Identify and test potential indicators of climate refugia across a broad range of terrestrial wildlife species; 2) Use selected indicators to identify micro- and macrorefugia within New Mexico; and 3) Evaluate the potential for Conservation Opportunity Areas (COAs) identified for New Mexico to provide climate refugia. To achieve these objectives, we reviewed existing literature on wildlife habitat and ecosystems and developed a rigorous process to identify the most appropriate indicators of climate refugia for New Mexico taxa. This step is important due to New Mexico's unique and diverse physical settings and the range of species of interest (Friggens et al. 2013). As a result of this analysis, we generated several composite indices that were specific to different taxonomic groups and pertained to macro- and microrefugia. We then compared and discussed these indices among the existing COAs.

2. Methods

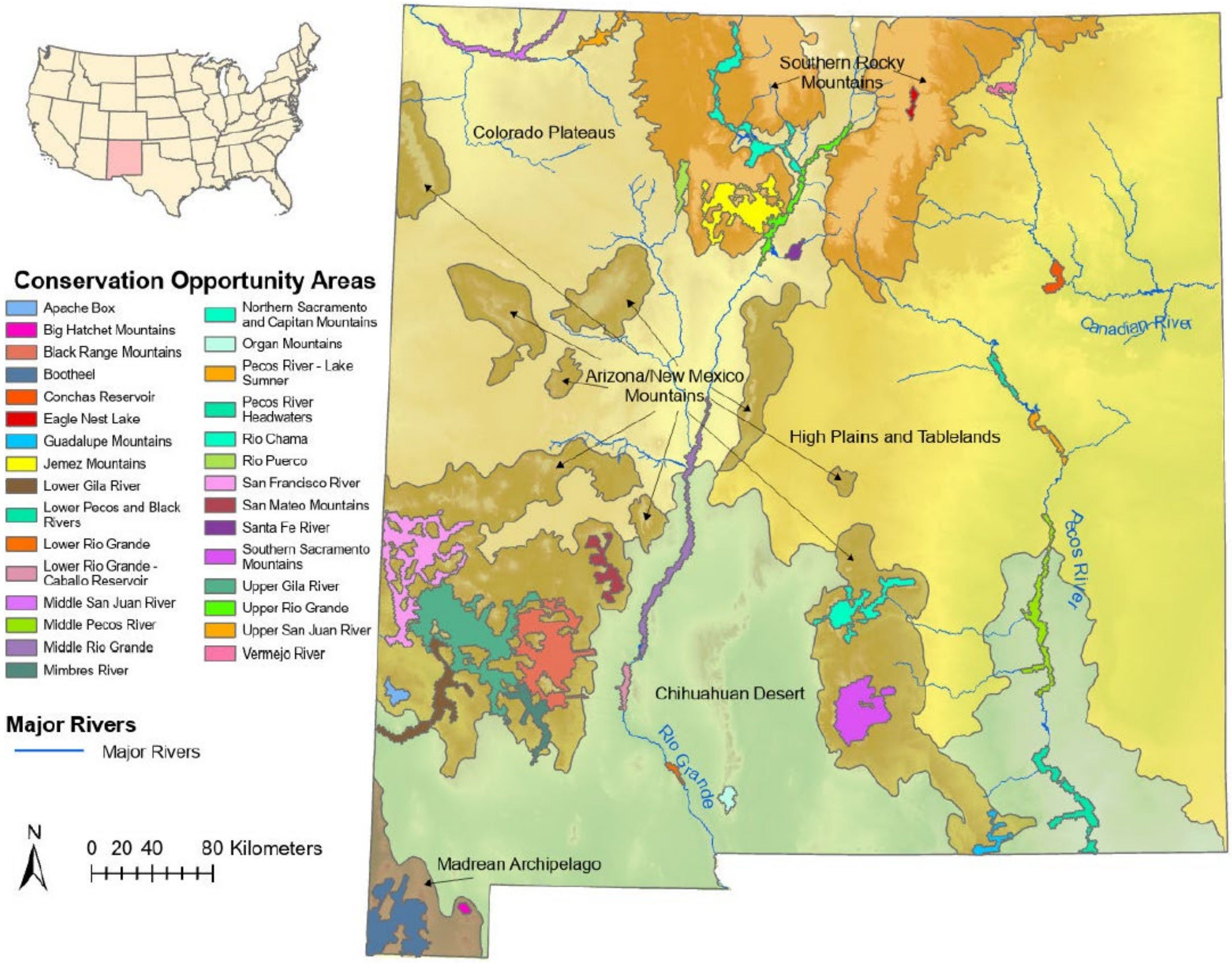


Figure 1. Major ecoregions and 30 Conservation Opportunity Areas (COAs) within New Mexico.

2.1. Study Area

This analysis is focused within the state of New Mexico, which covers an area of 315,194 km^2 (121,589 mi^2) and contains a diverse range of aquatic, desert, prairie, woodland, and forested ecosystems ranging in elevation from 867 to 4,013m (2,844-13,161 ft; NMDGF 2016). With more than 6,000 species of animals and 3,000 species of plants, New Mexico is considered to be among the most biodiverse in the contiguous U.S. (NMDGF 2016; Spackman 2023). This project was designed to facilitate efforts of the New Mexico Department of Game and Fish (NMDGF) to identify areas in which to implement climate-smart conservation actions as part of their 2025 comprehensive review and revision of the State Wildlife Action Plan (SWAP) for New Mexico. The SWAP considers species and habitats within six Level II ecoregions (Griffith et al. 2006; NMDGF 2016; CEC 2021; NMDGF 2025), denoted with modified Level III ecoregion names (Griffith 2010), that fall within New Mexico's boundaries (**Figure 1**): Upper Gila Mountains (Arizona/New Mexico Mountains), Warm Deserts (Chihuahuan Desert), Cold Deserts (Colorado Plateaus), South Central

Semi-Arid Prairies (High Plains and Tablelands), Western Sierra Madre Piedmont (Madrean Archipelago), and Western Cordillera (Southern Rocky Mountains).

To measure potential refugia across the entire state, we analyzed indicators and created composite indices based on hydrologic unit boundaries to the 12-digit (6th level), hereafter HUC12s. We obtained the HUC12 boundaries from the Watershed Boundary Dataset (WBD; USGS 2023). To assess the potential for areas currently managed for conservation to act as climate refugia, we compared characteristics of 30 delineated COAs. As part of their statewide effort to sustainably manage non-game wildlife within New Mexico, the NMDGF has identified COAs (**Figure 1**) as areas that contain an exceptionally high level of Species of Greatest Conservation Need (SGCN) diversity and higher-value habitats for wildlife; therefore, implementing conservation actions within these COAs may be especially beneficial for a diversity of SGCN and their habitats (NMDGF 2016, 2025). We used Ecoregion Level II boundaries and COAs to assess the potential for each ecologically distinct, broad region and each COA in the state to harbor climate refugia.

2.2. Literature Review

In Year 1, we searched scientific and government documents and summarized the current state of knowledge regarding climate change indicators in preparation for generating a list of climate refugia indicators (**Supplemental 1, Tables 1.1 and 1.2**). Details on those activities can be found in the Year 1 Final Report(Friggens and Chaudhry 2024).

Reflecting the status of research on climate change refugia, our list of refugia indicators was based almost entirely on studies of plant, especially forest, communities (**Table 1; Supplemental 1, Tables 1.1 and 1.2**). However, many of the indicators developed for these communities have relevance for wildlife; of particular importance are metrics that relate to the influence of topography on local climates. We selected these topography-related variables, in addition to other climate change indicators, to represent refugial potential that arises from proximity and stability factors. We selected a final set of indicators for wildlife climate change refugia based on three primary criteria:

1. They are traceable to an interdisciplinary understanding of the study system (*sensu* Kenney et al. 2018). Instead of simply identifying habitat associations for certain species, we sought out metrics that linked topography to climate or climate to ecosystem processes. In this way, we aimed to find environmental characteristics that are broadly important for a wide range of wildlife taxa.
2. Associated data must cover the entire state of New Mexico.
3. Metrics must represent conditions in one or more terrestrial habitats. The focus of the current analysis was on terrestrial systems, and we excluded many hydrological phenomena that do not directly relate to the provision of habitat for terrestrial vertebrate species.

Table 1. Metrics assessed for their potential to identify climate refugia in New Mexico. These metrics, identified from literature review and selected based on study criteria, were processed to provide meaningful indicators for terrestrial species and ecosystems. For each data type, we derived specific metrics and then conducted a series of analyses to test the potential relevance and relationships of each metric for use in estimating climate refugia for New Mexico taxa (See **Figure 2**). Data are grouped by category and refugial relationship; these relationships are hypothetical and based on information gathered in the literature review; none of these relationships have been supported with on the ground evaluations. Climate Change/Stability metrics measure absolute or relative change between current and future time periods. Climate Condition refers to metrics based on climate data that are used to indicate water deficit or drought. These may be used to assess current conditions or to evaluate areas of potential undesirable change under future, projected climate conditions. A full description of each metric can be found in the text. [A] = metric used to measure macrorefugia; [I] = metric used to measure microrefugia.

Category	Metric	Relevance	Refugial Relationship	Data Sources (or studies citing its use)
Species Richness	Mean for All Terrestrial Species, All Amphibians, All Birds, All Mammals, All Reptiles	Proxy for the biological importance or inherent value of location	Greater diversity = Better	EnviroAtlas https://www.epa.gov/enviroatlas
Climate Change/ Stability [A]	Backward and Forward Velocity	Values represent the distance between current and future climate analogues for a given time period	Lower = Less distance = Better	AdaptWest Project 2022; Carroll et al. 2017; Carroll and Noss 2020
Climate Change/ Stability [A]	Climate Dissimilarity	Represents the degree to which future climate will differ from current conditions	Context-specific	AdaptWest Project 2022; Carroll 2017
Climate Change/ Stability [A]	Temperature Change	Identifies the relative change in Annual and Seasonal Temperature	Lower or negative = Better	WorldCLIM: https://worldclim.org/data/v1.4/cmip5_30s.html
Climate Change/ Stability [A]	Percent Historic Precipitation	Identifies areas likely to have higher or near normal precipitation	Higher = Better	WorldCLIM: https://worldclim.org/data/v1.4/cmip5_30s.html
Climate Condition: Climate Change [A]	Climatic Water Deficit (CWD); Change CWD	Measure of water balance	Lower = Better	Ackerley et al. 2020; Schlaepferet al. 2022
Climate Condition: Climate Change [A]	Climatic Moisture Index (CMI): Change CMI	Measure of water balance	Context-specific	CMIP5 data; Stralberg et al. 2018

Category	Metric	Relevance	Refugial Relationship	Data Sources (or studies citing its use)
Climate Condition [A]	Heat Moisture Index (HMI)	Measure of temperature and water balance	Context-specific	CMIP5 data; Haire et al. 2022
Topography [I]	Elevation	Associated with temperature, moisture, and seasonality gradients	Higher = Better	Digital Elevation Model (DEM) https://databasin.org/datasets/3cf598b2d67b4f9f8e3ff47fd5b5ae37/
Topography [I]	Aspect	Proxy for solar insolation, evaporative demand, and protection from wind/desiccation	South-facing = Worse	DEM-derived; Haire et al. 2022
Topography [I]	Slope	Used to gauge exposure to solar energy	Lower = Better	DEM-derived; Cartwright 2018
Topography [I]	Curvature	Proxy for solar radiation and protection from wind/desiccation	Concave = Better	DEM-derived
Topography [I]	Northness	Represents exposure to incident radiation	Greater presence = Better	DEM-derived
Topography [I]	Landform	Can indicate areas of pooling/water holding capacity or shade potential (canyon walls)	Catchment-like areas = Better	DEM-derived; Jasiewicz and Stepiski 2012
Topographic Index [I]	Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)	Tendency of an area to drain of water	Higher values = Wetter areas = Better	https://edna.usgs. gov/; Gsech et al. 2002;; Lang et al. 2013; Millard and Richardson 2015; Cartwright 2018; O'Neil et al. 2019; Stark and Fridley 2022
Topographic Index [I]	Heat Load Index (HLI)	Direct measure of incident radiation	Lower = Better	Carroll et al. 2017

Category	Metric	Relevance	Refugial Relationship	Data Sources (or studies citing its use)
Topographic Index[I]	Topographic Position Index (TPI)*	Proxy for solar radiation and protection from wind/desiccation	Lower = Pixel lower than the surrounding areas = Better	DEM-derived
Landscape Diversity[I]	Topographic	Includes Vector Ruggedness Measure, Terrain Ruggedness Index, Ruggedness Index, Standard Deviation of Slope, Shannon Diversity Index for elevation, HLI, and aspect and slope in a 3 x 3 ($90m^2$) window	Higher = Better	DEM-derived; Carroll et al. 2017; Malakoutinakhah et al. 2018; Ackerley et al. 2020
Landscape Diversity[I]	Vegetation	Includes Shannon Diversity Index for Existing Vegetation Class, Height, and Canopy Cover	More diverse = Better	Landfire; GAP/LANDFIRE data Version 3.0 (2011)
Landscape Diversity[I]	Climate Novelty	Ranked value that represents climate diversity	More diverse = Better	AdaptWest Project 2022
Soils[I]	Percent Soil Bulk Density (SBD), 1m	Indicator of drought sensitivity	Lower = Better	Kerns 2000; Hengl et al. 2017
Soils[I]	Soil Water Availability (SWA)/Available Water Capacity (AWC)/Available Soil Moisture	Indicates capacity for soil to hold water	Higher = Better	Natural Resources Conservation Service (NRCS) U.S. Soils database: https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/

2.3. Spatial Data

Potential climate refugia indicator data were processed and summarized for three spatial extents: Ecoregions, Conservation Opportunity Areas (COAs), and Hydrological Unit Code 12 (HUC12) watersheds. We downloaded boundary data files for level-12 Hydrological Unit Codes (HUC12 watersheds) from the U.S. Geological Survey's (USGS's) National Record Clearinghouse (currently National Map at https://apps.nationalmap.gov/downloader/; USGS 2016). We obtained COA and Ecoregion data from NMDGF.

We prepared downloaded spatial data by projecting into the NAD 1983 UTM Zone 13N coordinate system and clipping to the state of New Mexico. Preparation and analysis of various climate, topographic, soil, species richness, and vegetation data were completed using ArcGIS Pro 4.2 and several tools within Spatial Analyst, Arc Hydro, and Surface Parameters ; Spatial Statistic Toolbox; and the Geomorphology and Gradient Metrics Tools and Diversity Tools (**Supplemental 1, Table 1.4** for full description) and R 3.4.4 (**Supplemental 1, Table 1.5** for list of packages).

Species Richness

Biodiversity itself serves as an indicator of refugia potential (Carroll et al, 2017; Barrows et al. 2020; Carroll and Noss 2020), representing an area's capacity for population recovery through metapopulation dynamics and colonization and possibly indicating the past presence of climate refugia (Kocsis et al. 2021). The relationship between biodiversity and abiotic factors such as soils, geology, and topography is used to identify biologically important refugia (Stein et al. 2014). Approaches to identify refugia as they relate to biodiversity typically incorporate factors such as topographic complexity, microclimate variation, connectivity, and habitat stability over time (e.g., Ashcroft 2010; Stralberg et al. 2018; Carroll and Noss 2020).

Species richness can be used as a surrogate for measuring biodiversity to gauge the relative conservation value of a particular area (www.epa.gov/enviroatlas; EPA 2023). We obtained species richness data for New Mexico to use to validate variable selection for potential refugia metrics (**Figure 2**). Species richness data for reptiles, mammals, birds, and amphibians were obtained from the EnviroAtlas (https://www.epa.gov/enviroatlas). Species richness estimates were based on USGS Gap Analysis Program (GAP) maps of potential habitat; this project has modeled habitat for 1,590 terrestrial vertebrate species. Data are available for several types of modeled richness; we used data on mean richness of all terrestrial species and mean amphibian, bird, mammal, and reptile richness summarized at the HUC12 unit.

Macrorefugia

We define "macrorefugia" as areas with higher climate stability as measured by lower relative change in current versus future conditions or the presence of less extreme or less dry conditions in both current and future landscapes. We only included metrics that have a clear and consistent relationship with climatic conditions relevant to New Mexico vertebrates. For instance, many topographic indices measure radiant exposure and water holding capacity. Sites that had less exposure to radiant energy or more water holding capacity were considered positive indicators of refugia under future climate conditions, which include projections for warmer temperatures and more variable precipitation.

Climate indicators represent both absolute and rates of change in climate conditions, which relate to species' ability to adapt to environmental changes or the distance they are required to disperse to track suitable conditions. To identify climate refugia for wildlife, we considered several factors, including: time window, potential redundancy among metrics, and how well a refugia indicator corresponded to observed habitat use (Friggens and Chaudhry 2022). We measured climate stability based on the calculated change between current and future temperature and precipitation and calculated additional climate metrics representing relative conditions across the landscape. We also considered recently developed data on climate velocity, represented as the rate (°C/km/yr) and direction of change in climate conditions associated with species presence, which has proven to be a useful concept in identifying potential macrorefugia for vertebrate species (Isaak et al. 2016; Carroll et al. 2017; Michalak et al. 2018).

Climate Variables

Climate stability metrics were calculated using gridded climate data from 1km WorldClim bioclimate variables (Fick and Hijmans, 2017; see **Supplemental 1, Table 1.3**) and 4km Bureau of Reclamation (BOR) hydrology variables (i.e., Evapotranspiration [ET], Potential Evapotranspiration [PET], Snow Water Equivalent [SWE]; BOR 2013; https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). For each climate variable, we obtained current or observed values (1970-2000 time period) and projections for the year 2050 (2041-2060). Future estimated climate was generated by an ensemble of 15-17 Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs under Representative Concentration Pathway (RCP) 4.5 (Fick and Hijmans 2017). To estimate change, we calculated the magnitude of change in temperature (°C) and percent change and percent of normal for precipitation variables. We calculated the mean and standard deviation of each climate variable for each HUC12, SWAP ecoregion, and COA.

We considered three climate indices: Climatic Moisture Index (CMI), Heat Moisture Index (HMI), and Climatic Water Deficit (CWD). CMI is calculated as the difference between annual precipitation and annual potential evapotranspiration (mm precipitation – mm potential evapotranspiration). CMI is available through the World Water Development Report II (Vorosmarty et al. 2005; https://databasin.org/datasets/65a60b2ba42b4a9281e915a8585be8ec/) at a resolution of 40km. We calculated a higher resolution version (4km) based on hydrological data (Annual Precipitation, Actual Evapotranspiration [EAT], PET) downloaded from the BOR (CMIP5, RCP4.5 multimodel ensembled data) for the period 1970-2010 (BOR 2013). HMI measures water balance and considers temperature. We use the following to calculate HMI:

$$\frac{(\text{Mean Annual Temperature } + 10)}{(\text{Mean Annual Precipitation}/1000)}$$

We estimated HMI using the raster calculator and the WorldClim bioclimate variables. CWD is used to predict spatial patterns in vegetation (Ackerly et al. 2015), long-term climate change (McIntyre et al. 2015), and impacts of drought (Das et al. 2013; Anderegg et al. 2015; Flint et al. 2018) and has been used to assess the potential vulnerability of vegetation to future climate change (Franklin et al. 2013; McCullough et al. 2016; Thorne et al. 2017). CWD is calculated as:

$$(\text{Potential Evapotranspiration (PET) - Actual Evapotranspiration (EAT)})$$

and captures seasonally integrated, excess energy loading relative to water availability. Schlaepfer et al. (2022) provides CWD data at 10km scale for annual and quarterly intervals for historic (1970-2010) and future (2021-2060) time periods. We also calculated a 4km version of CWD based on hydrological data (EAT, PET) provided by the BOR (BOR 2013). Where CMI and HMI represent current conditions and are used to identify areas of potential importance for biological diversity, higher values of CWD represent undesirable conditions.

AdaptWest (AdaptWest 2022; https://adaptwest.databasin.org/) provides spatial datasets for climate novelty, dissimilarity, and forward and backward climate velocity. These data were generated through a multivariate analysis of 11 bioclimate variables using a Principal Components Analysis (PCA). We downloaded data generated at a 1km resolution based on an ensemble of 15 CMIP5 GCMs under RCP 4.5 to correspond to other available data. Climate novelty is a ranked value that represents climate diversity, which is assumed to correspond to niche diversity and is considered among the suite of microrefugia indicators (see next section). Climatic dissimilarity is estimated as the Euclidean distance in PCA climatic space between current and future climate at a pixel (Carroll 2018). Measurements of climate velocity (°C/km/yr) are generated by considering the future climate condition of a pixel and calculating the distance between that pixel and the nearest existing pixel that currently has the same climatic condition. Backward velocity is created from the future perspective; lower values (i.e., less distance) indicate that a given area is mimicking the conditions of nearby areas. Forward velocity is created from the current perspective and is used to represent the distance (and speed) at which species must migrate over the Earth's surface to sustain constant climatic conditions (Carroll et al. 2015). We used velocity values estimated for the change that might occur during the period covering 1995 to 2055. We calculated the mean and standard deviation of climate velocity and climate dissimilarity for each HUC12, SWAP ecoregion, and COA.

Microrefugia

Microrefugia account for the potential for local terrain patterns to moderate regional changes in climate (Dobrowski et al. 2011) and benefit species by either buffering local sites from extreme conditions within the landscape or maintaining more stable conditions over time (e.g., future conditions remaining relatively similar to current conditions; Hoffrén et al. 2022). Topographic, soil, and vegetation variables were considered for their potential to identify areas that provide a buffer for extreme conditions or support more mesic conditions at a site. Following Stalberg et al. (2018), we also considered climate indicators that measure the current climatic diversity of an area and other topographic and vegetation-based metrics of landscape heterogeneity in our analysis of microrefugia.

Topographic Variables

We downloaded a 1 arc-second (~30 m resolution) Digital Elevation Model (hereafter DEM30) from DataBasin (supplied by the USGS). Elevation has been used as an indicator of climate refugia (Stark and Fridley 2022) such that higher-elevation areas are associated with greater potential for drought refugia (Cartwright 2018). The DEM30 represents distance above sea level in meters, and we calculated mean elevation for each HUC12 for our analysis. From this data, we derived topographic variables and topographic indices representing conditions that might influence local heat and moisture conditions (**Table 1**). We calculated aspect (degree and radian), slope (percent and degree), and curvature. Aspect is the direction from the highest point to the lowest point that a pixel faces. We calculated aspect as a degree where 0 and 360 = North, 60 = East, 180 = South, and 240 = West and on a linear scale based on the following calculation:

$$Aspect = \frac{(sin\ (degree))}{180}$$

In North America, south-facing slopes receive more solar radiation and are less mesic whereas northern slopes are potentially cooler and wetter. For each HUC12, we calculated northness as:

$$(cos(Aspect(radians)))$$

This calculation results in a value ranging from -1 (southward) to 1 (northward) with 0 representing either east or west. For each HUC12, we calculated the proportion of the HUC12 with a northness value >0.5. Slope is calculated as the percent change in vertical distance (m) over change in horizonal distance (m). Areas with steeper slopes are expected to be at higher risk of erosion and have shorter precipitation residence times. Curvature represents the convergence and divergence of flows across a topographic surface. We used mean value of slope and curvature for each HUC12 in the analysis. We used the Geomorphon landforms tool (Jasiewicz and Stepiski 2012) to classify the landscape into 10 common landform types: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit (Jasiewicz and Stepiski 2012) based on elevational (DEM30) differences within the three pixels surrounding a target cell. We calculated the percent of each HUC12 classified as a hollow, valley, or pit to use in later analyses.

We considered four topographic indices in our analysis: Compound Topographic Index (CTI), Topographic Wetness Index (TWI), Heat load index (HLI), and Topographic Position Index (TPI). These indices were calculated using ArcGIS Pro 4.2 tools (**Supplemental 1, Table 1.4**) and raster calculator. The CTI and the TWI are interchangeable indicators of terrain-driven variation in soil moisture. Both integrate potential water supply for upslope catchment area and downslope drainage for each cell in a DEM (TWI, Kopecký et al. 2021). We calculated CTI as:

$$ln(\frac{As}{(tan(\beta)})$$

where *As* = Area Value calculated as (flow accumulation + 1) * (pixel area in m^2) and β is the slope expressed in radians. The TWI calculation is:

$$ln\left(\frac{Adjusted\ flow\ accumulation}{tan\ (Slope)}\right)$$

The HLI integrates aspect and slope to quantify direct incident radiation. The TPI, an index based on the curvature of the Earth's surface, is used to distinguish topographic features including hilltops, valleys, upper or lower slopes, and flat plains. The TPI compares the elevation of each cell in the DEM30 to the mean elevation of a set number of cells surrounding the target cell such that positive values indicate elevated positions and negative values represent depressions (Weiss 2001).

Soil

Soil characteristics can also indicate local microrefugia potential (Carroll et al. 2017; Cartwright 2018; Ackerly et al. 2020), especially where the thermal inertia of moist soils buffers surface temperature changes (Ashcroft and Gollan 2013), with soil moisture determined by vapor pressure deficit, topographic position, and soil texture (Ashcroft et al. 2013). We processed soil properties from several datasets derived from the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases (NRCS). The STATSGO is a broadly based inventory of soils that are cartographically shown at a mapped scale of 1:250,000 for most of the U.S. SSURGO datasets consist of mapped and tabular data based on observations and lab analysis of soil properties collected by the National Cooperative Soil Survey (Natural Resources Conservation Service

[NRCS], various dates). We downloaded data processed by the Conservation Biology Institute for New Mexico and adjacent states from DataBasin (http://app.databasin.org). This dataset, based on the STATSGO2 1:250,000-scale U.S. soils database (soil descriptions from the NRCS website, http://ortho.ftw.nrcs.usda.gov/cgi-bin/osd/osdname.cgi)provided us with basic characteristics including soil order, drainage class, texture, climate regime, and caliche (special diagnostic horizon). From this dataset, we processed information relating to minimal average depth to bedrock; average water storage; and water storage at 0-50, 0-100, and 0-150 cm depths. We also summarized primary soil order, texture, and climate per HUC12, but this data was not used in later analyses.

We obtained soil bulk density (SBD) data from gridded data at 250m (SoilGrids250m -Hengl et al. 2017) and 800m resolution (Kern 2000; https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/). SBD), measured as g/cm^3, represents the mass of solid particles in each volume of soil, including sand, silt, clay, and organic matter. Lower SBD is associated with higher porosity, which in turn relates to soil water holding capacity (Cartwright, 2018); higher SBD is associated with greater drought sensitivity (Cartwright et al. 2020). SoilGrids250m is derived from an ensemble of machine learning algorithms used to relate empirical soil profile data to remote sensing data. The Kern (2000) dataset covers the contiguous U.S. and provides bulk density; mineral depth; and fractions of sand, clay, and rock fragments. For this study, SBD was summarized from SSURGO and STATSGO tabular data, joined to source feature data from the NRCS, and then converted to an 800m raster using the cell center to assign the values (based on methodology in Kern 1995). This layer was used to fill in blank areas within the 250m resolution data.

Landscape Heterogeneity

Measures of landscape heterogeneity, which represent local variation in topographic, vegetation, or climate conditions, are often considered a proxy for biological diversity (Carroll et al. 2017; Malakoutinakhah et al. 2018; Stalberg et al. 2018; Carroll and Noss 2020). As a result, assessing the degree of landscape heterogeneity (e.g., altitudinal gradient; Malakoutikhah et al. 2018) has emerged as a popular way to help identify refugia. The primary assumption underlying studies of landscape heterogeneity is that increasing variation in local terrain or microclimates increases the number of locally available niches. In turn, high landscape heterogeneity benefits species by reducing the distance needed to travel to find new suitable habitat or buffered sites as regional conditions change.

We calculated diversity metrics ("Ecosystem/ Ecotypic Diversity" sensu Sayre et al. 2014; Carroll et al. 2017) from climate, landform, lithology, and land-cover data (Sayre et al. 2014; Carroll et al. 2017) to measure landscape heterogeneity. We used climate novelty (AdaptWest, 2022), available at a 1km resolution, to represent climate diversity. AdaptWest's measure of climate novelty is based on a multidimensional analysis of multiple climate and precipitation variables and ranks areas based on their current degree of climate diversity.

We calculated local landscape heterogeneity based on topography using the Terrain Ruggedness Index (TRI; Riley et al. 1999), Vector Ruggedness Measurement (VRM), and Roughness (**Supplemental 1, Table 1.4**). The TRI measures elevation differences among a grid cell and its neighbors to highlight terrain variability (Riley et al. 1999). Specifically, TRI is the square root of the average elevational difference between a cell and each of its 8 neighboring cells. The VRM is a function that uses both slope and aspect in a single measure to capture variation in a threedimensional space. Typical values for natural terrains range between 0 and 0.5, with rugged landscapes often defined by values > 0.01 or 0.02. Roughness measures the mean magnitude of change in the gradient or slope in a given window.

We calculated Shannon and Simpson Diversity Indices for elevation, slope, aspect, HLI, and vegetation classes within 3x3 and 9x9 moving windows using Diversity Tools (https://apl.maps.arcgis.com/home/item.html?id=11caf84c98d04d498cf40d0e478f9f13). The Simpson's Diversity Index was calculated as:

$$\mathrm{D} = \mathrm{Sum}\left(\frac{ni(ni-1)}{N(N-1)}\right)$$

where *ni* is the number of individuals or pixels in group *i* and *N* is the total number of groups in the sample. The Shannon's Diversity Index (or Shannon-Weiner Diversity Index) is calculated as:

$$\mathrm{H}' = \frac{(N * \ln(N)) - Sum\big((ni * \ln(ni))\big)}{N}$$

where *N* is the total number of species or groups and *ni* is the number of individuals or pixels in species/group *i*.

D is a weighted arithmetic mean of the proportional abundance of species/groups and represents the probability that two individuals randomly selected from a sample will belong to the same group. D values range from 0 to 1, with 0 representing infinite diversity and 1 representing no diversity. In comparison, the H' is more sensitive to the number of groups in a sample and thus is biased toward measuring group richness. H' values usually range between 1.5 and 3.5 with higher values indicating greater group richness and greater group evenness.

Continuous variables were categorized into bins to facilitate calculations. We created bins for elevation based on 100m intervals and translated aspect into 8 categories representing North (N), West (W), East (E), South (S), NW, SW, SE, and NE. D and H' values were averaged for each HUC12. We also calculated the standard deviation of slope in a 3x3 and 9x9 unit space as a measure of topographic diversity.

We calculated D and H' values for three different types of vegetation data: 1) The GAP/LANDFIRE (LF) National Terrestrial Ecosystems data, Existing Vegetation Type (EVT) (GAP/LF data Version 3.0, 2011; Comer et al. 2002; Homer et al. 2015) available at a 30m x 30m cell resolution; 2) Existing Vegetation Height (EVH); and 3) Existing Vegetation Cover (EVC) from the LF vegetation layers. EVT data represent the current predominate species composition at a given site, EVH data identify the average height of different vegetation classes, and EVC data denote the vertically projected percent cover of the live canopy layer. All LF data were downloaded on 1/26/2024 from landfire.gov (USGS 2019). We reclassified EVT and EVC data to eliminate numerous very rare group types using the Geoprocessing tool. Specifically, the EVH CLASSNAMES field was reclassified to produce EVH_Groups_NW consisting of six groups: (1) Barren, developed, sparse and quarries; (2) cultivated/Nass; (3) herb height 0.1-1m; (4) open water, snow/ice (NODATA);(5) shrub height 0.1-3.0m; and (6) tree 1-38m. The EVC CLASSNAMES field was reclassified into EVC_TSH_NV consisting of four groups: (1) herb % cover; (2) non-vegetation % cover; (3) shrub % cover; and (4) tree % cover.

2.4. Indicator Analysis

We implemented workflows to analyze: 1) Macrorefugia variables based on climate data; 2) Microrefugia variables reflecting topographic, vegetation, and soils data; and 3) Microrefugia variables representing landscape heterogeneity (climate, vegetation, and topographic diversity data) **(Figure 2a**). We analyzed the entire suite of variables (**Table 1; Supplemental 1, Table 1.2**) using correlation and regression methods to determine the relationship of variables to each other and to species richness, and we also used machine learning methods to test the relationship between landscape heterogeneity and biodiversity (**Figure 2**). Results of these analyses were used to select a subset of datasets that best represent potential indicators of climate macro- and microrefugia for HUC12 watersheds (**Figure 2; Tables 1, 2**). For continuous data, we calculated the mean value for each HUC12. For discrete data, we calculated the percent area of each HUC12 for each category or a ratio reflecting desired properties or conditions of a given class within each HUC12. We assessed both macro- and microrefugia indicators for all vertebrates combined and then for each of the following taxonomic groups: amphibians, birds, mammals, and reptiles.

As mentioned above, we tested the relationship between metrics of landscape heterogeneity and species richness for amphibians, birds, mammals, and reptiles using the Forest-based algorithm of the Forest-based and Boosted Classification and Regression Tool (Random Forest; RF) in ArcGIS Pro 4.2 (**Supplemental 1, Table 1.4**). We excluded 15% of each run to test model performance and ran each model at least 3 times to assess average performance of metrics. The top four most important landscape heterogeneity variables, as determined by RF (**Supplemental 2, Figure 2.1**), were then used in further analysis of microrefugia indicators, as described below.

We explored correlations among climate, topographic, soils, and vegetation variables and between each set of these variables and species richness metrics using Pearson correlations in RStudio 2024 (04.2 +764, R 3.4.4; **Figure 2b; Supplemental 1, Table 1.5**). We identified redundancies, biases, and performance of potential macro- and microrefugia indicators using an iterative process based on the Exploratory Regression (Ordinary Least Squares [OLS]) Tool in ArcGIS Pro 4.2 and R 3.4.4 (R code available on request). Where we found significant ($p < 0.05$) and strong ($r > 0.7$) Pearson correlations between indicator variables, we selected the best representative for inclusion in later analyses and dropped redundant variables (**Figure 2**). These inclusion choices were informed by the results of the Exploratory Regression Tool. The Exploratory Regression Tool considers a range of candidate explanatory variables through an iterative process using OLS on every possible combination of variables to output a model based on maximizing variable performance and minimizing model biases and spatial autocorrelations. We used OLS to regress climate, topographic, vegetation, and soil variables against species richness to identify coefficients and multicollinearity across all variable sets (**Figure 2b**). We implemented OLS using default parameters, including a correlation coefficient cutoff of 0.05 and a maximum Variance Inflation Factor (VIF) of 7.5. Where multicollinearity was found (VIF > 7.5), we removed variables with the highest VIF scores and re-ran the tool on the remaining subset. We repeated this process until no variables had a VIF > 7.41. Where variables had similar VIFs, we considered the summary of variable significance provided by OLS to identify “good” (significant [i.e., higher percent significance] and consistent relationship) indicators for retention and “poor” (less significant or more varied relationship) indicators for exclusion. We used results indicating the significance and sign of variable coefficients to evaluate potential relationships between indicators and the richness of different taxonomic groups. We used model performance metrics (Adjusted R^2, Jarque-Bera p-values, Moran's I) reported by OLS analysis to evaluate potential biases in the sample data (e.g., non-normal distribution, spatial autocorrelation) that may lead to the identification of spurious relationships.

2.5. Optimization and Calculation of Composite Indices

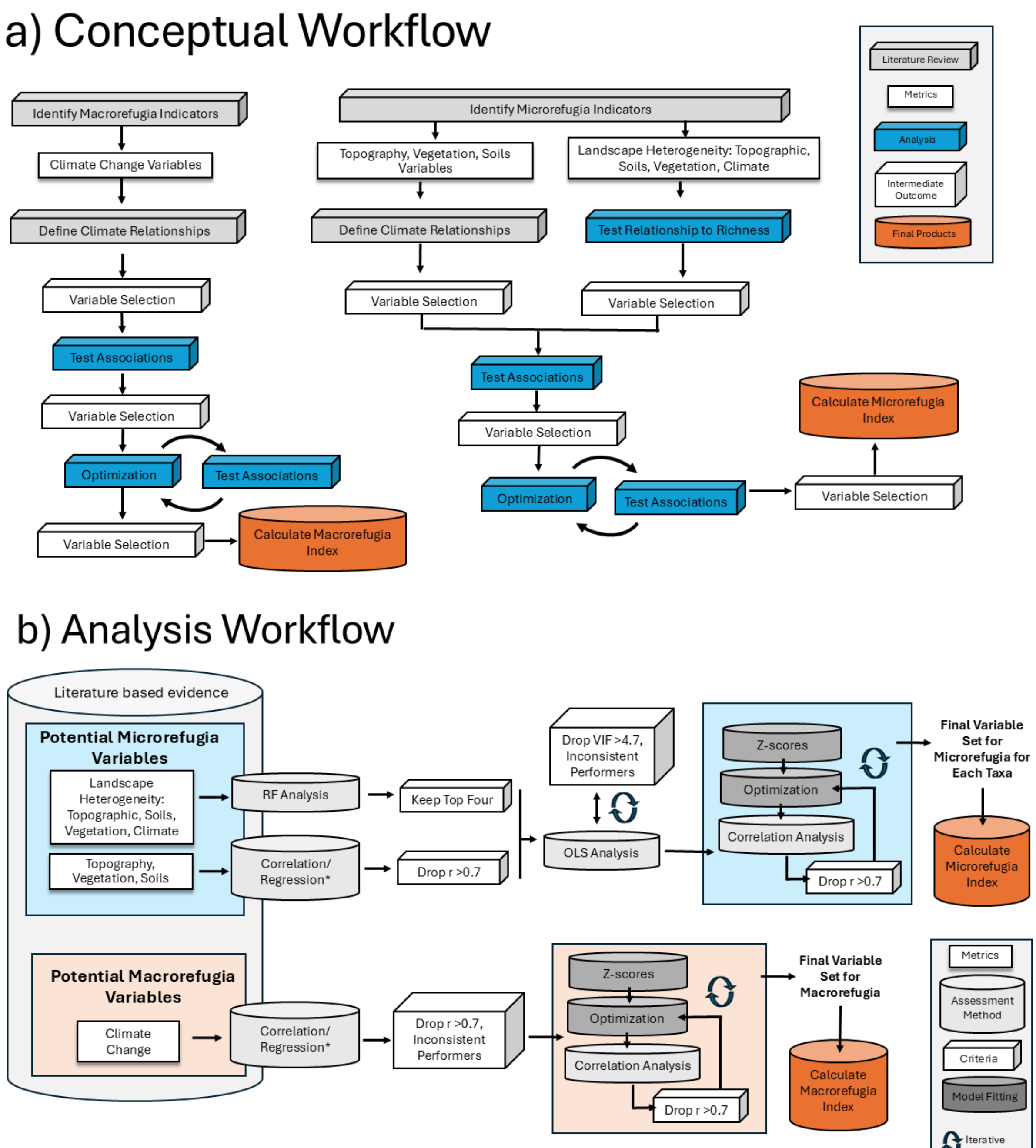
After obtaining a final set of indicators to represent macrorefugia and each of four microrefugia (one for each taxonomic group) indices, we transformed raw values using Z-scores to reduce potential biases arising from variation in the distributions of different metrics (Becker et al. 2017). Prior to standardization, we multiplied variables with inverse relationships to species richness or refugia (see Refugial Relationship column in **Table 1**) by -1. Resulting Z-scores, which typically fall between -4 and +4, were then used in optimization routines and to calculate final composite scores, in which higher scores indicated greater refugia potential.

We determined the most appropriate weights for each standardized indicator to ensure that each contributed equally to the final calculated composite index representing macro- or microrefugia (Paruolo et al. 2013; Becker et al. 2017). Weights were optimized using the Constrained by Linear Approximation (COBYLA) optimization algorithm implemented in SciPy (Powell 2009; Virtanen et al. 2020; https://docs.scipy.org/doc/scipy/) through the NLopt function (non-linear optimization routines) in R (Johnson 2008), with methodology guidance refined through consultation with conversational AI (Claude by Anthropic). We included a minimum constrained weight of 0.15, no maximum weight, and required all weights to sum to 1. We included entropy and variance penalties to encourage spread of values and discourage uniform and extreme-weight distributions. Standardizing variables often led to new correlations among variables, which were noted during optimization runs. Where found, we re-ran optimization on a reduced dataset until no two variables had a strong Pearson correlation coefficient ($r > 0.7$).

We calculated a composite index for macrorefugia and microrefugia (for each taxonomic group) within each HUC12 as:

$$Composite\ Index\ (CI) = \sum_{i}^{n} a_i * x_i$$

where *a* is the optimized weight of variable *i* and *x* is the value for the indicator variable *i*. Final composite scores were standardized to a value between 0 and 1. Higher values represent greater potential for refugia to be present.



*Correlation/Regression analysis to assess redundancy among variables and with species richness values

Figure 2. (a) Conceptual and **(b)** Analytical workflow for analysis of indicator datasets. **a)** Separate workflows were used to identify and assess macrorefugia (climate-based) and microrefugia (landscape-based), although we used similar steps for each including literature review, identification, evaluation, validation, exploratory statistics, and final optimization. Existing research informed the identification of potential indicators (see Year 1 report), which were then evaluated through review of experimental and theoretical research products or statistical tests where relationships were hypothesized but not validated in the literature (e.g., landscape heterogeneity). We then evaluated variables for their potential to inform conditions specific to New Mexico and New Mexico wildlife and identified potential redundancies among existing variables. We

Figure 2 (cont.). iteratively engaged in this process until we identified the best set of variables that consistently provided information on a range of potential conditions while also minimizing redundancy. After identifying a subset of meaningful indicators, we identified optimal weights that ensured that each variable was contributing equally to a final composite index representing macro- or microrefugia. **b)** We used Random Forest, Pearson Correlation, and Exploratory Regression methods to assess potential indicator candidate variables (see text for specific details). Specific workflows depended upon the nature of the variable and the level to which the relationships with refugia were established within the literature. Assessment methods are indicated in light grey icons and models used to process data are indicated in dark grey. White boxes indicate decision points (and criteria) where potential predictors were either included or dropped from further analysis. Transformation of raw values and optimization algorithms generated new correlations among variables, and we iteratively repeated this process until we identified the best set of indicator data that exhibited minimal redundancy.

3. Results

3.1. Refugia Indicators

Initial analysis showed little difference in the performance of Shannon versus Simpson Indices and high correlations between values generated at 3x3 and 9x9 windows (**Supplemental 1**, **Figure 2**). Therefore, all subsequent analysis used only Shannon 3x3 estimates. RF analysis of diversity indicators showed highly variable outcomes among the different taxa (**Table 2**; **Supplemental 2, Figure 2.1**). Diversity metrics representing the structural composition of vegetation were important for predicting amphibian and reptile species richness. Bird and mammal species richness was better explained by diversity metrics that describe local elevational differences (e.g., Roughness, VRM). Nine metrics of landscape heterogeneity (H' of elevation, EVH, and geomorphology; slope standard deviation [stdev]; CTI stdev, mean roughness, mean VRM, and mean novelty) were important for at least two of the four taxonomic groups. No one metric was the topmost important variable set for more than one taxonomic group (**Table 2**).

Table 2. Top six most important predictors of species richness for four taxonomic groups in New Mexico. For each taxon, most of the variation in richness was predicted by the topmost variable (**Supplemental 2, Figure 1.2**). A total of 15 metrics representing landscape heterogeneity were tested. We used Shannon Diversity Index (SDI) or the standard deviation (stdev) of elevation, slope, aspect diversity, and topographic indices (e.g., Compound Topographic Index [CTI], geomorphology) to represent heterogeneity within each 12-digit Hydrological Unit Codes (HUC12). Novelty is a ranked value indicating the degree to which a pixel contains unique climate characteristics as compared to neighboring pixels based on a multidimensional analysis of temperature and precipitation characteristics. SDIs for three vegetation classes (Existing Vegetation Height classes [EVH], Existing Vegetation Canopy [EVC], and GAP vegetation classes [GAP]) were also included. Additional abbreviations include DEM = Digital Elevation Model, Geomorph = geomorphology, HLI = Heat Load Index, VRM = Vector Ruggedness Measure.

Rank	**Amphibian**	**Bird**	**Mammal**	**Reptile**
1	Slope stdev	DEM SDI	Mean Roughness	Mean Novelty
2	DEM SDI	Slope stdev	Roughness stdev	EVH SDI
3	Mean Novelty	Mean Roughness	Mean VRM	CTI stdev
4	EVH SDI	HLI SDI	Geomorph SDI	EVC SDI
5	Mean Roughness	Mean VRM	GAP SDI	Aspect SDI
6	CTI stdev	Geomorph SDI	Aspect SDI	Geomorph SDI

To further refine our indicator dataset, we used correlation and OLS analyses to identify correlations among the topmost ranking landscape heterogeneity metrics and among other variables representing topography, soil and climate. Strong correlations were found between all three soil water availability data layers and among precipitation variables (15 of 34 comparisons; **Supplemental 2, Figures 2.1-2.6**); both variable sets were reduced before being used in further analysis. CTI was strongly correlated with other topographic indices, which were only moderately correlated ($r < 0.7$) with one another (**Supplemental 2, Figure 2.5**). CTI (mean and stdev) was therefore excluded from further analysis.

To reduce potential biases that could favor certain species groups, we dropped indicators with varying or contrasting relationships among the different taxonomic groups. For instance, species richness was strongly correlated with elevation for all taxonomic groups but the nature of that correlation varied: bird and mammal richness increased with elevation whereas amphibian and reptile richness decreased with elevation (**Supplemental 2, Figure 2.4**). Elevation was also strongly correlated with several topographic diversity (topographic diversity tended to be higher at higher elevations) and climate variables (higher elevation sites tended to be more mesic) (**Supplemental 2, Figure 2.2**). We also found differing trends among taxonomic groups for forward velocity and climate dissimilarity; these variables (elevation, forward velocity, climate dissimilarity) were dropped from further consideration.

As a result of the varying relationships of indicators with different taxonomic groups, we generated unique CIs from microrefugia indicators specific to each of the terrestrial vertebrate taxonomic groups: amphibians, birds, mammals, reptiles. We generated a single macrorefugia CI that applied to all vertebrates by using a subset of climate variables (dropping highly correlated metrics see **Supplemental 2, Figures 2.2-2.4)** that exhibited similar relationships with species richness among all taxonomic groups and were indicative of climate stability over time. We identified eight climate variables to estimate macrorefugia presence for all vertebrate taxa within HUC12s (**Table 3**).

Table 3. List of indicators used to identify climate refugia. Macrorefugia represent expected changes in climatic conditions. Microrefugia are associated with soil properties, topography, vegetation, and landscape diversity. Climate datasets are derived from future climate projections for mid-century time periods (~2050) under a Coupled Model Intercomparison Project 5 (CMIP5), Representative Concentration Pathway (RCP) 4.5 greenhouse gas emission scenario. Climate novelty and backward velocity are multidimensional measures of climate that consider both precipitation and temperature. Variables were compared and selected through an iterative process using Random Forest and Linear Regression Methods (see **Figure 2**). Group abbreviations: all = all taxa, a = amphibian, b = bird, m = mammal, r = reptile. Variable abbreviations: Diff = Difference, GAP = Gap Analysis Program, Max = Maximum, Pct = Percent, Precip = Precipitation, SDI = Shannon Diversity Index, and Temp = Temperature.

Macrorefugia Variable	**Group**
Backward Climate Velocity (C^{o}/km/yr)	all
Change Soil Moisture Content (SMC)	all
Diff Annual Mean Temp (Bio1)	all
Change Heat Moisture Index (HMI)	all
Diff Temp Seasonality (Bio4)	all
Diff Mean Temp Wettest Quarter (Bio8)	all
Diff Mean Temp Driest Quarter (Bio9)	all
Pct Normal Precip Warmest Quarter (Bio18)	all
Microrefugia Variable	
Soils	
Mean Soil Bulk Density#	all
Mean Water Storage (50cm)	b, m
Landscape Heterogeneity	
Climate Novelty	a, r
Mean Roughness	m
Mean SDI for GAP vegetation	m
Mean SDI for Existing Vegetation Height	r
Mean SDI for Elevation	b
Topography	
Pct Northern Aspect	b, m
Ratio of Low : High Heat Load Index	all
Mean Topographic Wetness Index	a, r
Mean Topographic Position Index	r

3.2. Composite Indices

We calculated one macro- and four microrefugia CIs based on an optimized weighting scheme (**Supplemental 2, Table 2.1**). Macrorefugia appeared to concentrate in areas at higher elevations and containing forest habitats (**Figure 3**). High-elevation habitats ranked higher as microrefugia for birds and mammals. Areas along the Rio Grande and Pecos Rivers appear to be most important for microrefugia for amphibians and reptiles. Overlaying macro- and microrefugia CIs shows several

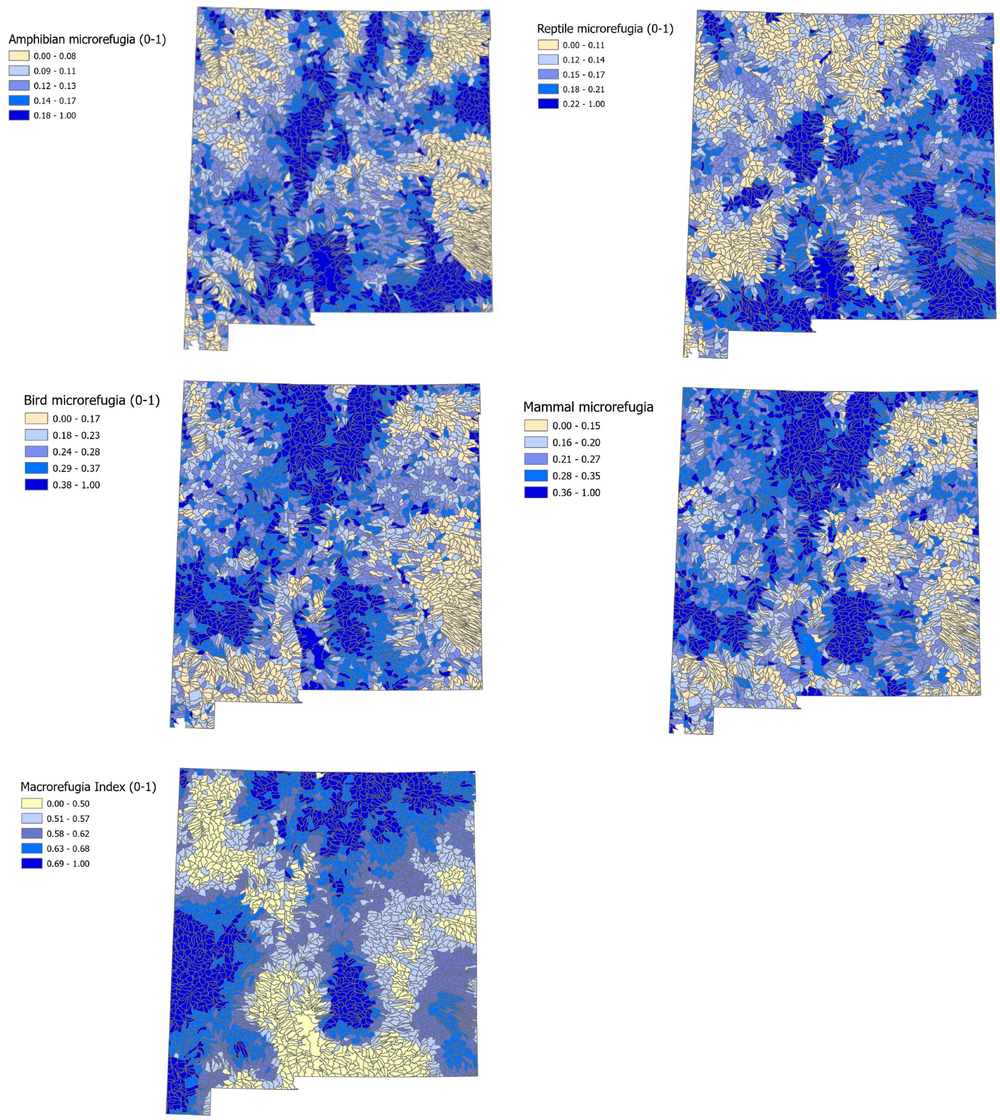


Figure 3. Composite Index (CI) scores indicating ranks (0-1 scale) of 12-digit Hydrological Unit Codes (HUC12s) for macrorefugia and four microrefugia representing different taxonomic groups. The macrorefugia CI was calculated based on a set of climate indicators that either held known and common relationships to all taxonomic groups or were indicated as important in a review of available literature. Microrefugia CIs were based on a unique subset of indicators representing local topography, soils, and landscape heterogeneity for each taxonomic group.

areas of high value both at both local and regional (climate-based) spatial scales for birds and mammals (**Figure 4**). Fewer HUC12s for amphibians and almost no HUC12s for reptiles show a high potential to contain both regional stable climates (i.e., macrorefugia) and local features indicative of climate refugia (i.e., microrefugia) (**Figure 4**).

3.3. Status of Current Conservation Areas

Most of New Mexico's COAs contain high-value refugia as indicated by CI scores, although not all COAs are likely to supply all types of refugia or refugia for all taxa equally (**Table 4**). There are 150 possible CI score categories when considering all combinations of four microrefugia, one macrorefugia, and thirty COAs (**Table 4**). Seventy-one percent of the combinations show some overlap with high-potential refugia and 29% show no overlap (**Table 4**). Fifty-five of the 150 (37%) possible combinations had values indicating that >50% of the COA contained HUC12s with the highest scoring CI; 44 of 150 (29%) possible combinations showed that 0% of the COA contained high-scoring HUC12s. No COA showed >50% overlap with high scoring HUC12s for all categories (four microrefugia and macrorefugia) and the Big Hatchet Mountains had no overlap with high-scoring HUC12s for any category. Pecos River - Lake Sumner and Pecos River Headwaters tended to contain fewer high-scoring HUC12s; these COAs had no overlap with high-scoring HUC12s in three of five categories and less than 20% of their area overlapped with high-scoring HUC12s for the remaining two categories. Eagle Nest Lake, Jemez Mountains, Northern Sacramento and Capitan Mountains, Organ Mountains, Rio Puerco, San Francisco River, and Upper Gila River all had at least three of five macro- and/or microrefugia categories with over 50% overlap.

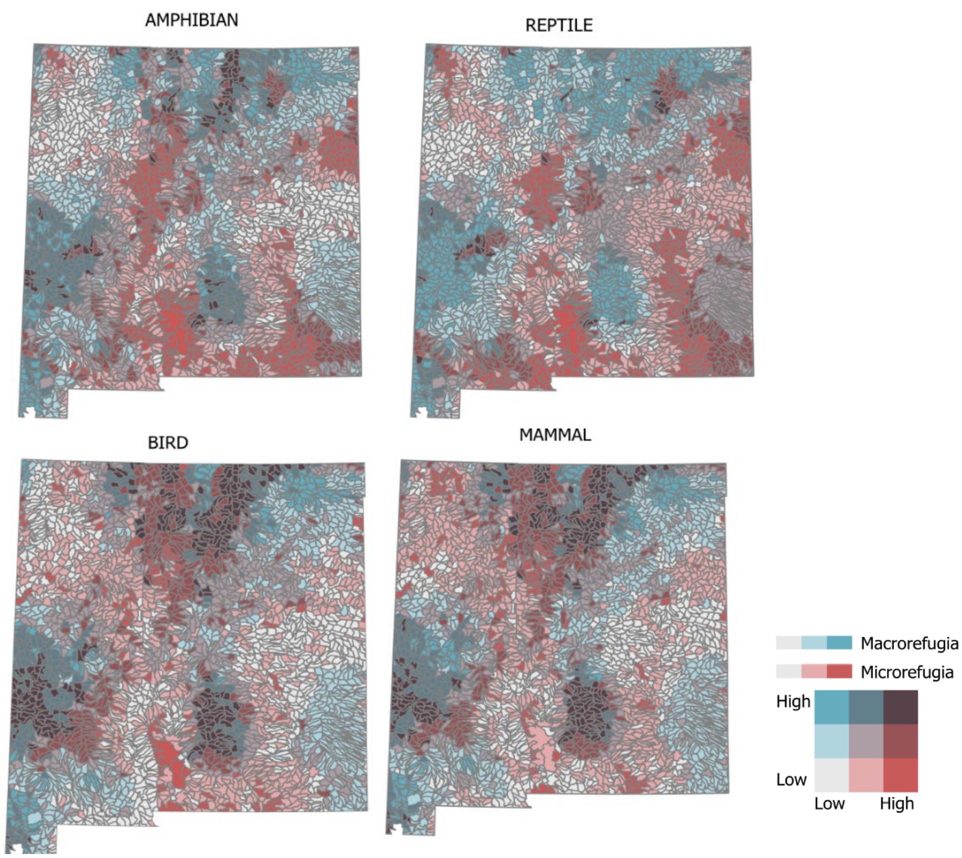


Figure 4. Composite of 12-digit Hydrological Unit Code (HUC12) scores for macro- and microrefugia by taxonomic group. Areas of high potential importance for both scales of refugia are shown in the darkest shades.

Table 4. Percent area of each Conservation Opportunity Area (COA) covered by high-ranking refugia scores (defined below). Composite Index scores for macrorefugia and taxon-specific microrefugia were scaled from 0-1 and divided into five quantiles. Numbers shown below report the proportion of each COA that overlapped with 12-digit Hydrological Unit Codes (HUC12s) that held the highest 20% of scores. COAs with more than 50% of their total areas overlapping landscapes with a high potential to contain refugia are indicated in bold. Blank cells indicate no overlap with high-potential areas.

	Microclimate				**Macroclimate**
COA Name	**Amphibian**	**Bird**	**Mammal**	**Reptile**	
Apache Box		2.1	33.0		**100.0**
Big Hatchet Mountains					
Black Range Mountains	27.6	**92.4**	**69.6**		8.2
Bootheel		8.5	23.6		**88.8**
Conchas Reservoir	**81.6**			**81.6**	
Eagle Nest Lake	**62.3**	**100.0**	47.7	37.4	**100.0**
Guadalupe Mountains	37.4	**82.9**	**94.3**	3.0	
Jemez Mountains	**69.8**	**99.3**	**99.3**		4.3
Lower Gila River	10.1	49.8	**57.7**		27.6
Lower Pecos and Black Rivers	**93.2**			**99.2**	
Lower Rio Grande	**54.2**	1.3	1.3		
Lower Rio Grande - Caballo Reservoir	**84.8**	3.4		**61.8**	
Middle San Juan River	29.9	3.7	**53.0**	30.2	
Middle Pecos River	**64.0**	2.1	6.4	**91.2**	
Middle Rio Grande	**79.2**	3.4	3.7	**55.2**	
Mimbres River		**64.3**	**63.7**	0.9	
Northern Sacramento and Capitan Mountains	32.3	**91.3**	**98.4**		**93.2**
Organ Mountains	**67.7**	**54.6**	**54.6**	1.6	
Pecos River - Lake Sumner	10.2			11.7	
Pecos River Headwaters	18.6			18.6	
Rio Chama	34.0	**86.6**	**87.7**	7.0	39.6
Rio Puerco		**84.8**	**84.8**		**72.7**
San Francisco River	11.5	**78.8**	**57.9**	2.1	**99.2**
San Mateo Mountains	30.2	**87.7**	**80.2**		30.0
Santa Fe River	41.5	**57.7**	**68.4**		
Southern Sacramento Mountains	14.5	**99.8**	**100.0**	0.8	48.6
Upper Gila River	14.0	**82.3**	**69.5**		**82.3**
Upper Rio Grande	33.2	**78.6**	**86.2**	8.2	31.6
Upper San Juan River	46.1	10.8	10.8	**50.4**	22.2
Vermejo River	**87.2**			**88.1**	11.1

Amphibian, bird, and mammal microrefugia scores show similar proportions of overlap among the 30 COAs with 25/30 (83%), 24/30 (80%), and 23/30 (77%) COAs, respectively, having some overlap with HUC12s with high refugia potential (**Table 4**). High-scoring macroclimate HUC12s were absent from 14/30 (47%) COAs, and 12/30 (40%) COAs did not overlap with high CI HUC12s for reptiles. All HUC12s within the Apache Box and Eagle Nest Lake COAs scored high for macrorefugia. The Lower Pecos and Black Rivers COA had the highest overlap with high CI for both amphibian and reptile microclimate refugia **(Table 4**). Eagle Nest Lake had 100% overlap with high CI for birds, and the Southern Sacramento Mountains had 100% overlap with high CI for mammals.

Of the 150 possible CI x COA comparisons, the majority (91/150, 61%) of COA CI scores were above the state-average CI (>0%, **Table 5**). Of these, 11 COAs had average CI values more than double that of the state-average CI. Fifty-nine (39%) of all possible combinations were lower than the state average (<0%). Of these, six had CI values less than half of the state-average CI. Thirty-four (23%) combinations had a relatively neutral (i.e., within 10% of the statewide average) percent difference value.

Table 5. Percent difference of Composite index (CI) scores for each Conservation Opportunity Area (COA) versus the mean calculated for the entire state of New Mexico. These numbers represent the degree to which the average CI score for HUC12s within each COA differ from the average of all HUC12 in New Mexico. A 100% increase means that the COA CI is more than double the state-average CI, whereas a 50% decrease means the COA CI is half of the state-average CI. A value near 0 indicates the COA and state-average CI are nearly identical. Positive values are in black and negative values are in red; values exceeding +100% or -50% are in bold.

	Microrefugia CI				
COA Name	**Amphibians**	**Birds**	**Mammals**	**Reptiles**	**Macrorefugia CI**
Apache Box	-23	22	34	-44	32
Big Hatchet Mountains	-22	-11	6	-19	3
Black Range Mountains	8	55	51	**-54**	-4
Bootheel	-36	5	9	-41	26
Conchas Reservoir	**292**	-13	-19	**238**	-4
Eagle Nest Lake	90	56	42	36	27
Guadalupe Mountains	39	60	**110**	-11	**-78**
Jemez Mountains	31	**106**	**114**	-36	-3
Lower Gila River	-5	26	45	-43	8
Lower Pecos and Black Rivers	**121**	-3	-16	98	-16
Lower Rio Grande	29	-24	-7	-15	-26
Lower Rio Grande - Caballo Reservoir	**164**	6	1	83	-34
Middle San Juan River	4	-4	36	3	-22
Middle Pecos River	43	-17	8	64	-14
Middle Rio Grande	63	-18	-19	36	-24
Mimbres River	-31	2	7	**-56**	-16
Northern Sacramento and Capitan Mountains	8	95	**127**	-39	30
Organ Mountains	31	23	60	0	-35
Pecos River - Lake Sumner	-26	-31	-6	3	-17
Pecos River Headwaters	14	-2	-11	12	-8
Rio Chama	34	58	74	-6	13
Rio Puerco	4	45	58	-41	30
San Francisco River	1	41	34	-46	21

San Mateo Mountains	12	65	77	-47	-1
Santa Fe River	18	86	90	-1	9
Southern Sacramento Mountains	21	**107**	**112**	-41	18
Upper Gila River	-5	46	47	**-52**	11
Upper Rio Grande	-14	19	26	-42	-19
Upper San Juan River	**103**	9	11	62	12
Vermejo River	88	**-65**	**-68**	98	12

***COA-Specific Trends*:**

All thirty COAs had at least one micro- or macrorefugia CI above the state-average scores. All of the CI scores (four micro- and one macrorefugia) for Eagle Nest Lake and the Upper San Juan River were above state average (**Table 5**). The Conchas Reservoir, Lower Pecos and Black Rivers, Lower Rio Grande - Caballo Reservoir, and Upper San Juan River COAs had CI scores well above average (> + 100%) for amphibians. The Jemez Mountains and Southern Sacramento Mountains COAs had CI scores well above average (> + 100%) for birds. Mammal CI scores were well above average (> + 100%) in the Guadalupe Mountains, Jemez Mountains, Northern Sacramento and Capitan Mountains, and Southern Sacramento Mountains COAs. Conchas Reservoir was the only COA with a CI score above >+100% for reptiles. Among these COAs, eight including the (Big Hatchet Mountains, Conchas Reservoir, Lower Pecos and Black Rivers, Lower Rio Grande, Middle Rio Grande, Mimbres River, Pecos River - Lake Sumner, Pecos Headwaters, and the Upper Rio Grande) had at least three of five (four micro- and one macrorefugia) categories with lower-than-average CI scores.

Taxon-specific Trends:

Amphibian CI scores ranged from -36% at the Bootheel COA to +292% at the Conchas Reservoir. For bird CI scores, COA percent differences ranged from -65% at the Vermejo River COA to +107% at the Southern Sacramento Mountains. Mammal CI scores were also lowest at the Vermejo River COA (-68%) and the highest percentage difference was located at the Northern Sacramento and Capitan Mountains (+127%). The lowest percentage difference for reptile CI scores was at the Mimbres River (-56%) COA with the highest CI scores of +238% at Conchas Reservoir. The Guadalupe Mountains COA had the lowest percent difference for macrorefugia (-78%) and Apache Box had the highest (+32%). Amphibians exhibited the greatest variation in scores, which spanned a range of 328 percentage points. COA CI scores for macrorefugia and for reptile microrefugia tended to be lower than state averages; 53% and 60%, respectively, of COAs had lower-than-average scores (<0%) (**Table 5**). Amphibians, birds, and mammals had a greater number of higher-scoring COAs with ≥50% of COAs having a CI value higher than the state-average CI scores.

4. Applications and Conclusions

This analysis identifies high-value (i.e., containing higher value CI scores) watersheds and COAs using established and novel methods to investigate a suite of potential refugia indicator data. Most COAs (71%) overlapped with high-scoring HUC12s, indicating the presence of climate refugia (**Table 4**). The Eagle Nest Lake, Jemez Mountains, Northern Sacramento and Capitan Mountains, Organ Mountains, Rio Puerco, San Francisco River, and Upper Gila River COAs intersect higher-scoring watersheds for multiple taxonomic groups and have a greater area of overlap with high-scoring watersheds. Considering the area of overlap with high-scoring watersheds, the Apache Box and Eagle Nest Lake COAs appear to be particularly important for macrorefugia. The Lower Pecos and Black Rivers COA appears important for amphibian and reptile microrefugia. Eagle Nest Lake contained the highest proportion (100% overlap) of high CI scores for birds, while the Southern Sacramento Mountains held the largest (100% overlap) proportion of high CI scoring watersheds for mammals **(Table 4**). We found distinct trends among COAs for taxonomic groups. When compared to state-average values, some COAs contained a disproportionately higher score for Cis for certain taxonomic groups. All thirty COAs had at least one micro- or macrorefugia CI above the state-average scores and the Eagle Nest Lake and Upper San Juan River COAs appeared to have above-average values for all categories of refugia (**Table 5**). Individual comparisons among the different CI categories show four COAs for amphibians, two COAs for birds, four COAs for mammals, and one COA for reptiles held scores more than double state averages.

Looking at the top three highest and lowest CI scores for each taxonomic group and microrefugia among COAs reveals distinct patterns (**Figures 5, 6**). Birds were more likely to share top- or bottom-ranking COA with mammals, and amphibians were more likely to share top- or bottom-ranking COA with reptiles. For example, birds and mammals shared the same top three COAs: Jemez Mountains, Northern Sacramento and Capitan Mountains, and Southern Sacramento Mountains (**Figure 5**). Vermejo River was among the lowest-scoring COAs for both birds and mammals (**Figure 6**). Amphibians and reptiles shared two top-scoring COAs, Conchas Reservoir and Lower Pecos and Black Rivers, and one low-scoring COA, the Mimbres River. One COA, Northern Sacramento and Capitan Mountains, was among the top three high-scoring COAs for birds, mammals, and macrorefugia. The Rio Puerco and Apache Box COAs also fell in the top three for macrorefugia. We saw direct contrasts between top- and bottom-scoring COAs among taxonomic groups that probably reflect habitat association among those groups; Vermejo River, among the bottom-scoring COAs for birds and mammals, was one of the highest three for reptiles and Conchas Reservoir, important for both amphibians and reptiles, was among the lowest scoring for mammals.

Collectively, the results of this analysis indicate that the COAs from NMDGF (2025) cover a range of habitats and conditions that will support maximal biological diversity in New Mexico.
These results demonstrate overlap among taxonomic groups that may help guide management actions that are meant to benefit multiple species. At the same time, differences among taxonomic groups in terms of top-scoring COAs indicate the need for specific actions for which the target may be a particular taxonomic group.

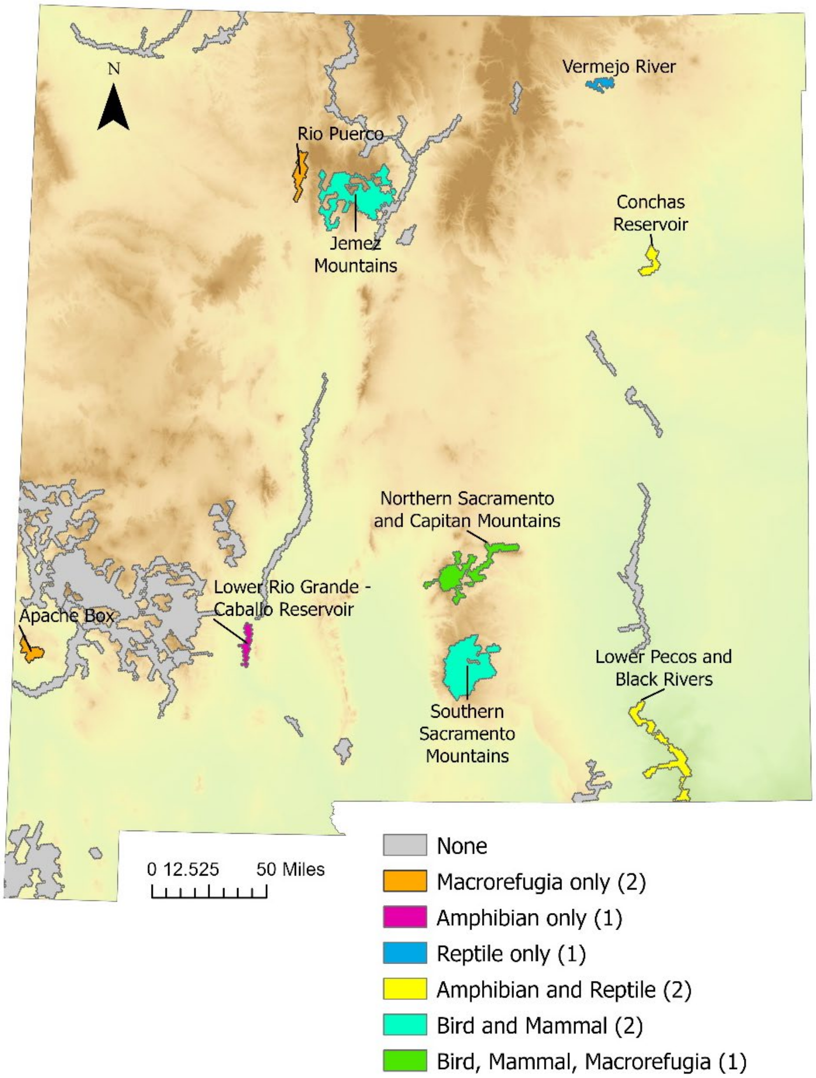


Figure 5. This image displays COAs with the three highest mean CI scores for microrefugia for amphibians, birds, mammals, reptiles, and macrorefugia. Only the COAs with top three mean CI scores are labeled and shown with a non-grey color in this image. Some COAs had high CI scores for more than one category, as noted in the figure legend. Parenthetical numbers refer to the total number of COAs in that category.

Conserving the right type and quantity of habitat is paramount to successful climate adaptation. A primary goal in delineating climate refugia is to identify areas where local conditions may mitigate climate change impacts on biodiversity (Hoffrén et al. 2022). Microrefugia are climatically buffered, local sites, where the degree to which local climate is buffered relates to local geographic position, topography, and characteristic vegetation (Barrows et al. 2020). We identified several variables that indicate whether local conditions are likely to change less or be buffered against future changes in climate conditions (**Table 1**). In general, sites that can maintain more moisture (e.g., due to

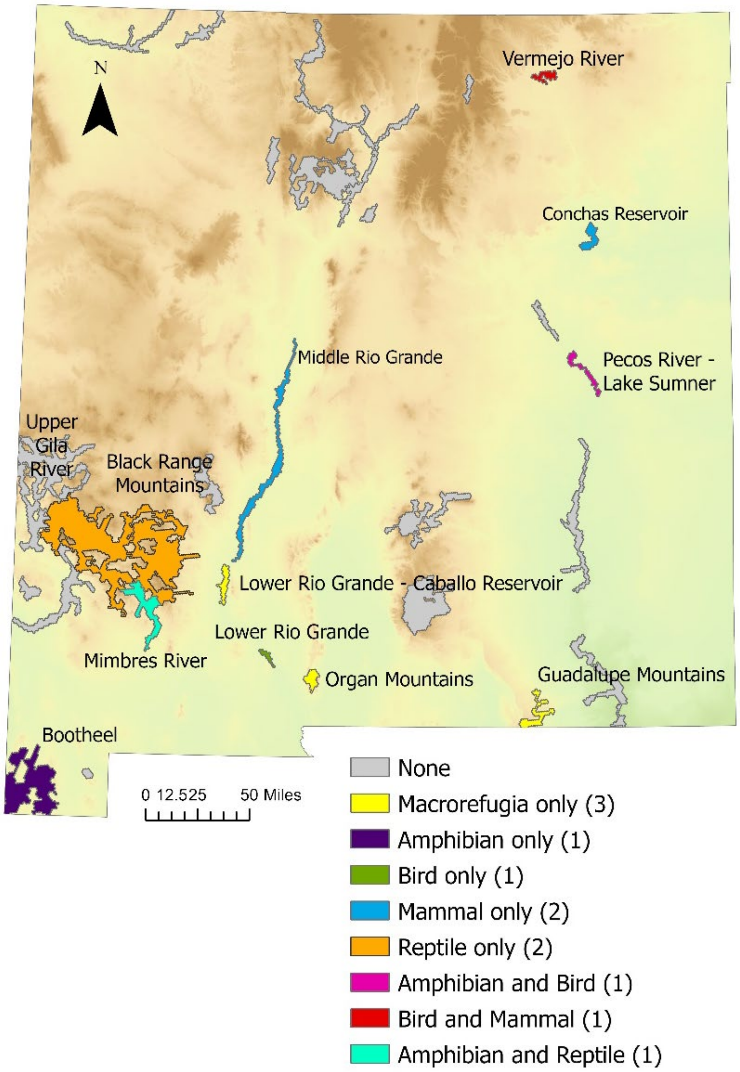


Figure 6. This image displays COAs with the lowest mean CI scores for microrefugia for amphibians, birds, mammals, reptiles, and macrorefugia. Only the COAs with the lowest three mean CI scores are labeled or shown in a non-grey color in this image. Some COAs had low CI scores for more than one category, as noted in the figure legend. Parenthetical numbers refer to the total number of COAs in that category.

topographic or soil characteristics) are considered better able to buffer local taxa against climate changes, particularly increased heat (**Supplemental 1, Table 1.2**). This analysis considered a range of indicators of microrefugia hypothesized to be important in arid environments: north-facing slopes, cold-air drainages, local topographic concavity (features that experience less exposure to hot winds and radiation and have higher soil moisture), canopy density (thermal buffering and moisture retention), and higher elevations (cooler temperatures and more precipitation) (Kennedy 1997; Noss 2001; Bennett and Provan 2008; Ashcroft et al. 2009, 2010; Fridley 2009; Dobrowski 2011; Lenoir et al. 2017). The process used to select a final subset of indicators was designed to minimize redundancy and the potential for spurious representations (**Figure 2**). During our selection analysis, we found strong but contrasting correlations between selected refugia metrics and species richness of the four focal taxonomic groups (**Supplemental 2, Figures 2.1-2.6)**, leading us to develop separate indicator sets to represent microrefugia potential for each group. Resulting microrefugia indices provide an estimate for each HUC12 watershed's potential to harbor microrefugia for specific taxonomic groups.

We also found that the importance of variables related to climate, topography, and landscape heterogeneity varied among the vertebrate taxa considered; a result with serious implications for other studies that aim to identify refugia across a range of taxonomic groups (**Supplemental 2, Figures 2.1-2.6**). Among the potential metrics used to estimate climate refugia, we noted several important associations between elevation and species richness, elevation and landscape heterogeneity (particularly related to topographic heterogeneity), and elevation and climate variables. We found strong but distinct correlations among taxonomic group richness and elevation (**Supplemental 2, Table 2.4**). Specifically, bird and mammal richness increased with increasing elevation and amphibian and reptile richness decreased with increasing elevation. There are two implications of these findings: 1) We must carefully consider the relationship of elevation with other metrics when including variables in a CI meant to represent refugia potential; and 2) Refugia are likely to differ between the different taxonomic groups and between endothermic (birds and mammals) and exothermic (amphibians and reptiles) species. We found correlations between many measures of topographic diversity (usually representing elevational variation) and elevation itself (**Supplemental 2, Figures 2.1-2.6**). Therefore, we found it necessary to identify specific subsets of indicators for each taxonomic group that we knew were not biased against the group of interest (**Table 3**). For similar reasons, we excluded plant composition measures (aside from vegetation diversity metrics) from this analysis to reduce the potential that our results would favor species with specific habitat associations (e.g., forests), and we do not recommend use of plant composition measures in broad-scale applications.

It is well known that climate varies with elevation, which can complicate efforts to measure the responses of multiple species that have varying associations with both metrics. In this analysis, including climate variables that favor the cooler, wetter conditions found at higher elevations might lead to results that favor birds and mammals, which we found to be positively associated with increasing elevation (**Supplemental 2, Figures 2.1-2.6**). However, except for climate dissimilarity and climate velocity, we found either positive (bird and mammal richness) or neutral (amphibian and reptile richness) associations between species richness and climate variables. Therefore, we do not consider estimated macrorefugia, which are based upon metrics meant to identify areas that would undergo relatively less change (e.g., less increase in temperature or decrease in precipitation), to be biased against amphibian and reptile species. Although we were able to use these methods to limit biases in our estimations of refugia potential, these observations point to the need for caution in similar efforts to identify refugia for multiple species, particularly where amphibians or reptiles are the focal taxa.

We found bird and mammal richness tracked with topographic diversity measures based on altitudinal heterogeneity. In contrast, amphibian and reptile richness tended to associate with higher climate novelty and vegetation SDI (**Table 2**), reflecting unique habitat interactions underlying diversity patterns within each taxon. This tendency for amphibians and reptiles to be associated more strongly with non-topographic metrics has implications for the common assumption that species will move up in elevation in response to warming climates. Specifically, these assumptions may overestimate the potential responses of reptiles and amphibians.

Limitations and Future Direction

The presence of characteristics (e.g., topography) representing stable conditions is only one facet of what constitutes usable wildlife habitat. Our analysis did not consider measures of habitat resilience, such as the presence of non-climate disturbances or different types of land use. Land-use changes and other types of disturbance are likely to be important to consider when ranking potential refugia from all types of change (not just from climate change) and protected areas. Changing disturbance regimes are recognized as an important consequence of climate change in forest ecosystems, and there is a need to simultaneously investigate possible refugia from drought, fire, and various anthropogenic disturbances (Larson et al. 2016; Cartwright 2018; Rojas et al. 2021). Because changing climatic conditions may create novel ecosystems and climates, and climate change impacts interact with various types of disturbance, it is prudent to consider non-climate stressors to better describe all of the dynamic landscape features that influence local refugial capacity.

Best practices for identifying refugia include considering a diverse set of biotic data and fine- and coarse-scale measures that can capture a range of potential environmental variabilities and species dynamics (Ashcroft and Gollan 2013). The results of indicator selection and optimization outlined in this report and the accompanying supplemental files can inform fine-scale strategies focused on individual taxa (Tingley et al. 2014). The results of applying these methods to identify regions with high refugia potential provides a coarse filter to identify watersheds of potential importance for further study and survey (Stralberg et al. 2019). Even where practices are employed to address fine- and coarse-scale processes, conservation strategies developed solely from such efforts will be limited to the temporal and spatial scale of the effort used to estimate climate refugia (Tingley et al. 2014). The resolution of this analysis is probably most meaningful for species that have ranges encompassed by the average area of the watersheds used in this analysis (i.e., watershed/range areas from $146m^2$-$1120km^2$, with an average size of $97km^2$). In general, higher-value watersheds (i.e., with higher-scoring CIs) are presumed to be able to support animals with larger range requirements for at least short time periods (Morelli et al. 2020) but may be suboptimal areas for population preservation over longer periods. This analysis focuses on relatively near-term (i.e., midcentury) climate projections and may have limited utility where conditions relevant to species persistence are not well represented by 30-year averages (e.g., drought frequency and duration). However, in terms of general trends, midcentury projections provide an accurate representation of likely future conditions in New Mexico.

Malakoutikhah et al. (2018) note that most coarse-scale (i.e., ~1km or larger) analyses are probably adequate to identify refugia for larger species such as larger mammals but not for smaller terrestrial vertebrates, which are likely to select habitat based on finer-scale environmental factors. Correspondingly, climate refugia (i.e., macrorefugia) scores might better represent larger species and microrefugia point to important areas for smaller species. Integrating considerations of climate corridors into analyses like the one in this study will improve our capacity to assess the long-term potential of refugia to maintain populations of larger and more wide-ranging organisms (Stralberg et al. 2019). For birds and mammals, future outcomes are hypothesized to be more reliant on larger-scale processes (i.e., macrorefugia) or on the connectivity of watersheds containing high microrefugia potential (Malakoutinkhah et al. 2018).

Conclusion:

Our results show distinct patterns of variable importance in terms of refugia for different taxa. In essence, the concept of "refugia" means different things to different taxonomic groups, in agreement with findings from other studies that identify unique, taxon-specific responses influencing species' vulnerability to changing climatic conditions (Friggens et al. 2013; Hannah et al. 2014; Kocsis et al. 2021). Refugia analyses must consider these taxonomic differences in order to avoid taxonomic bias in conservation planning efforts. The results of this analysis support strategies that aim to select a diverse range of ecosystems and habitats, because no single conservation area will be able to support all species and achieve all goals.

This analysis takes the first steps toward identifying widely applicable characteristics that are important for maintaining vertebrate taxa diversity in a changing environment. This is important because different species respond to climate change in unique ways (Hannah et al. 2014). In the context of adaptive management, climate refugia not only provide more time for species to acclimate or evolve in response to climate impacts but may also provide the time required for resource managers who struggle to plan and implement conservation measures in step with observed changes (Morelli et al. 2020). However, in any effort to identify climate refugia, project leads need to carefully assess the implications of the specific metrics used to evaluate and rank the areas to be protected. Approaches considering a wide range of species will have to include refugia of varying sizes and that represent distinct environmental characteristics important to different focal taxa; refugia may not always encompass areas likely to experience less intense or slower change but instead may facilitate movement to other suitable locations.

The goal of this analysis was to assess the natural environment across the state of New Mexico to identify areas with higher potential to contain climate refugia that may help species adjust to future, changing climate conditions. Current COAs appear to have relatively high potential for encompassing climate macro- and microrefugia. However, as conditions and available information change, COA and climate refugia designations will need to be reevaluated for performance and relevance. Existing COAs may act as static refugia, exposing species to less change and providing an "evolutionary incubator" where species have time to adapt to rapidly changing climate conditions. On the other hand, refugia may be more temporary and serve as steppingstones for species moving through the landscape, tracking suitable environmental conditions (Morelli et al. 2020). The degree to which current refugia fall into these categories depends on the environmental factors that identify them as refugia, the movement abilities and generation times of local species assemblages, and the non-climate threats facing these areas. The identification of refugia is just the first step in the process of protecting and enhancing these refugia as needed and assisting species in adapting to climate change. Monitoring wildlife populations and implementing genetic and demographic studies will be instrumental in validating the presence of hypothesized refugia and assessing their importance for specific species (Barrows et al. 2020).

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Part II. Climate Change Refugia for Aquatic Species

D. Max Smith, Rocky Mountain Research Station, David.Smith3@usda.gov
Megan Friggens, Rocky Mountain Research Station, Megan.friggens@usda.gov
Karen Cooper Chaudhry, Rocky Mountain Research Station, Karen.CooperChaudhry@usda.gov

1. Introduction

1.1. Background

Freshwater ecosystems are imperiled by anthropogenic activities including water extraction, water pollution, and introduction of exotic species (Dudgeon et al. 2006). In the southwestern U.S., most waterbodies have been modified to meet human needs and there is growing demand and use of surface and ground water (Sabo et al. 2010). As a result of changes to freshwater ecosystems, dozens of water-dependent species are federally threatened or endangered and several species have been extirpated (Platania et al. 1991; Hoagstrom et al. 2010). These include fully aquatic taxa such as fishes, arthropods, and mollusks, and amphibians and reptiles with aquatic life stages or dependence on aquatic habitats.

Climate change also threatens aquatic ecosystems by changing the volume and quality of surface water. For aquatic communities, climate impacts are expected to be greatest at mid latitudes in areas where freshwater ecosystems have already been heavily modified, such as the southwestern U.S. (Strayer 2006). Documented impacts include increases in water temperatures (Isaak et al. 2018), reduction in snowpack (Mote et al. 2005; Stewart 2009; Harpold et al. 2012; Elias et al. 2021), reduction in runoff efficiency (annual stream volume relative to annual precipitation volume) (Woodhouse et al. 2016; Lehner et al. 2017; Chavarria and Gutzler 2018), and seasonal reductions in precipitation (Woodhouse and Udall 2022).

Region-wide climate trends, such as increases in air temperatures, reductions in streamflow, and changes in streamflow timing have been observed, but there is variation among locales (Zeigler et al. 2012). The potential exists, therefore, for local conditions to buffer some areas from changes in temperature and precipitation. Managers can use information about these conditions to prioritize restoration or protection of aquatic habitats to protect imperiled species (Zeigler et al. 2012). Climate refugia analysis is an initial step in developing this information. Climate refugia are defined as locations that remain suitable for species as the climate changes (Ashcroft 2010). For aquatic animals, such as salmonid fishes, refugia have been identified at various spatial and temporal scales, from macrorefugia defined as broader landscapes that are projected to buffer populations against future climate changes to localized hydrological features that protect individuals or populations from disturbance (Sedell et al. 1990; Isaac and Young 2023). Local features are defined as hydrological or thermal *refuges*, to which individuals can move for temporary relief. Hydrological features are considered *refugia* if entire populations are buffered from unfavorable conditions for a period long enough to influence population persistence (Sullivan et al. 2021).

Instead of mapping continuous physical features across landscapes, as is commonly done for terrestrial refugia, studies of refugia for aquatic ecosystems have focused on identification of discrete features, such as stream reaches remaining watered or cool during hot and dry periods (Ebersole et al. 2003; Magoulick and Kobza 2003). Additional refugia include springs that continue to flow during droughts (Cartwright and Johnson 2018) and ephemeral pools that are to some extent decoupled from changes in precipitation and temperature (Cartwright et al. 2022). Aquatic refugia have been specifically evaluated for stream-dwelling fishes, species dependent upon springs, and amphibians that breed in ephemeral pools (Isaak et al. 2015; Cartwright and Johnson 2018; Cartwright et al. 2022). However, a joint assessment across these and other taxa is needed for managers to prioritize large-scale conservation efforts in response to climate change.

1.2. Objectives

We applied a robust analysis to explore multiscale processes that are important for identifying climate refugia for a wide range of aquatic species. Our goal is to inform conservation strategies and protected area planning by identifying and characterizing the best set of indicators to estimate refugia potential for New Mexico's varied aquatic habitats. We use our results to compare the distribution of aquatic climate refugia across the state's landscapes in relation to current conservation planning efforts. New Mexico's unique assemblage of surface water and groundwater networks support highly specialized aquatic ecosystems, including cold-water mountain streams, karstic springs, and desert playas. These features provide an ideal and critical opportunity for the development of aquatic refugia analyses in the arid west.

Our objectives were to 1) Identify and test potential indicators of climate refugia for aquatic taxa within New Mexico; 2) Use indicators to identify different types of aquatic refugia within the state, and 3) Evaluate the potential for currently identified Conservation Opportunity Areas to provide climate refugia. To achieve these objectives, we identified aquatic habitats and taxa of interest to create a set of habitat groups. We then extend a process for identifying predictors of climate refugia to these groups. We identify several variables that relate to conditions indicating less severe change or locally buffered conditions. Finally. we tested whether the importance of indicators and distribution of refugia varied among habitat groups. As a result of this analysis, we generate several composite indices specific to different types of aquatic habitats and of refugia.

2. Methods

2.1. Study Area

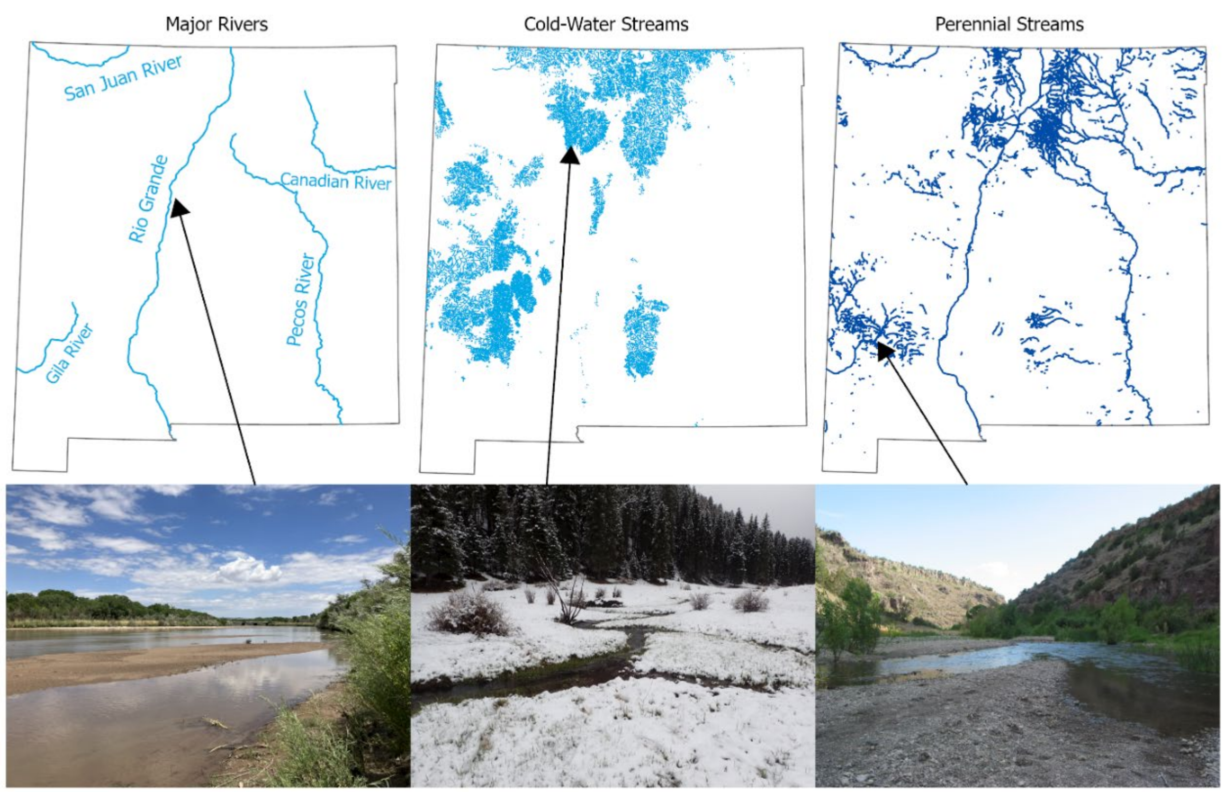
This analysis is focused within the state of New Mexico (see **Part I, Figure 1**), which covers an area of 315,194 km^2 (121,589 mi^2). Although much of New Mexico is considered arid, the state contains a variety of aquatic ecosystems including 11,058 km (6,011 mi) of cold-water streams; 9,474 km (5,921 mi) of perennial warm-water streams; thousands of lakes, reservoirs, and ponds (**Figure 1)**; and many specialized organisms dependent on surface water and groundwater (NMDGF 2016). Among the major streams are the Rio Grande and the San Juan River, both of which originate in Colorado and flow through New Mexico. Other major streams include the Canadian, Gila, and Pecos Rivers, which all originate in New Mexico.

A variety of aquifer systems affect the movement and storage of groundwater, which in turn influences the distribution and dynamics of springs and perennial streams throughout the state.

Major aquifer systems include carbonate aquifers in the San Andreas Mountains and Roswell basin in the southeastern part of the state (Eastoe and Rodney 2014), the Rio Grande basin-fill aquifer system that runs through the central part of the state (Bexfield 2010), and the High Plains aquifer in the eastern part of the state (Rawling and Rinehart 2017). There are also smaller, locally important sources of groundwater such as the volcanic and carbonate aquifers of the Jemez Mountains (Trainer 1974). Some catchments, such as playa lakes, are major sources of recharge for the High Plains aquifer and other groundwater systems (Smith et al. 2011, McKenna and Sala 2017).

New Mexico has a complicated system of water use, reflecting the complex history of land use by Indigenous peoples; Spanish settlers; federal, state, and local governments; and non-government entities (Raheem et al. 2015). The use of water is governed by the state's prior appropriation laws, the 1938 Rio Grande Compact, and the 1944 water-use treaty with Mexico (Hill 1974). Throughout the 20th century, the federal government funded the construction of large water storage and delivery projects in the state. These projects helped the state meet compact and treaty obligations while supporting agriculture and urban growth but also caused significant changes to aquatic ecosystems (Benson et al. 2014). With surface flows becoming fully allocated and new pumping technologies emerging in the mid-20th century, groundwater became increasingly relied upon for agricultural, industrial, and municipal uses, causing additional impacts to aquatic ecosystems and local communities (Mix et al. 2012, Ellis and Perry 2020). Southwestern states have adjusted water rights laws to prevent overexploitation of this resource, but these laws are often difficult to enforce, and certain types of groundwater use remain unregulated (Abdelmohsen et al. 2025).

a



b

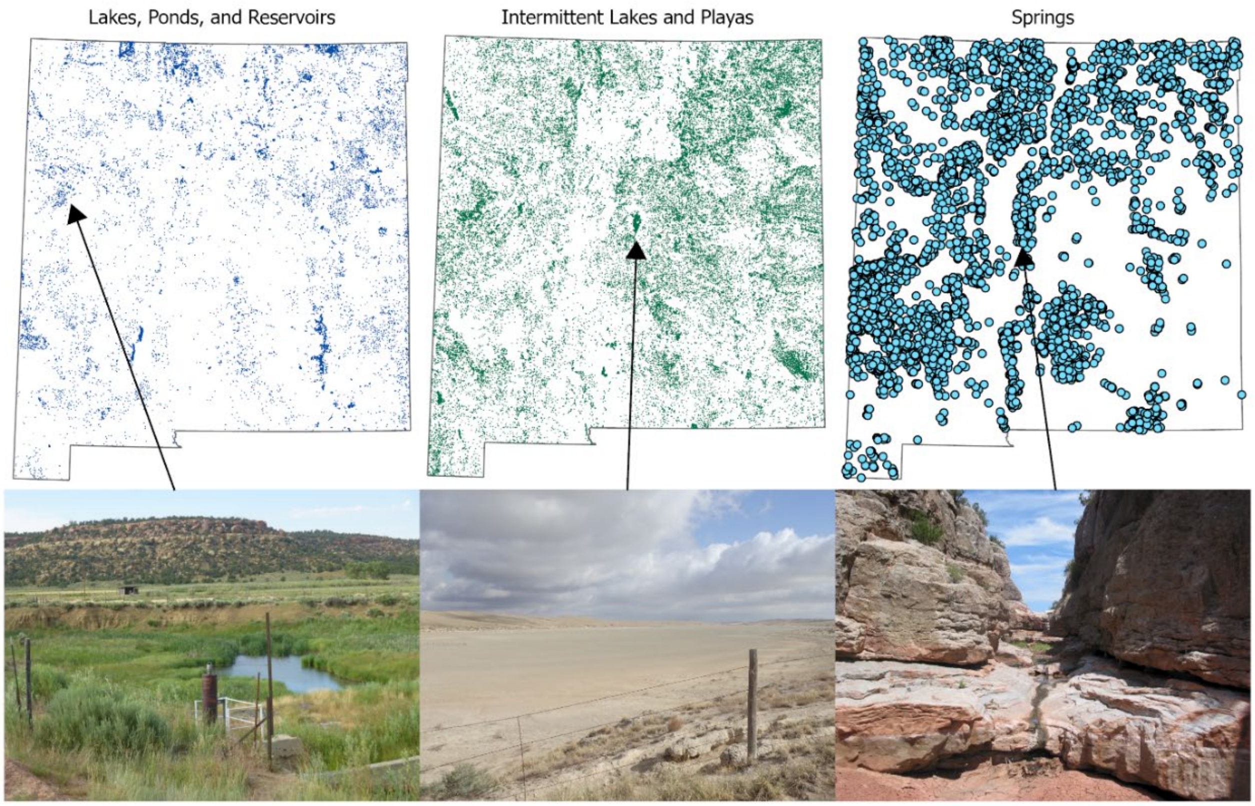


Figure 1. Distribution and examples of (a) stream-based aquatic habitats and (b) lakes, ponds, reservoirs, playas, and springs in New Mexico.

2.2. Literature Review

We expanded our literature search, described in Part I, to identify aquatic climate change indicators and generate a list of aquatic refugia indicators (**Supplemental 1. Tables 1.1 and 1.2)**. We focused our search on literature that described climate impacts from direct changes in precipitation and temperature and related changes in water volume and water quality. We limited papers and documents to those that discussed responses of aquatic species and ecosystems to climate impacts. To identify relevant literature, we searched databases for papers that included the terms Climate Change + Aquatic + Refugia. We also combined the Climate Change and Refugia search terms with specific aquatic habitats (Ephemeral Pools, Playas, Rivers, Springs, Streams).

2.3. Habitats and Species

We used a habitat- and taxa-based approach to select the focal resources for this assessment. First, we used information from the State Wildlife Action Plan for New Mexico (SWAP; NMDGF 2016) to inform our selection of focal habitats and taxa. The SWAP describes eight types of aquatic habitats: perennial cold-water streams; perennial warm-water streams; perennial lakes, cirques, and ponds; perennial marshes, cienegas, springs, and seeps; perennial cold-water reservoirs;

perennial warm-water reservoirs; ephemeral marshes, cienegas, and springs; and ephemeral catchments.

The SWAP also lists Species of Greatest Conservation Need (SGCN). We selected taxa from this list that are entirely aquatic or are dependent on aquatic ecosystems for a considerable portion of their lives (Table in Supplemental Information). These taxa are fishes, amphibians, reptiles (garter snakes, water snakes, turtles), and invertebrates (species listed in appendix). We reviewed the scientific literature and species profiles in the Biota Information System of New Mexico (BISON-M database; bison-m.org) for these taxa to identify their aquatic habitat needs in the southwestern U.S. By identifying areas of overlap between aquatic SGCN habitat needs and the aquatic habitats in the SWAP, we developed five habitat groups for assessment: (1) cold-water fish habitat, (2) perennial streams, (3) perennial water amphibian and reptile habitat, (4) ephemeral catchments, and (5) springs. Below we describe the habitat groups in greater detail.

Cold-Water Fish Habitat

Tributary streams in mountainous areas provide habitat for trout and other cold-water fishes. Wahlberg et al. (2023) define cold-water streams in the southwestern U.S. as those with reaches having mean August stream temperatures ≤ 17° C. We include perennial lakes and perennial cold-water reservoirs in this habitat as well. Several populations of the Rio Grande cutthroat trout (*Oncorhynchus clarkii virginalis*), listed as a sensitive game species in New Mexico, occur in cold-water tributary streams in the headwaters of the Rio Grande and Canadian and Pecos Rivers (Zeigler et al. 2012). The Rio Grande chub (*Gila pandora*) and Rio Grande sucker (*Catostomus plebeius*), both SGCN, occur in cold-water Rio Grande tributaries as well (Calamusso et al. 2002). The federally threatened Gila trout (*Oncorhynchus gilae*) occurs in a few reaches of headwater streams of the Gila River basin in the southwestern portion of the state (Brown et al. 2001).

Perennial Streams

Perennial streams include the Gila, Pecos, and San Juan Rivers and Rio Grande and many of their tributaries. We consider perennial warm-water reservoirs in this habitat as well. Perennial streams are used by fishes adapted to a variety of aquatic habitats, with wide fluctuations in volume, temperature, and turbidity (Olden and Poff 2005). Native taxa, such as crayfish, snails, clams, and mussels, are also dependent on perennial streams (Burdett et al. 2015). Many of these invertebrates are characterized by low dispersal ability and high rates of endemism and imperilment (Williams 1993; Strayer 2006). Historically, pulses in streamflows created a variety of microhabitats including braided channels, backwaters, side channels, and floodplain pools (Pease et al. 2006). The extent of these habitats has been reduced along the Rio Grande and other streams as modifications were made to optimize water storage and conveyance (Cowley 2006). In addition, nonnative aquatic taxa have become a major component of stream faunas throughout the state (Platania 1991; Gido and Probst 1999; Whitney et al. 2016). As a result of these changes, most of the fishes native to the Rio Grande and Colorado basins are extinct, extirpated, or imperiled (Olden and Poff 2005; Hoagstrom et al. 2010).

Perennial Water Amphibian and Reptile Habitat

Many of New Mexico's amphibians rely on perennial bodies of standing or slow-moving water for successful reproduction. Some species, including the Chiricahua leopard frog (*Lithobates chiricahuensis*), also spend considerable portions of their adult life stages in water (Degenhardt et al. 1996). In New Mexico, garter snakes (*Thamnophis* spp.) and the yellow-bellied water snake

(*Nerodia erythrogaster transversa*) are dependent on perennial streams and lakes to forage for prey such as fish and amphibians (Degenhardt et al. 1996). Most of the turtle species in New Mexico require perennial water in lakes, ponds, or streams for food, social interactions, and protection from predators (Degenhardt et al. 1996). In addition to natural streams, ponds, and lakes, anthropogenic features such as stock tanks and irrigation ditches are important aquatic habitats for imperiled amphibians and reptiles in New Mexico (Stone et al. 2014).

Ephemeral Catchments

Ephemeral catchments include vernal pools, playas, intermittent stream pools, and tinajas (NMDGF 2016). We include ephemeral marshes in this habitat as well. These are used by animal species with unique life history strategies for surviving extended dry periods and reproducing quickly when catchments are filled by runoff from rain (MacKay et al. 1990). Several species of amphibians, including spadefoot toads (*Scaphiopus couchii; Spea* spp.) and the western narrow-mouthed toad (*Gastrophryne olivacea*), lay eggs in ephemeral catchments following heavy precipitation events (Anderson et al. 1999). The process of egg laying, hatching, and transformation from tadpole to metamorph occurs quickly (e.g., in 30 days or less), before the catchments desiccate (Degenhardt et al. 1996). Aquatic invertebrates, such as fairy shrimp and clam shrimp, survive desiccation as eggs, later hatching and quickly completing their life cycles when water returns (MacKay et al. 1990). When flooded, ephemeral catchments are also used by mud turtles (*Kinosternon* spp.), tiger salamanders (*Ambystoma* spp.), and other taxa (Haukos and Smith 1994; Stone 2001).

Springs

New Mexico has a variety of unique aquatic habitats, such as cienegas, fens, springbrooks, and seeps, that are fed by groundwater. Hereafter we collectively refer to these habitats as springs. In some parts of the state, springs are components of larger floodplain and wetland complexes (Land and Huff 2010; Collins 2020). In other areas, springs occur as isolated aquatic habitats (Jormalainen and Shuster 1997). In the arid west, numerous aquatic vertebrate and invertebrate species are dependent on the stable hydrothermal regimes provided by springs; many of these species are imperiled, endemic, and relict (Strayer 2006; Frus et al. 2020; Work 2023).

2.4. Spatial Data

Potential climate refugia indicator data were processed and summarized for three spatial extents: Ecoregions, Conservation Opportunity Areas (COAs), and Hydrological Unit Code 12 (HUC12) watersheds. We downloaded boundary data files for HUC-12s from the U.S. Geological Survey's (USGS's) National Record Clearinghouse (now National Map at https://apps.nationalmap.gov/downloader/). We obtained COA and Ecoregion data from NMDGF. Datasets unique to the aquatic ecosystem analysis are listed in **Table 1**.

We prepared downloaded spatial data by projecting into the NAD 1983 UTM Zone 13N coordinate system and clipped to the state of New Mexico. Preparation and analysis of data were completed using ArcGIS Pro 4.2 and several tools within Spatial Analyst, Arc Hydro, and Surface Parameters; Spatial Statistics Toolbox; and the Geomorphology and Gradient Metrics Tools and Diversity Tools; and R 3.4.4.

Extent

We determined the extent of analysis for each habitat group by selecting HUC12s that were likely to contain its habitat features. The number of HUC12s we assessed varied among the five habitat groups. The extent of cold-water fish habitat and perennial streams is limited in New Mexico; these habitat groups therefore had the smallest number of HUC12s included for analysis. For cold-water fish habitat, we selected stream reaches from the NORWEST database with current modeled August stream temperatures of 17 °C or less (Wahlberg et al. 2023). HUC12s containing any of these stream segments were included in the analysis for cold-water fish habitat. When examining overlap with COAs, we excluded HUC12s from cold-water fish habitat analysis if the cold-water stream segments did not overlap the COA boundaries. For perennial streams, we merged National Hydrography Database reaches with flowline fcode 46006 (which represents perennial stream reaches) with an ArcGIS Online Major Rivers of the U.S. shapefile. We included all HUC12s containing any of these stream reaches in the analysis. We initially included all New Mexico HUC12s for analysis of perennial water amphibian and reptile habitat, but we later excluded HUC12s that lacked indicator data (described below) that were specific to the habitat needs of these taxa. Ephemeral catchments and springs are widespread in the state (Fig. 2) and therefore we included all of the state's HUC12s in those analyses, apart from those lacking taxa-specific indicator data.

Value Indicators

For each habitat group, we calculated two indicators of conservation value for a particular area. One was based on physical habitat features appropriate to each habitat group (described below); the other was species richness, a measure of biotic value. We used these value indicators to identify the most important refugia indicators among measures of topography, lithology, soil, and landscape heterogeneity.

Habitat features

We summarized hydrological spatial data to create an indicator of value based on availability of specific habitat features. For cold-water fish habitat, we calculated the percentage of stream reaches for each HUC12 that are currently colder than ideal temperatures for salmonids (≤ 10° C) but may warm to suitable temperatures in the future (data sources and methods included in supplemental information). For perennial streams, we calculated the percentage of stream reaches currently classified as perennial for each HUC12. For perennial water amphibian and reptile habitat, we obtained total waterbody area for each HUC12. For ephemeral catchments, we calculated the percent coverage of waterbodies classified as playas or intermittent lakes for each HUC12. Finally, for springs, we calculated the density of springs mapped in each HUC12.

Species Richness

We used spatial data to estimate species richness of four taxa groups: fishes, ephemeral catchment-dependent amphibians, perennial water-dependent amphibians and reptiles, and native aquatic species. For fishes, ephemeral catchment-dependent amphibians, and perennial water-dependent amphibians and reptiles, we downloaded shapefiles of species distributions from the International Union for Conservation of Nature (https://www.iucnredlist.org/resources/spatial-data-download) and the USGS Gap Analysis Program (https://www.usgs.gov/programs/gap-analysis-project), then calculated the number of native species with ranges that overlap each HUC12 (species listed in supplemental information) . We used lists compiled by NMDGF to differentiate between native and introduced species, then excluded introduced species (most of which are fishes) from our estimates. We obtained data for total native aquatic species richness from the U.S. Environmental Protection Agency's (EPA's) EnviroAtlas (https://www.epa.gov/enviroatlas/enviroatlas-data).

Refugia Indicators

We selected indicators of refugia separately for each habitat group because we expected to observe considerable variation in the dynamics of different aquatic habitats and in the responses of associated species to changes in temperature and precipitation.

For each taxonomic group, we selected indicators for two types of climate refugia: macrorefugia and hydrorefugia. *Macrorefugia* represent areas with sustained climatic suitability across broad spatial and temporal gradients (Stralberg et al. 2018; Isaak and Young 2023), and we identified watersheds that are expected to have stable conditions relative to changes in the regional climate (in terms of air temperature, precipitation, streamflow volume, and water temperature). We define *hydrorefugia* as areas where local features maintain the stability of water volume and/or quality. Areas with high potential for hydrorefugia may contain cold-water stream segments (Isaak and Young 2023), springs (Davis et al. 2013; Cartwright et al. 2020), and frequently inundated pools (Cartwright et al. 2022). For our purposes, hydrorefugia is an umbrella term for ecological and thermal refuges (protection for individuals) and evolutionary refugia, climate refugia, and hydrologic refugia (protection for populations) used in the studies cited above. We consider hydrorefugia to be independent of spatial and temporal considerations because, at the scale of our assessment, refugia apply to aquatic species that vary widely in characteristics such as lifespan and geographic range. Therefore, the concepts of refuges and refugia can both apply to a single hydrorefugium. For example, a cold-water spring can protect an entire population of springsnails (*Pyrgulopsis* spp.) while also providing temporary relief for individual stream fishes. Macrorefugia indicators were measures of projected changes in temperature, precipitation, and variables derived from precipitation and temperature. Hydrorefugia indicators were characteristics of soils, topography, lithology, and vegetation likely to influence the volume and/or temperature of water available for aquatic organisms.

Scale of Indicators

We summarized indicator values and calculated composite index (CI) scores for HUC12 watersheds, which are nested within larger watersheds. For habitats that are influenced by the movement of surface water and/or groundwater (e.g., streams and springs), habitat dynamics within a HUC12 may be influenced by dynamics occurring at scales larger than the HUC12 (Strayer 2006, Yang et al. 2025). We therefore summarized indicators involving movement of surface water or groundwater at the larger HUC8 scale for certain habitat groups (cold-water fish habitat, perennial streams, perennial water amphibian and reptile habitat, and springs). We then applied indicator values summarized at the HUC8 scale to the HUC12 within each HUC8.

Macrorefugia

We define macrorefugia as areas with higher climate stability as measured by lower relative change in current versus future conditions or the future presence of less extreme or less dry conditions. In addition to the indicators described in Part I, we used Bureau of Reclamation (BOR) data to calculate projected changes in evapotranspiration (ET), potential evapotranspiration of native vegetation (PNV), snow water equivalent (SWE), and soil moisture content (SMC) using differences averaged over historical (1970-2020) and midcentury (2040-2060) projections.

We also developed two streamflow indicators: percent change in mean June streamflow (obtained from the U.S. Forest Service's (USFS's) Stream Flow Metric Dataset, https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and percent change in mean August stream temperature (from the USFS's NORWEST database, https://www.fs.usda.gov/rm/boise/AWAE/projects/NorWeST.html). We used these datasets to calculate mean percent change in streamflow volume and stream temperature from historical (1993 to 2011) to midcentury (2030-2059) projections.

Hydrorefugia

We considered the topography, soils, and landscape heterogeneity indicators described in Part I, as well as lithology and vegetation indicators that pertain to aquatic ecosystems (described below).

Lithology Variables

We used several datasets from the USGS to describe the potential for groundwater contributions to streamflow and spring discharge in each watershed. We obtained shapefiles representing the extent of carbonate karst, evaporite karst, piping karst, unconsolidated aquifers, and volcanic aquifers. We used these shapefiles to calculate the percentage of a watershed with underlying karstic, volcanic, and unconsolidated aquifers. We also calculated aquifer richness, which is the number of different types of aquifers and karsts within a watershed.

Vegetation Variables

We used several datasets to describe the extent, structure, and composition of riparian vegetation. To estimate riparian canopy height, we downloaded a canopy height raster from Ecovision Lab (Lang et al. 2023) and clipped this file to the New Mexico Riparian Habitat Map shapefile (Muldavin et al. 2023). We used the zonal statistics tool to calculate mean height for each HUC12 watershed. We used the EnviroAtlas calculation of percent of stream buffer with tree canopy to estimate the extent of shading vegetation along streams. We calculated percent cover of marsh/wet meadow vegetation and riparian woodland/shrubland vegetation types using shapefiles from the New Mexico Riparian Habitat Map.

Table 1. Data used to generate metrics specific to analysis of aquatic climate refugia in New Mexico. We also considered datasets described in **Part I, Table 1**. These data, identified from a literature review and selected based on study criteria, are processed to provide meaningful indicators for aquatic ecosystem refugia. For each data type we derived specific metrics and then conducted a series of analyses to test the potential relevance and relationships of each metric for use in estimating climate refugia for New Mexico aquatic habitat groups.

Category	Metric	Relevance	Refugial Relationship	Data Sources
Species Richness	Estimate for all native aquatic species, native fishes, ephemeral catchment-dependent amphibians, and perennial water-dependent amphibians and reptiles	Proxy for biological importance or inherent value of watershed.	Greater diversity = Better	International Union for Conservation of Nature https://www.iucnredlist.org/resources/spatial-data-download U.S. Geological Survey Gap Analysis Program https://gapanalysis.usgs.gov/apps/species-data-download/ U.S. Environmental Protection Agency's EnviroAtlas https://www.epa.gov/enviroatlas
Habitat Features	Estimated density, extent, or proportion of cold stream reaches, perennial stream reaches, intermittent lakes and playas, total waterbodies, and springs	Proxy for biological importance or inherent value of watershed.	Greater density, extent, or proportion = Better	Springs Stewardship Institute https://springsdata.org/ National Hydrography Dataset https://www.usgs.gov/national-hydrography/national-hydrography-dataset Western Stream Flow Metric Dataset https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Climate Condition: Climate Change	Difference in snow water equivalent (SWE)	SWE (i.e., amount of water captured within existing snowpack) on April 1st of each year. Used to infer changes in snowpack and snowpack duration and associated water availability.	Higher = Better	U.S. Bureau of Reclamation http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf

Category	Metric	Relevance	Refugial Relationship	Data Sources
Climate Condition: Climate Change	Difference in evapotranspiration (ET)	ET is the measured amount of water loss from soil and plants, considering vegetation type. Seasonal metrics have been identified as important climate change indicators.	Lower = Better	U.S. Bureau of Reclamation http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf
Climate Condition: Climate Change	Difference in potential evapotranspiration of natural vegetation (PNV)	The amount of evapotranspiration that would occur from natural vegetation if water availability were unlimited. Annual metric represents relative water availability and is used in derived indices. Seasonal metrics have been identified as important climate change indicators.	Lower = Better	U.S. Bureau of Reclamation http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf
Climate Condition: Climate Change	Difference in soil moisture content (SMC)	Change in the amount of water in a soil profile. Used as a proxy for the ability of ephemeral catchments to retain water.	Higher = Better	U.S. Bureau of Reclamation http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf
Soils	Percent of slow-infiltrating soils	Percentage of soils in s HUC12 categorized as slow infiltrating. Indicator of catchment's ability to hold surface water.	Higher = Better for ephemeral catchment-dependent species	STATSGO 2 https://databasin.org/datasets/de1a45d142f34bbca8010903eef966d9/

Category	Metric	Relevance	Refugial Relationship	Data Sources
Lithography	Percent with carbonate karst, volcanic aquifers, or unconsolidated aquifers; aquifer richness (includes carbonate karst, evaporite piping karst, unconsolidated aquifers, and volcanic aquifers)	Presence of karst and other aquifers indicate greater groundwater discharge and greater stability of streamflow volume and temperature.	Higher = Better	U.S. Geological Survey Karst Map https://pubs.usgs.gov/of/2014/1156/ U.S. Geological Survey Principal Aquifers of the United States https://www.usgs.gov/mission-areas/water-resources/science/principal-aquifers-united-states
Vegetation	Extent and height of riparian vegetation in watersheds and stream buffers	Riparian vegetation presence increases potential for stream shading, bank stabilization, and floodplain water storage.	Higher = Better	EcoVision Lab https://langnico.github.io/globalcanopyheight/ New Mexico Riparian Habitat Map https://nhnm.unm.edu/riparian/NMRipMap U.S. Environmental Protection Agency's EnviroAtlas https://www.epa.gov/enviroatlas

2.5. Indicator Analysis

We implemented workflows to analyze macrorefugia variables based on climate data and hydrorefugia variables reflecting physical features (**Figure 2a**). We analyzed the entire suite of variables (**Table 1; Supplemental 1. Table 1.2**) using correlation and regression methods to determine the relationship of variables to each other and we used machine learning methods to test the relationship between hydrorefugia and value indicators (i.e., species richness and habitat group-appropriate features). Results of these analyses were used to select a subset of datasets that best represent potential indicators of macro- and hydrorefugia for HUC12 watersheds. For continuous data, we calculated the mean value for each HUC12. For discrete data, we calculated the percent area of each HUC12 reflecting the desired properties or conditions of a given class within each HUC12. We assessed both macro- and hydrorefugia indicators separately for the five habitat groups.

More specifically, for machine learning methods, we tested the relationship between hydrorefugia indicators (metrics of topography, landscape heterogeneity, lithology, soils, and vegetation) and value indicators (species richness and density, extent, or proportion of habitat features) using the Forest-based algorithm of the Forest-based and Boosted Classification and Regression Tool (Random Forest, RF) in ArcPro 3.3.1. We excluded 15% of each run to test model performance and ran each model at least three times to assess average performance of metrics. The top four most important hydrorefugia variables, determined by RF, were then used in further analysis to identify redundancies and biases and evaluate performance, as described in Part I of this report.

2.6. Optimization and Calculation of Composite Indices

After obtaining a final set of indicators to represent macrorefugia and hydrorefugia, we transformed raw values using Z scores, as described in Part I of this report. We applied the methods used in the terrestrial analysis (e.g., Constrained by Linear Approximation (COBYLA) optimization algorithm and standardized summation) to calculate indicator weights and composite scores for macrorefugia and hydrorefugia (**Supplemental 2. Table 1.2)**. We tested climate variables for correlations and kept or dropped correlated variables by determining which were most important to each habitat group, based on results from literature review. This analysis produced separate macrorefugia and hydrorefugia scores for each of the five habitat groups **(Figure 2b)**.

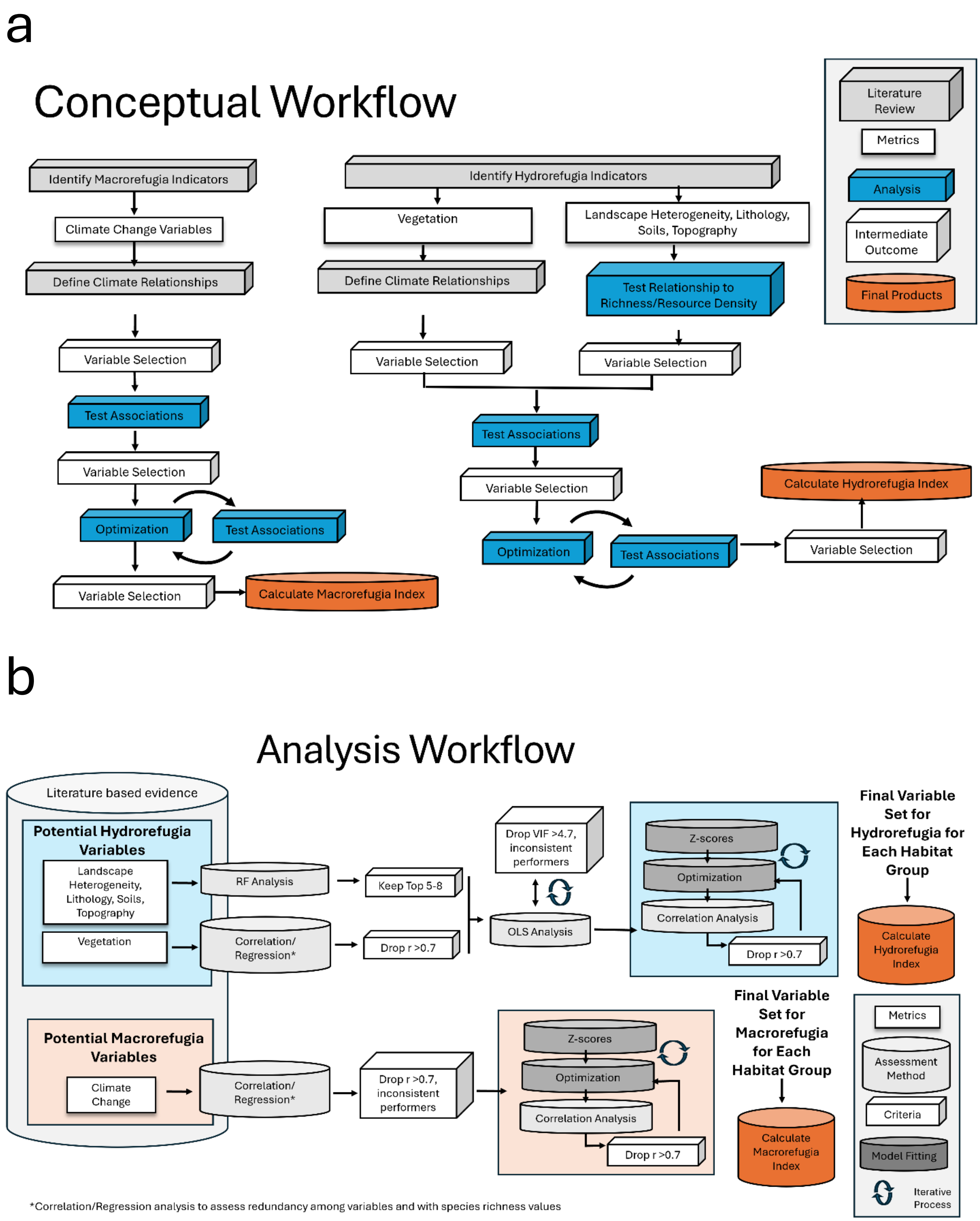


Figure 2. (a) Conceptual and **(b)** Analytical workflow for analysis of indicator datasets. **a)** Separate workflows were used to identify and assess macrorefugia (climate-based) and hydrorefugia (physical features) although

we engaged similar steps for each, which included literature review, identification, evaluation, validation, exploratory statistics, and final optimization. Existing research informed the identification of potential indicators (Year 1 activities), which were then evaluated through review of experimental and theoretical research products or statistical tests in which relationships were hypothesized but not validated in the literature (e.g., landscape heterogeneity). We then evaluated variables for their potential to inform conditions specific to the aquatic ecosystems of New Mexico and identified potential redundancies among existing variables. We engaged in this process iteratively until we identified the best set of variables that consistently provided information on a range of potential conditions while also minimizing redundancy. After identifying a subset of meaningful indicators, we identified optimal weights that ensured that each variable was contributing equally to a final composite index representing macro- or hydrorefugia. **b)** We used Random Forest, Pearson Correlation, Ordinary Least Squares (OLS) and Exploratory Regression methods to assess potential indicator candidate variables (see text for specific details). Specific workflows depended upon the nature of the variable and the level to which a relationship with refugia was established within the literature. Assessment methods are indicated in light grey columns and models used to process data are indicated in dark grey. White blocks indicate decision points (and criteria) where potential predictors were either included or dropped from further analysis. Transformation of raw values and optimization algorithms generated new correlations among variables, and we iteratively ran through this process until we identified a set of indicator data that were not highly correlated.

3. Results

3.1. Species Richness and Habitat Features

Species Richness

Patterns in species richness, our indicator of biotic value, varied among the habitat groups (Fig. 3) but, in general, richness was greatest in the Pecos River basin in the southeastern portion of the state. In addition, there were HUC12s with high species richness of fishes and perennial water-dependent amphibians and reptiles in the southwestern portion of the state. There were also HUC12s with high species richness of ephemeral catchment-dependent amphibians in the northeastern portions of the state (**Figure 3**).

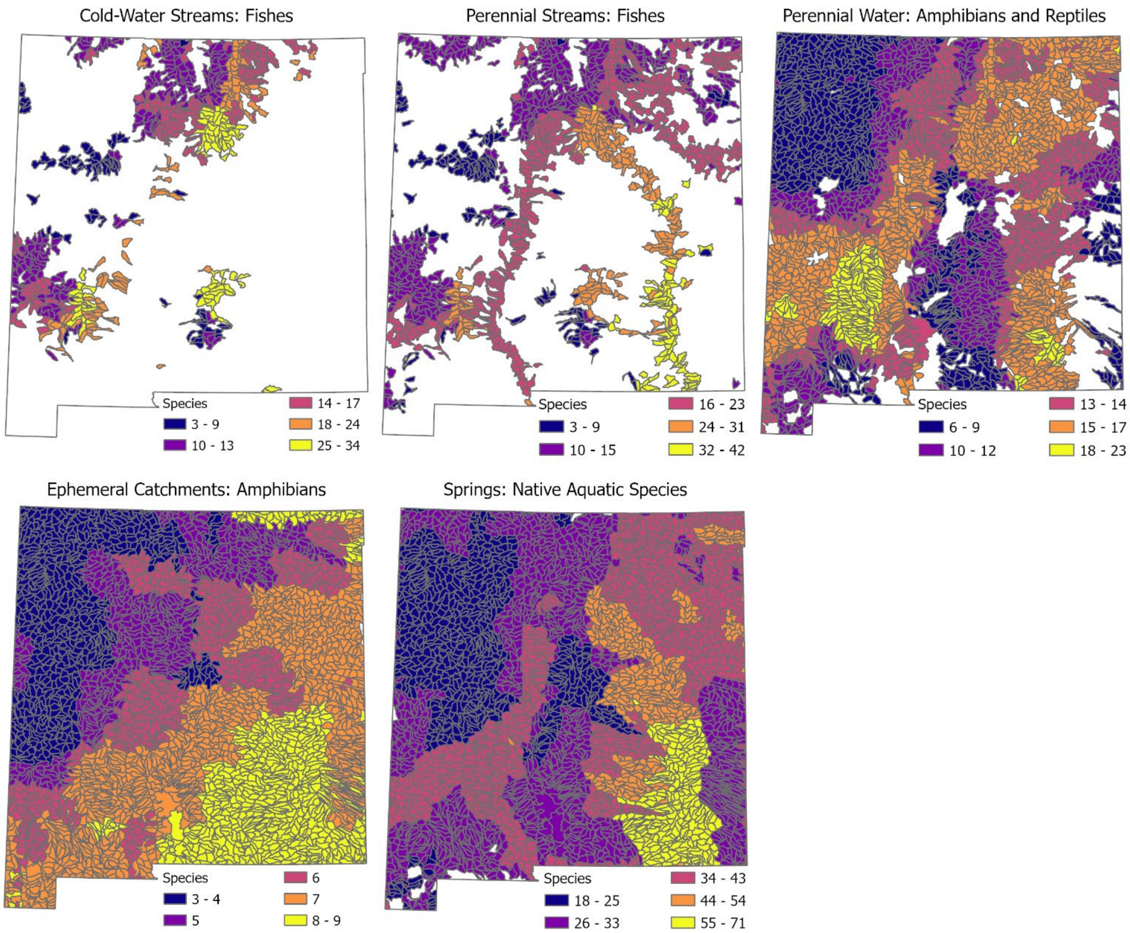


Figure 3. Biotic value indicators (species richness) for animals associated with the five aquatic habitat groups assessed for climate refugia.

Habitat Features

In terms of physical value indicators, the areas of New Mexico with the greatest importance varied among habitat groups (**Figure 4**). The HUC12s with the highest percentages of perennial stream reaches and reaches with very cold temperatures are in the northern portion of the state. The HUC12s with the greatest amounts of waterbody area and playa/intermittent lake coverage are scattered throughout. The HUC12s with the greatest density of springs are in the northern, south-central, and southwestern portions of the state.

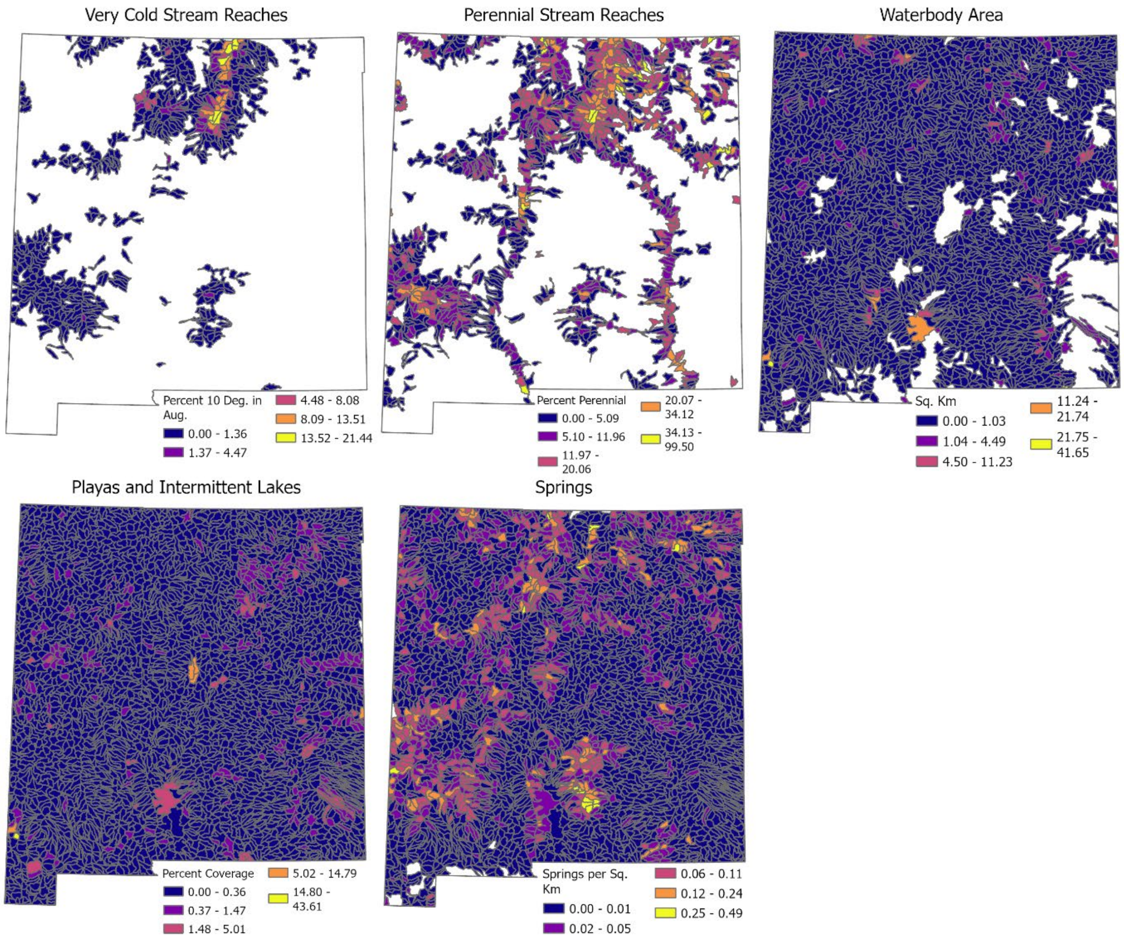


Figure 4. Physical value indicators (habitat features) for animals associated with the five aquatic habitat groups assessed for climate refugia.

3.2. Refugia Indicators

Results from Random Forest analysis of hydrorefugia indicators varied among the five aquatic habitat groups (**Table 2**). Mean elevation and the presence of carbonate karst were important for predicting the richness of each group for which they were considered. Aspect diversity, heat load index, and soil bulk density were also important predictors. We selected 15 climate variables to estimate macrorefugia (**Table 3**). Of these, seven are bioclimate variables and eight are derived climate indices. We selected 17 potential indicators for hydrorefugia. Variables included in final indicators sets varied among habitat groups (**Supplemental 2. Table 2.1, Supplemental 3. Tables 3.1 to 3.5)**.

Table 2. Top six most important predictors of species richness and habitat features for aquatic taxa groups in New Mexico. The total number of predictors (i.e., hydrological indicators of refugia) varied from 6 to 13 among groups. Rankings are based on Random Forest importance scores generated by forest-based and boosted classification.

	Cold-Water Fish Habitat		**Perennial Streams**		**Perennial Water Amphibian and Reptile Habitat**		**Ephemeral Catchments**		**Springs**	
Rank	**Species Richness**	**Habitat Features**	**Species Richness**	**Habitat Features**	**Species Richness**	**Habitat Features**	**Species Richness**	**Habitat Features**	**Species Richness**	**Habitat Features**
1	Carbonate Karst	Mean Elevation	Mean Elevation	Mean Elevation	Carbonate Karst	Topographic Wetness Index	Mean Elevation	Mean Vector Ruggedness	Carbonate Karst	Mean Elevation
2	Soil Bulk Density	Aspect Diversity	Carbonate Karst	Soil Bulk Density	Soil Bulk Density	Mean Elevation	Heat Load Index	Compound Topographic Index	Soil Bulk Density	Topographic Position Index
3	Aspect Diversity	Soil Bulk Density	Soil Bulk Density	Unconsolidated Aquifers	Mean Elevation	Compound Topographic index	Aspect Diversity	Mean Roughness	Volcanic Karst	Mean Vector Ruggedness
4	Volcanic Karst	Volcanic Karst	Unconsolidated Aquifers	Carbonate Karst	Heat Load Index	Geomorphic Diversity	Compound Topographic Index	Geomorphic Diversity	Aquifer Richness	Slope Diversity
5	Heat Load Index	Slope Diversity	Volcanic Aquifers	Volcanic Karst	Aspect Diversity	Slope Diversity	Mean Roughness	Mean Elevation	Heat Load Index	Aspect Diversity
6	Geomorphic Diversity	Topographic Wetness Index	Aquifer Richness	Aquifer Richness	Compound Topographic Index	Topographic Position Index	Mean Vector Ruggedness	Heat Load Index	Mean Vector Ruggedness	Heat Load Index

Table 3. List of indicators used to identify climate refugia. Macrorefugia represent expected changes in climatic conditions. Hydrorefugia are associated with soil properties, lithology, topography, vegetation, and landscape heterogeneity. Climate datasets are derived from future climate projections for mid-century time periods (~2050) under a Coupled Model Intercomparison Project 5 (CMIP5), Representative Concentration Pathway 4.5 (RCP 4.5) greenhouse gas emission scenario. Climate Novelty and Backwards Velocity are multidimensional measures of climate (i.e., they consider both precipitation and temperature). Variables were compared and selected through an iterative process using Random Forest and linear regression methods. Group abbreviations: All = all habitat groups, AmpRep = Perennial water amphibian and reptile habitat, ColWat = Cold-water fish habitat, EphCat = Ephemeral catchments, PerStr = Perennial streams, Spr = Springs. Variable abbreviations: Change = Change from current to future conditions, Diff = Difference, Max = Maximum, Pct = Percent, Precip = Precipitation, SDI = Shannon Diversity Index, and Temp = Temperature.

Macrorefugia Variable	**Group(s)**
Backwards Climate Velocity	AmpRep, ColWat, EphCat
Change Soil Moisture Content (SMC)	EphCat
Change Snow Water Equivalent (SWE)	AmpRep, ColWat, PerStr, Spr
Change Evapotranspiration (ET)	AmpRep, EphCat
Change Potential Evapotranspiration of Natural Vegetation (PNV)	ColWat, PerStr, Spr
Diff Max Temp Warmest Month (Bio5)	AmpRep, ColWat, EphCat, PerStr
Diff Mean Temp Wettest Quarter (Bio8)	AmpRep, ColWat, PerStr, Spr
Diff Mean Temp Driest Quarter (Bio 9)	All
Pct Change Precip Driest Month (Bio14)	EphCat
Pct Change Precip Wettest Month (Bio13)	PerStr
Pct Change Precip Warmest Quarter (Bio18)	AmpRep, ColWat, EphCat
Pct Change Precip Coldest Quarter (Bio19)	AmpRep, ColWat, PerStr, Spr
Pct Change June Streamflow Volume	AmpRep, ColWat, PerStr
Pct Change August Stream Temp	ColWat
Hydrorefugia Variable	
Landscape Heterogeneity	
Mean SDI for Aspect	AmpRep, ColWat, EphCat
Mean SDI for Geomorphology	AmpRep, ColWat, EphCat
Mean Vector Ruggedness	Spr
Lithology	
Aquifer Richness	PerStr, Spr
Pct Carbonate Karst	AmpRep, ColWat, PerStr, Spr
Pct Volcanic Aquifers	ColWat, PerStr, Spr
Pct Unconsolidated Aquifers	PerStr
Soils	
Mean Soil Bulk Density	AmpRep, ColWat, PerStr, Spr
Mean Soil Water Storage	AmpRep
Pct Slow-Infiltrating Soils	EphCat
Topography	
Mean Compound Topographic Index	AmpRep, EphCat
Mean Elevation	AmpRep, ColWat. PerStr
Mean Heat Load Index	AmpRep, ColWat, EphCat, Spr
Vegetation	
Mean Riparian Canopy Height	AmpRep, ColWat
Pct Marsh/Wet Meadow Vegetation	AmpRep, ColWat, PerStr
Pct Riparian Woodland/Shrubland	ColWat

Macrorefugia Variable	Group(s)
Pct Stream Buffer with Tree Canopy	AmpRep, ColWat

3.3. Composite Indices

We calculated five hydrorefugia and five macrorefugia composite indices using our weighting scheme. For most habitat groups, macrorefugia are concentrated in higher elevations and forested areas, especially in the northern and southwestern portions of the state (Fig. 5). Areas with high potential for hydrorefugia are dispersed throughout the state, with patterns varying among habitat groups. For example, areas along the lower Rio Grande and Pecos River have high potential for hydrorefugia for ephemeral catchments, whereas the northern mountains contain the greatest potential for hydrorefugia for cold-water fish habitat.

Areas with high potential for both hydrorefugia and macrorefugia include high-elevation areas for perennial water amphibian and reptile habitat in the northern and western portions of the state; mid-elevation areas for cold-water fish habitat in the northern portion; lowland areas for ephemeral catchments in the northern, western, and central portions of the state; areas in the northern portion for perennial streams; and mountainous areas in the northern, southeastern, and western portions of the state for springs (**Figure 5**). For several habitat groups, these areas of high climate refugia potential do not overlap areas where refugia may be most important, based on species richness or habitat features. One example is the southeastern portion of the state, where fishes and ephemeral catchment-dependent amphibians are the most species rich but where few areas have high potential for hydrorefugia *and* macrorefugia. Also, there are few areas with high potential of both refugia types in the mountains in the northern and southwestern portions of the state where cold-water streams are abundant. There is, however, high refugia potential in the Jemez, Mogollon, and Sacramento Mountains where springs are abundant, highlighting the conservation value of these areas.

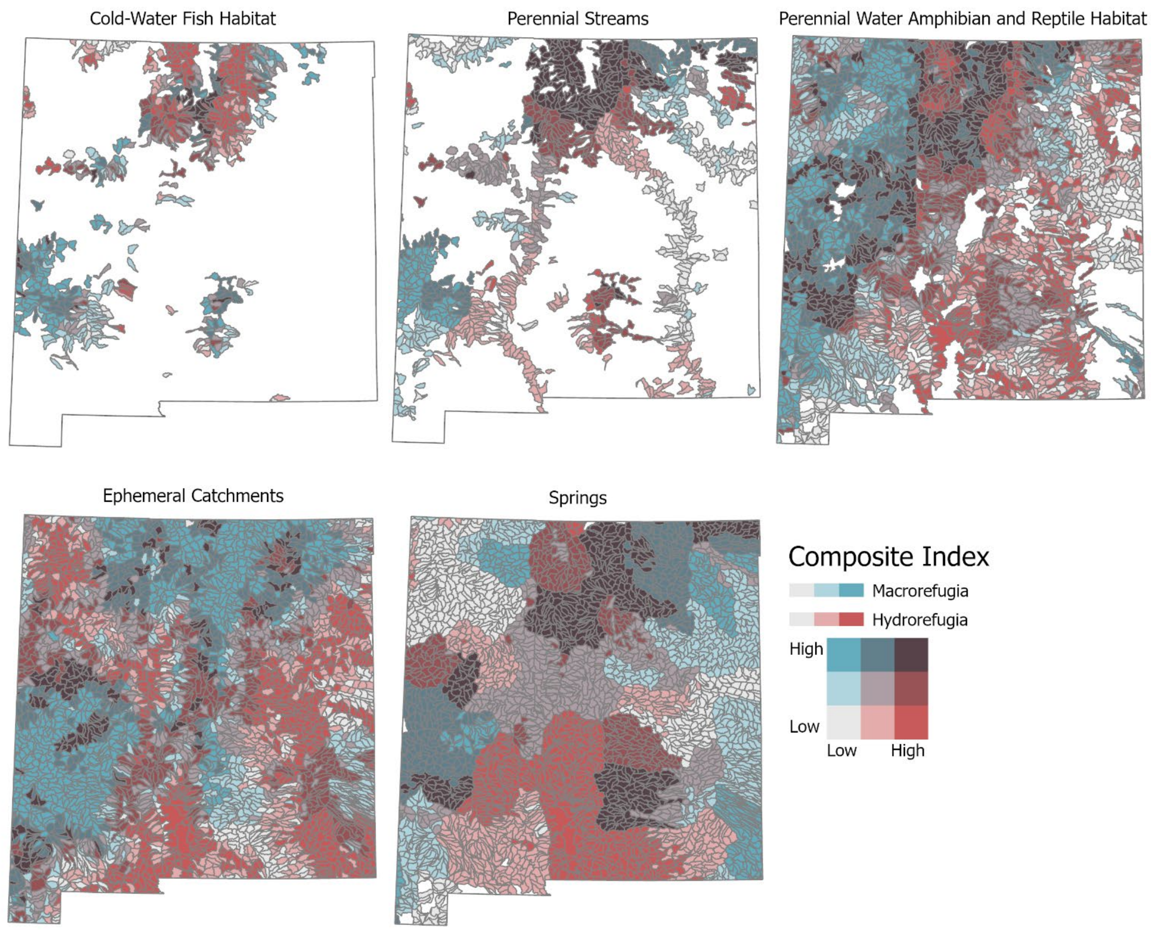


Figure 5. HUC12 composite scores for macrorefugia and hydrorefugia by habitat groups.

3.4. Status of Current Conservation Areas

Several New Mexico COAs contain high-value aquatic refugia as indicated by CI scores. However, most COA are unlikely to supply both macrorefugia and hydrorefugia, nor are any COA likely to support refugia for all taxa groups equally (**Table 4**).

There are 272 possible CI score categories that can arise from the five habitat group hydrorefugia, five habitat group macrorefugia, and 30 COAs. This number is less than 300 because some COAs don't overlap any HUC12s containing a particular habitat group. Among hydrorefugia, 60 of the 136 scores (44%) were <10% of the statewide average (i.e. average of all HUC12s containing each habitat group), 43 of the 136 (32%) were >10% of the statewide average, and 33 of the 136 (24%) were within 10% of the statewide average. Among macrorefugia, 64 of the 136 scores (47%) were <10% of the statewide average, 35 of the 136 (26%) were >10% of the statewide average and 37 of the 136 (27%) were within 10% of the statewide average.

COA-Specific Trends

For hydrorefugia, the Apache Box, Big Hatchet Mountains, Bootheel, Lower Gila River, Mimbres River, and Upper San Juan River COAs had lower-than-average CI scores for each habitat group represented (**Table 5**). Most of these COAs are in the southern part of the state. Several COAs had hydrorefugia scores that were above average for most of the habitat groups represented: Eagle Nest Lake, Jemez Mountains, Lower Pecos and Black Rivers, Northern Sacramento and Capitan Mountains, Rio Chama, Rio Puerco, and Santa Fe River. These COAs are largely in mountainous areas.

For macrorefugia, the Big Hatchet Mountains, Guadalupe Mountains, Lower Pecos and Black Rivers, Lower Rio Grande, Lower Rio Grande - Caballo Reservoir, Middle Rio Grande, Organ Mountains, and Pecos River - Lake Sumner COAs had lower-than-average CI scores for each habitat group represented. These COAs are in the southern part of the state. Several COAs had macrorefugia scores above average for most of the habitat groups represented: Eagle Nest Lake, Rio Puerco, San Francisco River, Santa Fe River, and Upper Gila River. These COAs are in the northern and southwestern parts of the state.

Habitat-Specific Trends

When compared to the entire state of New Mexico, COAs tend to have lower-than-average hydrorefugia CI scores for cold-water fish habitat and perennial streams (**Table 5**). The springs habitat group has the greatest percentage of COAs with above-average hydrorefugia scores, with 47% of COAs having a greater than 10% above the statewide average.

Table 4. Percent area of each Conservation Opportunity Area (COA) encompassing high-ranking refugia scores. Composite Index scores for hydrorefugia and macrorefugia were scaled 0-1 and divided into five quantiles. Numbers shown below report the proportion of each COA that overlapped with the 12-digit Hydrological Unit Codes (HUC12) holding the highest 20% of scores. COAs with more than 50% of their total areas overlapping landscapes with a high potential to contain refugia are indicated in bold. Blank cells indicate no overlap with high-potential areas. "N/A" indicates no overlap with HUC12s that contain habitat for the taxonomic group.

	Cold-Water Fish Habitat		**Perennial Streams**		**Perennial Water Amphibian and Reptile Habitat**		**Ephemeral Catchments**		**Springs**	
	Hydro-refugia	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**
Apache Box	N/A	N/A		2.1		**100**		**74.6**		2.1
Big Hatchet Mountains	N/A	N/A	N/A	N/A						
Black Range Mountains	3.0	0.2			34.4	31.8		**87.2**	42.8	31.8
Bootheel	N/A	N/A					6.4			
Conchas Reservoir	N/A	N/A			6.4		40.3			
Eagle Nest Lake	**100**		**100**		**100**			**100**		**100**
Guadalupe Mountains									**81.5**	
Jemez Mountains	48.6		**78.7**	12.5	**91.9**	33.2		39.9	**100**	**87.5**
Lower Gila River		0.6				**92.0**	20.3	10.3	4.0	13.9
Lower Pecos and Black Rivers	N/A	N/A			45.0		**50.9**		3.4	
Lower Rio Grande	N/A	N/A					**52.9**			
Lower Rio Grande - Caballo Reservoir	N/A	N/A			29.7		42.4		1.4	
Middle Pecos River	N/A	N/A			**67.2**		**63.8**		13.1	11.5
Middle San Juan River					41.3	10.8	33.2			
Middle Rio Grande	N/A	N/A			**69.3**		**58.9**		6.1	
Mimbres River					18.6	1.1		**65.4**		1.1
Northern Sacramento and Capitan Mountains		27.1			**70.1**			0.4	**100**	**73.7**
Organ Mountains					0.7		3.5		**67.7**	

	Cold-Water Fish Habitat		**Perennial Streams**		**Perennial Water Amphibian and Reptile Habitat**		**Ephemeral Catchments**		**Springs**	
	Hydro-refugia	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**
Pecos River - Lake Sumner	N/A	N/A			10.2		**60.1**			
Pecos River Headwaters	N/A	N/A			**72.3**		48.4			
Rio Chama	34.7	25.9	**83.0**	**58.5**	**58.2**	0.3	0.3	**54.0**	34.5	
Rio Puerco	**57.0**	41.1			**72.7**	**100**		**100**		
San Francisco River	6.9	**84.0**		**97.4**	23.9	**100**		**100**		**100**
San Mateo Mountains	0.2				30.8			**82.6**	**84.9**	
Santa Fe River	N/A	N/A	8.4		**78.4**	21.6	20.7	**50.7**	**100**	**100**
Southern Sacramento Mountains		8.5	32.2		**80.2**		0.3		**100**	**87.4**
Upper Gila River	1.2	**61.8**		18.5	**50.5**	**80.1**		**97.3**	15.8	**93.0**
Upper Rio Grande	40.2	14.2	**54.1**	**52.2**	**79.8**	**53.5**	14.7	47.1	**99.9**	47.1
Upper San Juan River						**85.5**		41.7		
Vermejo River	N/A	N/A		**66.1**			**88.9**	5.6		**100**

Table 5. Percent difference in aquatic refugia Composite Index (CI) scores for COA vs. the entire state of New Mexico. This represents the degree to which the average CI score for HUC12s within each COA differed from the average of all HUC12s across the state. “N/A” indicates no overlap with HUC12s containing habitat for the taxa group. Differences greater than or equal to an absolute value of 50% are indicated in bold. Numbers in red indicate negative values, such that CI scores are lower than the average across the state.

	Cold-Water Fish Habitat		**Perennial Streams**		**Perennial Water Amphibian and Reptile Habitat**		**Ephemeral Catchments**		**Springs**	
	Hydro-refugia	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**
Apache Box	N/A	N/A	**-137**	8	-45	28	-33	18	-36	8
Big Hatchet Mountains	N/A	N/A	N/A	N/A	-33	**-50**	-6	-10	**-69**	-27
Black Range Mountains	**-87**	-10	-37	-48	-7	-10	**-63**	13	25	-30
Bootheel	N/A	N/A	**-127**	-16	-37	1	-8	6	**-91**	-9
Conchas Reservoir	N/A	N/A	**-102**	-7	5	-30	11	-11	-46	6
Eagle Nest Lake	**59**	-15	42	19	**58**	-13	-39	39	12	32
Guadalupe Mountains	**-57**	**-90**	-5	**-286**	-7	**-150**	-25	**-880**	37	-21
Jemez Mountains	40	-11	44	7	40	15	-41	5	44	18
Lower Gila River	**-212**	-9	**-161**	4	-29	22	-17	9	-31	6
Lower Pecos and Black Rivers	N/A	N/A	-26	**-224**	25	**-134**	12	-37	10	-21
Lower Rio Grande	N/A	N/A	-10	**-268**	-10	**-80**	6	**-56**	16	**-82**
Lower Rio Grande - Caballo Reservoir	N/A	N/A	-44	**-190**	4	**-59**	4	-12	16	**-122**
Middle Pecos River	N/A	N/A	**-85**	-45	29	-39	16	-15	-14	-7
Middle San Juan River	-47	**-101**	**-288**	**-113**	3	7	8	-28	**-72**	**-188**
Middle Rio Grande	N/A	N/A	-21	**-50**	23	-25	13	-19	9	-36
Mimbres River	**-198**	**-54**	**-76**	**-128**	-45	-33	**-66**	-5	-18	**-64**

	Cold-Water Fish Habitat		Perennial Streams		Perennial Water Amphibian and Reptile Habitat		Ephemeral Catchments		Springs	
	Hydro-refugia	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**	**Hydro-refugia**	**Macro-refugia**
Northern Sacramento and Capitan Mountains	-10	11	15	9	20	-9	-25	9	48	23
Organ Mountains	**-71**	-30	-1	**-153**	-4	**-91**	-1	**-122**	38	**-58**
Pecos River - Lake Sumner	N/A	N/A	**-141**	**-124**	-3	**-97**	18	**-52**	-31	-23
Pecos River Headwaters	N/A	N/A	-43	**-92**	12	**-58**	11	-34	9	6
Rio Chama	26	-3	31	31	25	-2	-6	19	26	9
Rio Puerco	24	11	6	15	24	45	-4	46	12	-4
San Francisco River	**-57**	13	**-59**	39	0.4	41	-49	20	-5	47
San Mateo Mountains	**-70**	-15	-11	**-121**	1	-23	-47	15	36	**-80**
Santa Fe River	N/A	N/A	23	8	21	22	0.1	16	33	19
Southern Sacramento Mountains	-28	10	25	-10	23	-33	-47	-2	**54**	31
Upper Gila River	**-69**	6	**-55**	21	1	22	**-63**	16	9	32
Upper Rio Grande	7	-24	31	6	-7	9	-36	-7	39	-8
Upper San Juan River	**-148**	**-105**	**-275**	2	-15	28	-10	15	**-97**	8
Vermejo River	N/A	N/A	-38	34	1	9	13	8	-24	34

4. Applications and Conclusions

Our analysis identifies high-value watersheds (i.e., those containing higher-value CI scores) and COAs using established and novel methods to identify aquatic habitat groups, quantify value indicators, and assess a suite of aquatic indicator datasets. Most COAs overlapped high-scoring HUC12s for macrorefugia (63%) and hydrorefugia (70%). The Rio Puerco, San Francisco River, Santa Fe River, and Upper Rio Grande were more likely to contain high-scoring watersheds for multiple groups and to have a greater area of overlap with high-scoring watersheds. Considering the area of overlap with high-scoring watersheds, the San Francisco River COA appears to be a particularly important area for macrorefugia. Eagle Nest Lake and the Jemez Mountains appear to be important for hydrorefugia **(Table 4**).

Looking at the highest and lowest CI scores for each COA reveals distinct patterns among habitat groups and refugia types (**Table 5**). Eagle Nest Lake, the Jemez Mountains, and Rio Chama were frequently among the top three scorers for hydrorefugia. Pecos River - Lake Sumner, Middle Pecos River, Middle Rio Grande, and Vermejo River scored high for ephemeral catchment hydrorefugia, but not for other habitat groups. Likewise, the Northern Sacramento and Capitan Mountains and Southern Sacramento Mountains scored high for springs hydrorefugia but not for other groups. For macrorefugia, Rio Chama and Rio Puerco were among the top three scorers in four of the five habitat groups. The COAs with the lowest CI scores for hydrorefugia included the Bootheel, Middle San Juan River, Mimbres River, and Upper San Juan River. The Guadalupe Mountains and Lower Rio Grande often had the lowest scores for macrorefugia.

Collectively, the results of this analysis indicate that the COAs associated with mountainous areas cover a range of habitats with moderate to high potential for aquatic refugia. These COAs may be critical to preserving the biodiversity of amphibians, fishes, reptiles, and spring-dependent species. Several lowland COAs have potential refugia for ephemeral catchments, but additional COAs in locations such as the eastern playa lakes region would increase this potential.

To prioritize areas for protection of aquatic species, information is needed on the distributional patterns of native species, in addition to the aquatic habitat features necessary for these species' survival in a warming climate (Costelloe and Russell 2014, Dudgeon et al. 2006). For our assessment of aquatic refugia, we calculated richness of native species and the density of important habitat features that were specific to each aquatic habitat group. Our results indicate that the southeastern portion of New Mexico supports high biodiversity for several groups, whereas the distribution of important habitat features varies among the groups examined. In general, stream reaches with cold water temperatures and perennial flows are most abundant at higher elevations in the northern portion of the state. In contrast, watersheds with high density of springs and/or ephemeral catchments are distributed throughout the state. Conservation strategies that include a variety of taxa, habitats, and geographical locations are therefore most likely to protect New Mexico's aquatic biodiversity.

Our methods for assessing aquatic refugia differed from those developed for terrestrial refugia in several ways. First, we selected indicators for macrorefugia separately for each of the five habitat groups. Second, we replaced microrefugia with the concept of hydrorefugia, to reflect the importance of aquatic habitat features in maintaining the volume and quality of surface water required by each habitat group. This approach allowed us to incorporate the variation inherent in the state's aquatic ecosystems, which include small, spring-fed creeks; large, turbid rivers; and rain-fed playa lakes.

We found considerable spatial variation in values of refugia indicators and CI scores (**Supplemental 4, Figure 5**) both across the state and among habitat groups. Our results highlight some of the challenges that managers will face when attempting to protect aquatic species in a warming climate. Areas with high potential for macrorefugia are often in different locations than the areas with high potential for hydrorefugia. As a result, there may be few opportunities for managers to protect both types of aquatic refugia within a single watershed or protected area. We also found that some of the most important areas for aquatic species have low potential for at least one type of refugia. Examples include the ecologically important playa lakes of eastern New Mexico, where many watersheds have low macrorefugia scores for ephemeral catchments. Likewise, many species-rich watersheds in the Pecos River basin have low hydrorefugia scores for perennial streams.

Limitations and Future Direction

Our results highlight areas of high refugia potential for certain taxa and their habitats, but these results were influenced by our selection of refugia indicators and habitat groups and the extent of analysis. Species-specific management plans would require the incorporation of more information regarding species' habitat requirements and current habitat conditions in a finer-scale analysis.

Our assessment used macrorefugia indicators based on temperature, precipitation, and related variables. Climate change is also affecting habitats by interacting with disturbances such as wildfire, post-fire flooding, and invasive species (Dunham et al. 2007; Isaak et al. 2010; Leonard et al. 2017; Touma et al. 2022). Future assessment should therefore include these impacts. In addition, current and future anthropogenic activities such as water use and watershed development should be assessed to determine the suitability of watersheds and COAs for management as refugia.

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71. Zeigler, M.P., Todd, A.S., and Caldwell, C.A. (2012) "Evidence of recent climate change within the historic range of Rio Grande cutthroat trout: implications for management and future persistence." *Trans. Am. Fish. Soc.* 141(4): 1045–1059.

Supplemental Files 1-4 for Final Report Part I: Climate Change Refugia for Terrestrial Species

Agreement # 23-CO-11221632-013

State Wildlife Grant # T-80-R-1

Prepared by Megan M. Friggens/Karen Cooper Chaudry

Contents

Supplemental 1. Background and Results of Literature Review

Table 1.1. List of indicators identified in review of the literature focused on climate change refugia. Papers that focused on the identification of climate change refugia are cited in this list and indicators are listed as they are presented in each paper. Some studies focused on a concept in its entirety (e.g., landforms) and others focused on certain aspects of a concept (e.g., percent valleys). Some variables are specific to certain ecosystems. Importantly, this list does not include variables listed in papers assessing species distributions or analyzing climate resilience/resistance. However, papers covering those topics were considered during the final selection of refugia indicators. For citations see full Year 1 Report (Friggens and Chaudhry 2022).

Category Metric		**Citations**
Biological diversity		
	Species Richness	Carroll et al. 2017; Carroll and Noss 2020
	Ecotypic Diversity	
Carbon		
	Aboveground Carbon	Carroll and Noss 2020
	Soil Carbon	
Climate		
	Climate Connectivity	Carroll and Noss 2020; Dobrowski 2011; Haire et al. 2022; Rojas et al. 2013; Stalberg et al. 2018; Stark and Fridley 2022;
	Interpolated Mean Annual Temperature	
	Mean Annual Temperature	
	Mean Annual Maximum Temperature	
	Mean Annual Minimum Temperature	
	Mean Seasonal or Quarterly Temp	
	Macroclimate Mean Annual Temperature	
	Microclimate Mean Annual Temperature	
	Maximum Synoptic Temperature	
	Minimum Synoptic Temperature	
	Temperature (Hottest-Coldest) Difference	
	Total Precipitation Per Season or Quarter	
	Total Annual Precipitation	
Climate Extremes		

Category Metric		Citations
	Extreme Summer Temp	Ashcroft et al. 2012; Rojas et al. 2013
	Highest Mean Annual Temp	
	Lowest Mean Annual Temp	
	Frequency of Drought	
	Length of Drought	
	Number of Heat Waves	
	Snow vs. Rain Proportion	
Climate Index		
	Backward Climatic Velocity	Ashcroft et al. 2012; Carroll et al. 2017; Carroll and Noss 2020; Haire et al. 2022; Stalberg et al. 2018
	Forward Climatic Velocity	
	Climate Dissimilarity (Over Time)	
	Climate Stability	
	Climatic Isolation	
	Climatic Moisture Index (CMI)	
	Heat Moisture Index	
	Current Climate Diversity	
Climate- Water Balance		
	Actual Evapotranspiration (AET)	Ackerley et al. 2020
	Climatic Water Deficit (CWD)	
	Potential Evapotranspiration (PET)	
Continental position		
	Coastal Distance	Stalberg et al. 2018
	Latitude	
Drought refugia		
	Drier Climate (Relative)	Cartwright et al. 2020
	Ecotones	
	Elevation	
	Soil Available Water Capacity	

Category Metric		Citations
	Soil Bulk Density	
Fire		
	Fire Regime Changes	Rojas et al. 2013
Hydrology		
	Hydrology and Water Quantity	Rojas et al. 2013
Land Cover Extent		
	Percent Cover (e.g., Forest)	Cartwright 2018; Estevo et al. 2022; Hoffrén et al. 2022
	Percent Ecotype/Area (e.g., Fir)	
	Total Basal Area (e.g., Forests)	
Land Cover Pattern/Landforms		
	Canyons	Carroll et al. 2017; Cartwright et al. 2018; Dobrowski 2011; Estevo et al. 2023; Gentili et al. 2014; Haire et al. 2022; Stalberg et al. 2018; Stark and Fridley 2022
	Catchment Area	
	Catchment Slope	
	Convergent Features	
	Distance To Ecotone (e.g., Fir)	
	Facet ID Values	
	Hilltop Present	
	Landforms	
	Presence of Debris-Covered Glaciers, Rock Glaciers and Boulder-Streams (for Alpine)	
	Presence of Incised Valleys	
	Proportion Headwater	
	Presence of Ridges	
	Stream Distance	
	Topofacet Layer	
	Valley Bottoms Presence	
	Valley Bottoms Proportion	
	Valley Depth	
Land Use		

Category	Metric	Citations
	Human Footprint	Carroll and Noss 2020; Rojas et al. 2013
	Human Use of Wildlands	
	Urban Expansion	
Soils		
	Moisture Holding Capacity	Ackerly et al. 2020; Carroll et al. 2017; Cartwright 2018; Duniway et al. 2021
	Presence of Nonsaline Alluvial Soils	
	Soil Bulk Density	
	Soil Order	
Topography		
	Aspect	Ackerley et al. 2021; Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2014; Haire et al. 2022; Hoffren et al. 2023; Stalberg et al. 2018; Stark and Fridley 2022
	Elevation	
	Landform	
	Mid-Slope Position	
	North–South Corridor Potential	
	Slope	
Topographic Index		
	Annual Radiation	Ackerley et al. 2021; Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2014; Haire et al. 2022; Stalberg et al. 2018; Stark and Fridley 2022
	Compound Topographic Index (CTI) / Topographic Wetness Index (TPI)*	
	Daily Radiation	
	Heat Load Index (HLI)	
	Presence of NorthFacing Slope	
	Slope + Aspect (Southness)	
	Terrain Roughness/Terrain Roughness Index*	
	Terrain Ruggedness Index (TRI)*	
	Topographic Convergence Index	
	Topographic Position Index (TPI)*	
Topodiversity**		
	Aspect Diversity	Carroll et al. 2017;

Category Metric		**Citations**
	Ecotype Diversity	Carroll and Noss 2020; Malakoutinakhah et al. 2019
	Elevational Diversity	
	Heat Load Index (HLI) Diversity	
	Land Facet Diversity	
	Proportion High Land Facet Diversity Represented Across Land Facet Types	
	Topographic Diversity	
Topodiversity Index		
	Elevation + Topodiversity	Carroll et al. 2017; Carroll and Noss 2020
	Elevational and HLI Diversity	
Vegetation		
	Normalized Difference Moisture Index (NDMI)	Haire et al. 2022
	Normalized Difference Vegetation Index (NDVI)	
*Variations exist in how these are calculated. Studies also employ these at different spatial scales, which are not elaborated on here.		
**Diversity metrics that include combinations of other diversity metrics are not noted here.		

Table 1.2. Candidate list of climate refugia indicators considered for inclusion in analysis of New Mexico landscapes. These data were gathered from existing sources ("Available") or were derived from elevation or climate information ("Calculated") and are currently stored in either a geodatabase or the collaborative ArcGIS Online folder.

Category/Metric	Source (Available or Calculated)
Biodiversity	
Species Richness	Available
Ecosystem/Ecotypic Diversity	Available; Calculated
Climate Indices	
Forward Velocity	Available
Backward Velocity	Available
Presence of Climate Corridors*	Available
Climate Dissimilarity (over time)	Available; Calculated
Current Climate Diversity	Calculated
Climate Stability	Calculated
Climatic Isolation	Calculated
Climatic Moisture Index (CMI)	Calculated
Heat Moisture Index (HMI)	Calculated
Derived Climate Variables (based on current and projected temperature and precipitation) variables)	
Aridity Index (AI)	Available
Climatic Water Deficit (CWD)	Available
Mean Annual Temperature	Calculated
Annual Minimum Temperature	Calculated
Annual Maximum Temperature	Calculated
Interannual Range of Temperatures	Calculated
Interannual Range of Precipitation	Calculated
Mean Annual Isothermality	Calculated
April Snow Water Equivalent (SWE)	Calculated
Total Annual Precipitation	Calculated
Total Precipitation Warmest Quarter	Calculated
Potential Evapotranspiration (PET)	Calculated
Actual Evapotranspiration (AET)	Calculated
Summer Vaper Pressure Deficit (VPD)	Calculated
Spring AET	Calculated
Summer AET	Calculated
Spring PET	Calculated
Summer PET	Calculated
Mean Dry Degree Days	Available
Future Change	
Magnitude Change Mean Annual Temperature	Calculated
Magnitude Change Summer Maximum Temperature	Calculated
Magnitude Change in Winter Minimum Temperature	Calculated
Percent of Normal Future Annual Precipitation	Calculated
Percent of Normal Future Winter Precipitation	Calculated
Percent of Normal Future Spring Precipitation	Calculated
Percent of Normal Future Summer Precipitation	Calculated
Topography	
Elevation	Calculated
Slope	Calculated
Ruggedness	Calculated

Category/Metric	Source (Available or Calculated)
Aspect (radians)	Calculated
Aspect (linear)	Calculated
Derived Topographic	
Landform	Calculated
Catchment Area	Calculated
Curve	Calculated
Mean Elevation	Calculated
Topographic Indices	
Heat Load Index (HLI)	Available
Terrain Ruggedness Index (TRI)	Calculated
Northness (cosine of Aspect in radians)	Calculated
Eastness (sine of Aspect in radians)	Calculated
Topographic Position Index (TPI)*	Calculated
Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)	Available; Calculated
Slope + Aspect (Southness)	Calculated
Topographic Convergence Index	Calculated
Vector Ruggedness Index	Calculated
Standard Deviation of Slope	Calculated
Land Cover Pattern / Landforms	
Topofacet Layer	Available
Facet ID values	Available
Convergent Features (e.g., Catchments, Valleys, Headwaters, Canyons)	Calculated
Presence of Ecotones	Calculated
Distance to Ecotone (e.g., Fir)	Calculated
Percent Cover (e.g., Forest)	Calculated
Stream Distance	Calculated
Topographic Diversity	
Aspect Diversity	Calculated
Elevational Diversity	Calculated
HLI Diversity	Calculated
Land Facet Diversity	Calculated
Topographic Diversity	Calculated
Soils	
Percent Soil Bulk Density, 1m	Available; Calculated
Soil Water Storage / Available Water Capacity	Available
Available Soil Moisture	Available; Calculated
Mean Duration Dry Soil Intervals	Available
Presence of Shallow or Finer Textured Soils	Available; Calculated
*Climate corridors are areas that form the best route between current or future climate types.	

Table 1.3. WorldClim* data generated at a 1-km scale and summarized into 19 bioclimatic variables representing annual and seasonal trends in temperature (ºC) and rainfall values (mm). Bioclimatic data were downloaded and processed for the following variables:

BIO1 = Annual Mean Temperature

BIO2 = Mean Diurnal Range (Mean of monthly [max temp - min temp])

BIO3 = Isothermality (BIO2/BIO7) (×100)

BIO4 = Temperature Seasonality (standard deviation × 100)

BIO5 = Max Temperature of Warmest Month

BIO6 = Min Temperature of Coldest Month

BIO7 = Temperature Annual Range (BIO5-BIO6)

BIO8 = Mean Temperature of Wettest Quarter

BIO9 = Mean Temperature of Driest Quarter

BIO10 = Mean Temperature of Warmest Quarter

BIO11 = Mean Temperature of Coldest Quarter

BIO12 = Annual Precipitation (mm)

BIO13 = Precipitation of Wettest Month (mm)

BIO14 = Precipitation of Driest Month (mm)

BIO15 = Precipitation Seasonality (Coefficient of Variation)

BIO16 = Precipitation of Wettest Quarter (mm)

BIO17 = Precipitation of Driest Quarter (mm)

BIO18 = Precipitation of Warmest Quarter (mm)

BIO19 = Precipitation of Coldest Quarter (mm)

*We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Table 1.4. Tools/Toolsets used in ArcGIS PRo 4.4.2. Note: there is no consistent terminology for tool designations among references available in ArcGIS Pro interfaces, ESRI webpage, and primary references*. Many tools do not provide a self-designation. We have created designations of "toolbox," "toolset," and "tool" here to help identify hierarchies among tools used for our analyses but these designations may or may not correspond to other reference material. We use "toolbox" to indicate the first source of a tool usually designated as a red box in the ArcGIS Pro software. Each toolbox may contain multiple toolsets and each toolset may contain multiple tools.

Toolbox	**Toolset**	**Tools**
Spatial Analysis Tools	Zonal Statistics	Zonal Statistics, Tabulate Area
	Surface	Aspect, Curvature, Slope, Surface Parameters
	Neighborhood	Focal Statistics
	Hydrology	Fill
	Reclass	Reclassify, Slice
Raster Calculator	--	--
Arc Hydro Pro Toolbox (Dilts 2023)	Terrain Preprocessing	Vector Ruggedness Metric, Topographic Position Index, Terrain Ruggedness Index, Flow Accumulation, Flow Direction, Fill Sinks
Surface Parameters and the Geomorphology and Gradient Metrics Tools (Evans et al., 2014)	Gradient Metrics Tool	Roughness, Curvature, Slope Position, Linear Aspect, Heat load index, Mean Slope, Compound Topographic Index, Slope/Aspect Transformations
Spatial Statistics Tools*	Modeling Spatial Relationships	Generalized Linear Regression, Ordinary Least Squares, Forest-based and Boosted Classification and Regression
Diversity Tools		https://apl.maps.arcgis.com/home/item.html?id=11caf84c98d04d498cf40d0e478f9f13
*In ArcGIS Pro Tools this is "Spatial statistics tools", on the ESRI webpage, this is called "Spatial Statistics toolbox"		

1. Dilts, K. 2023. Topography Toolbox for ArcGIS Pro. University of Nevada Reno. Available at: https://www.arcgis.com/home/item.html?id=247fbe56c7ff48229c9b1fe132d1b5e9
2. Evans J. S., Oakleaf, J., Cushman, S. A., and D Theobald. 2014. An ArcGIS Toolbox for Surface Gradient and Geomorphometric Modeling, version 2.0-0. Available: http://evansmurphy.wix.com/evansspatial.

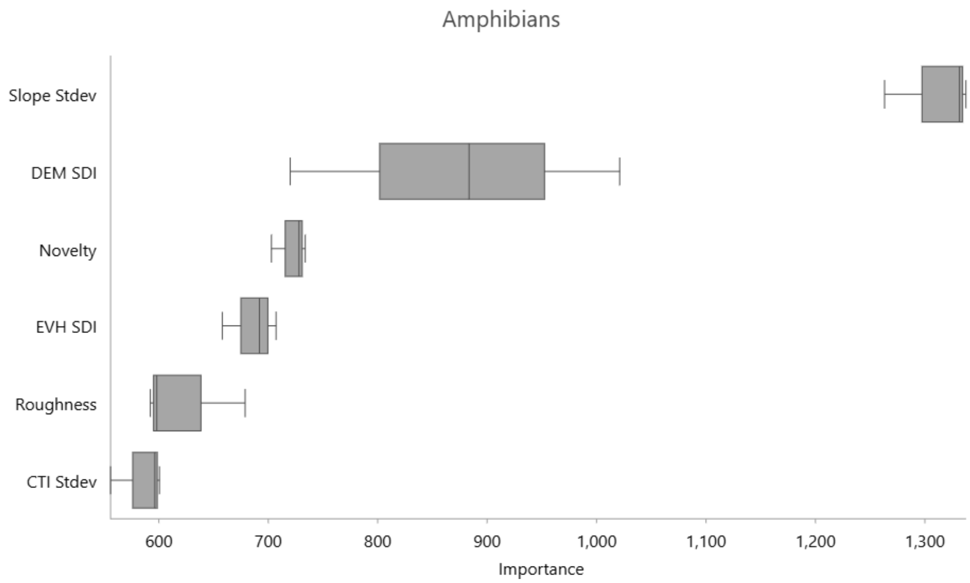
Table 1.5. R packages used for analysis of New Mexico Refugia. This list does not include packages used for data management.

Name	Description	Citation
NLopt	R interface to NLopt - provides access to optimization algorithms developed for Python	Johnson, S.G. 2008. The NLopt nonlinear-optimization package, https://github.com/stevengj/nlopt Ypma, J. and Johnson, S.G. 2023. nloptr: R Interface to Nlopt. R package version 2.0.3.
COBYLA (Constrained by Linear Approximation)	Iterative optimization method	https://docs.scipy.org/doc/scipy/; Powell, M.J.D. 2009. The BOBYQA algorithm for bound constrained optimization without derivatives. DAMTP/NA 06. https://www.damtp.cam.ac.uk/user/na/NA_papers/NA2009_06.pdf; Virtanen, P., et al. 2020. SciPy 1.0: Fundamental algorithms for scientific computing in Python. Nature Methods 17: 261–272.
Hmisc	Correlation methods	Lzola, C.F. and Harrell, F.E. 2004. An Introduction to S and the Hmisc and Design Libraries at https://hbiostat.org/R/doc/sintro.pdf
corrplot	Visualize correlations	Friendly, M. 2002. Corrgrams: Exploratory displays for correlation matrices. The American Statistician 56: 316–324. Murdoch, D.J. and Chow, E.D. 1996. A graphical display of large correlation matrices. The American Statistician 50: 178–180. Hahsler, M., Buchta, C., and Hornik, K. 2020. seriation: Infrastructure for Ordering Objects Using Seriation. R package version 1.2-9. https://CRAN.R-project.org/package=seriation Hahsler, M., Hornik, K., Buchta, C. 2008. Getting things in order: An introduction to the R package seriation. Journal of Statistical Software, 25(3): 1-34. ISSN 1548-7660, doi: 10.18637/jss.v025.i03 (URL: https://doi.org/10.18637/jss.v025.i03), <URL: https://www.jstatsoft.org/v25/i03/>.
stats	Summary stats	Becker, R.A., Chambers, J.M., and Wilks, A.R. 1988. The New S Language. Wadsworth & Brooks/Cole.
Rpart	Recursive partitioning and regression tress (Random Forest)	Therneau, T.M. and Atkinson, E.J. 1997. An introduction to recursive partitioning using the rpart routines. Division of Biostatistics 61, Mayo Clinic.

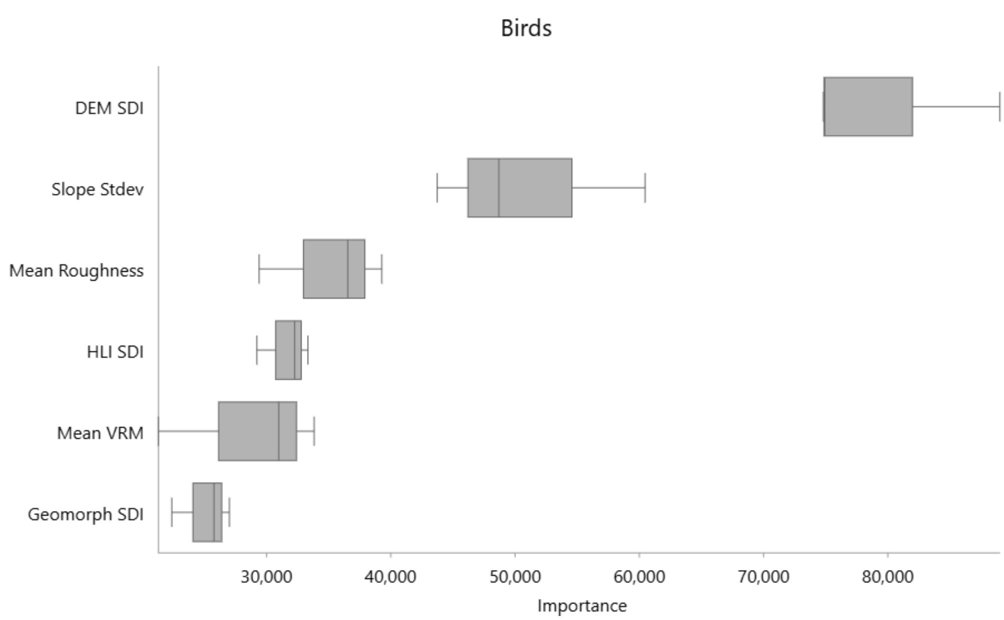
Supplemental 2. Methodology Supplemental

Figure 2.1. Importance rankings from Random Forest analysis of landscape diversity metrics for (a) amphibians, (b) birds, (c) mammals, and (d) reptiles.

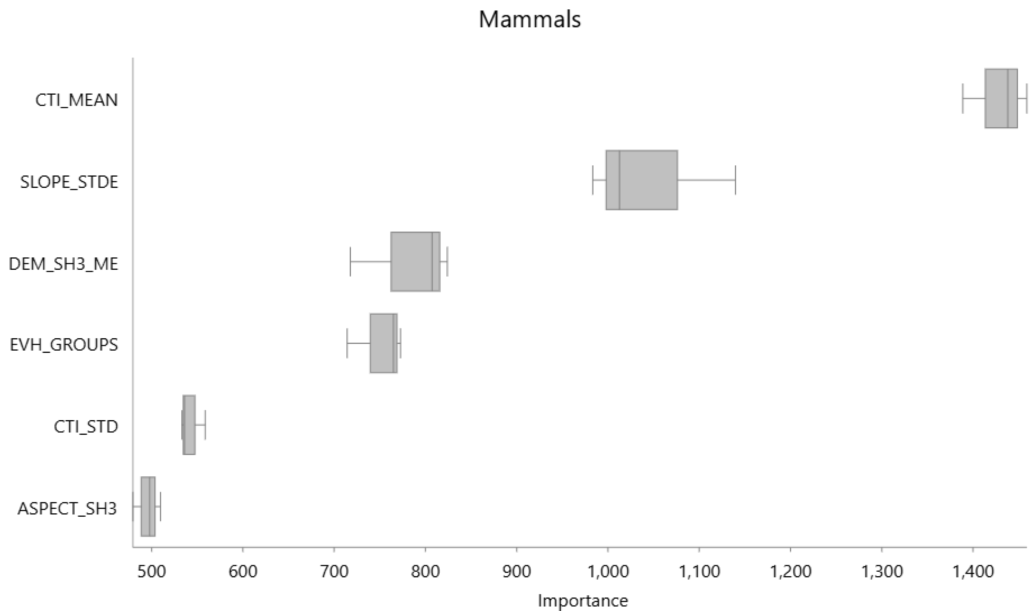
(a)



(b)



(c)


Mammals
CTI_MEAN
SLOPE_STDE
DEM_SH3_ME
EVH_GROUPS
CTI_STD
ASPECT_SH3
500
600
700
800
900
1,000
1,100
1,200
1,300
1,400
Importance

(d)

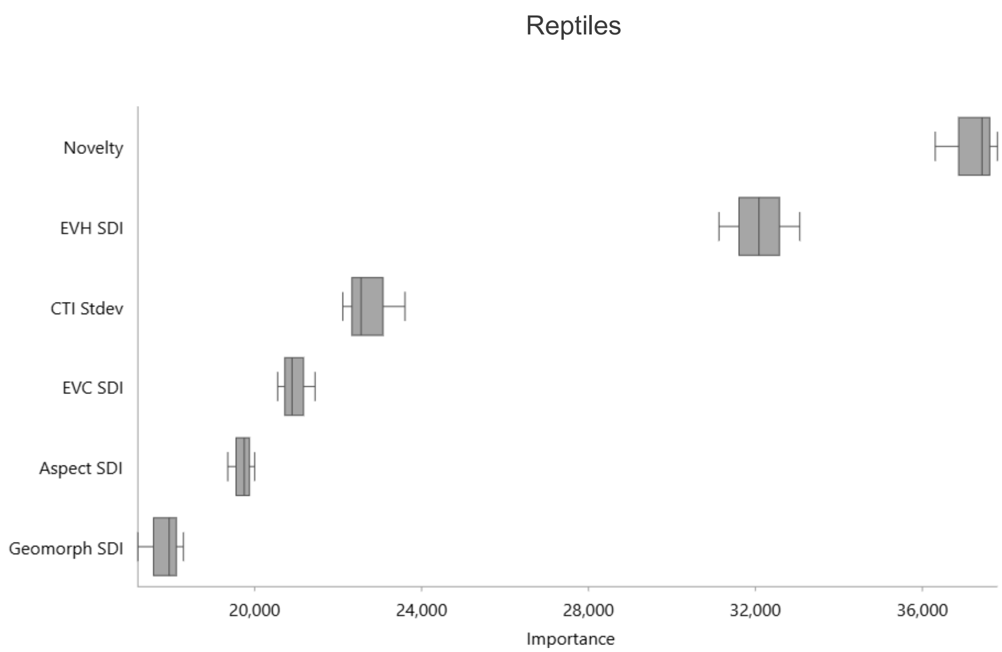

Reptiles
Novelty
EVH SDI
CTI Stdev
EVC SDI
Aspect SDI
Geomorph SDI
20,000
24,000
28,000
32,000
36,000
Importance

Figure 2.2. Correlations among climate variables and among climate and species richness. Blue numbers indicate positive correlations, red negative. Color saturation corresponds to the strength of the correlation between variables. "X" indicates non-significant results.

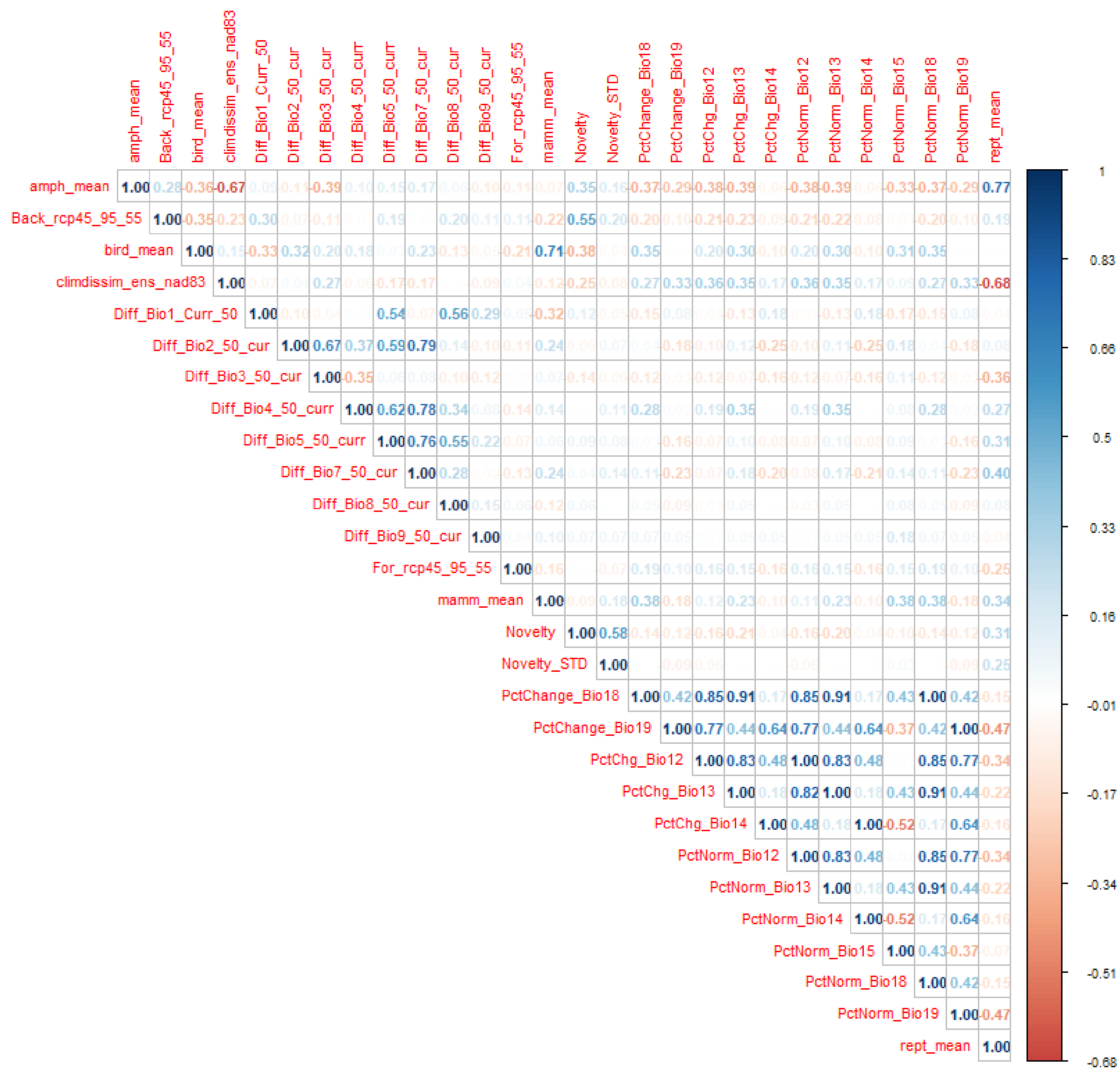


Figure 2.3. Correlations among topographic diversity variables for HUC12. Blue numbers indicate positive correlations, red negative. Color saturation corresponds to the strength of the correlation between variables. “X” indicates non-significant results.

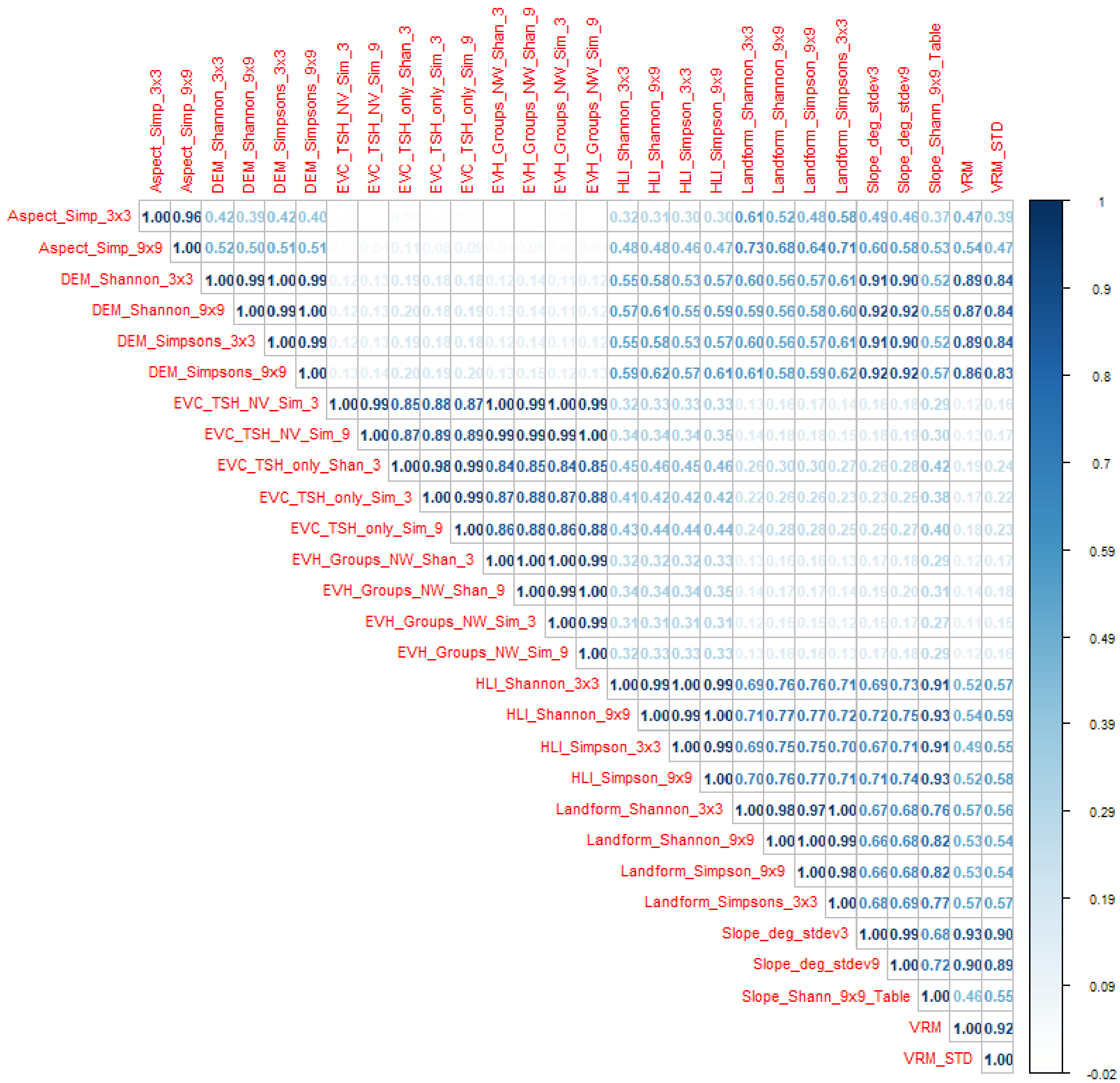


Figure 2.4. Correlations among species richness variables and DEM for HUC12. Blue numbers indicate positive correlations, red negative. Color saturation corresponds to the strength of the correlation between variables. "X" indicates non-significant results.

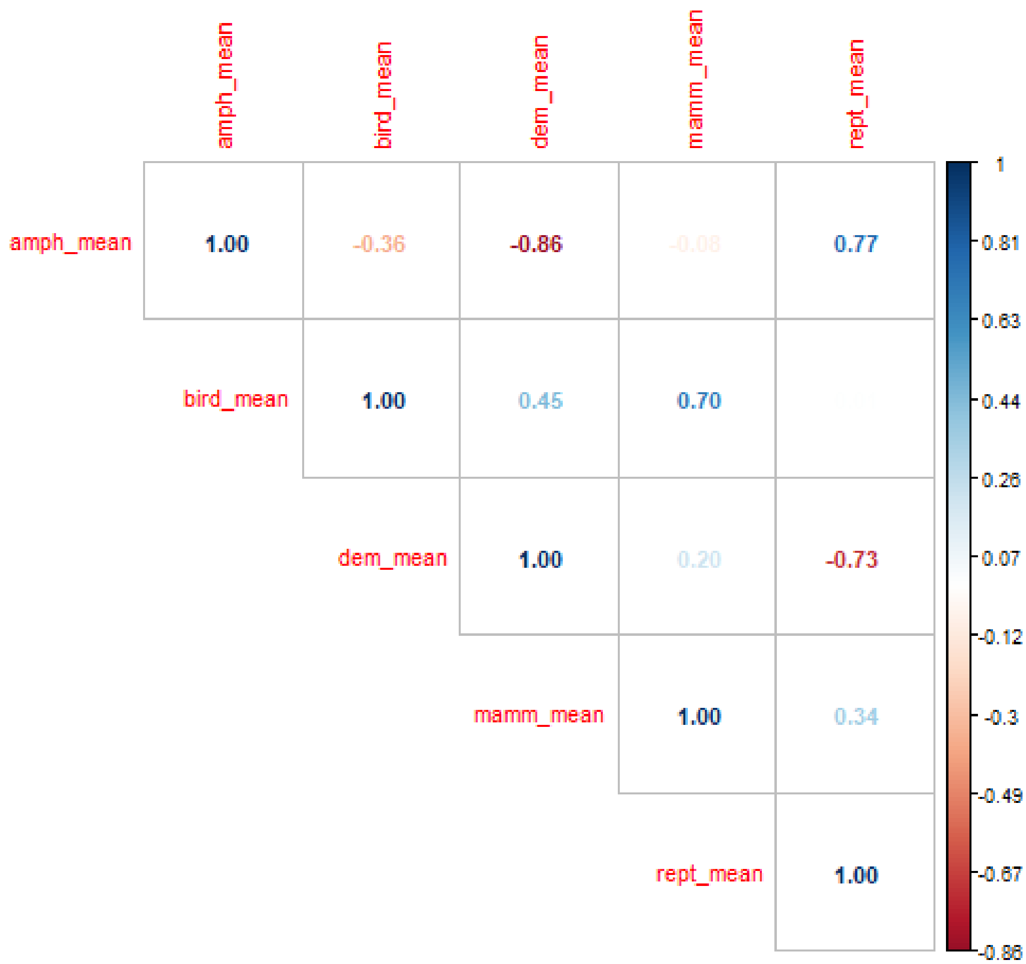


Figure 2.5. Correlations among topographic and heterogeneity variables. Blue circles indicate positive correlations, red negative. Color saturation, circle size and reported number corresponds to the strength of the correlation between variables. "X" indicates non-significant results.

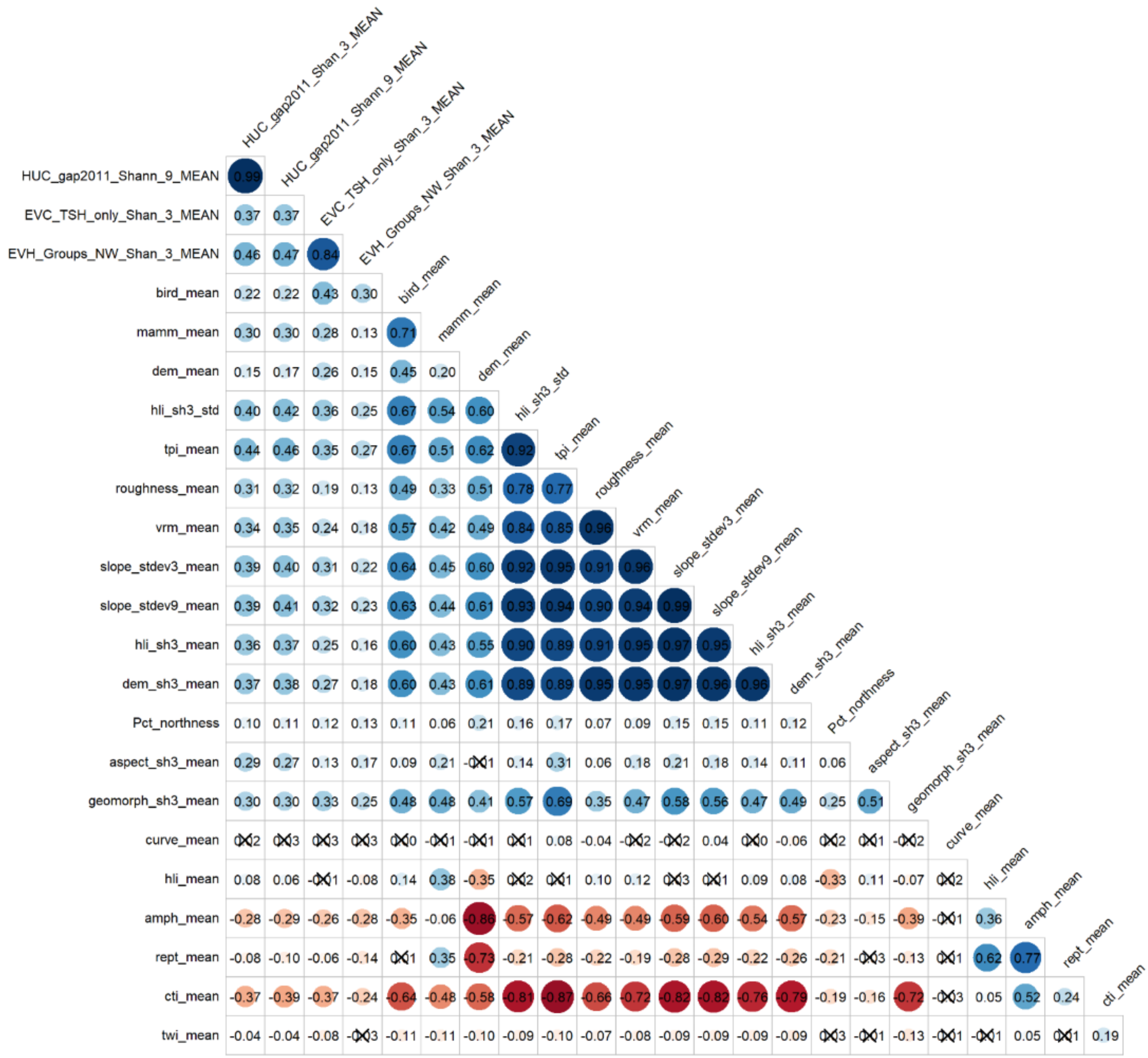


Figure 2.6. Correlations among species richness and soil variables.

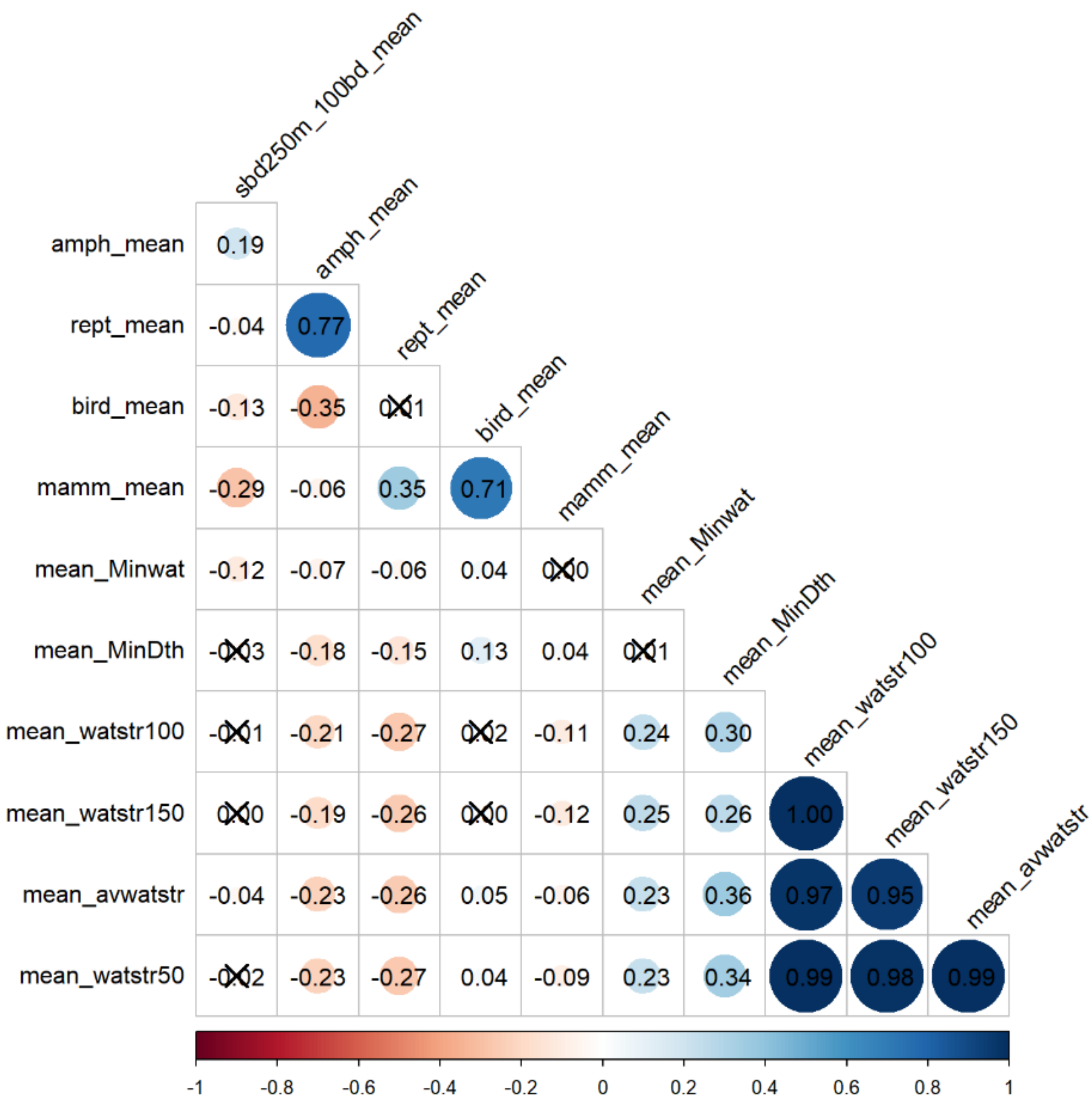


Figure 2.7. Correlations among reduced set of variables.

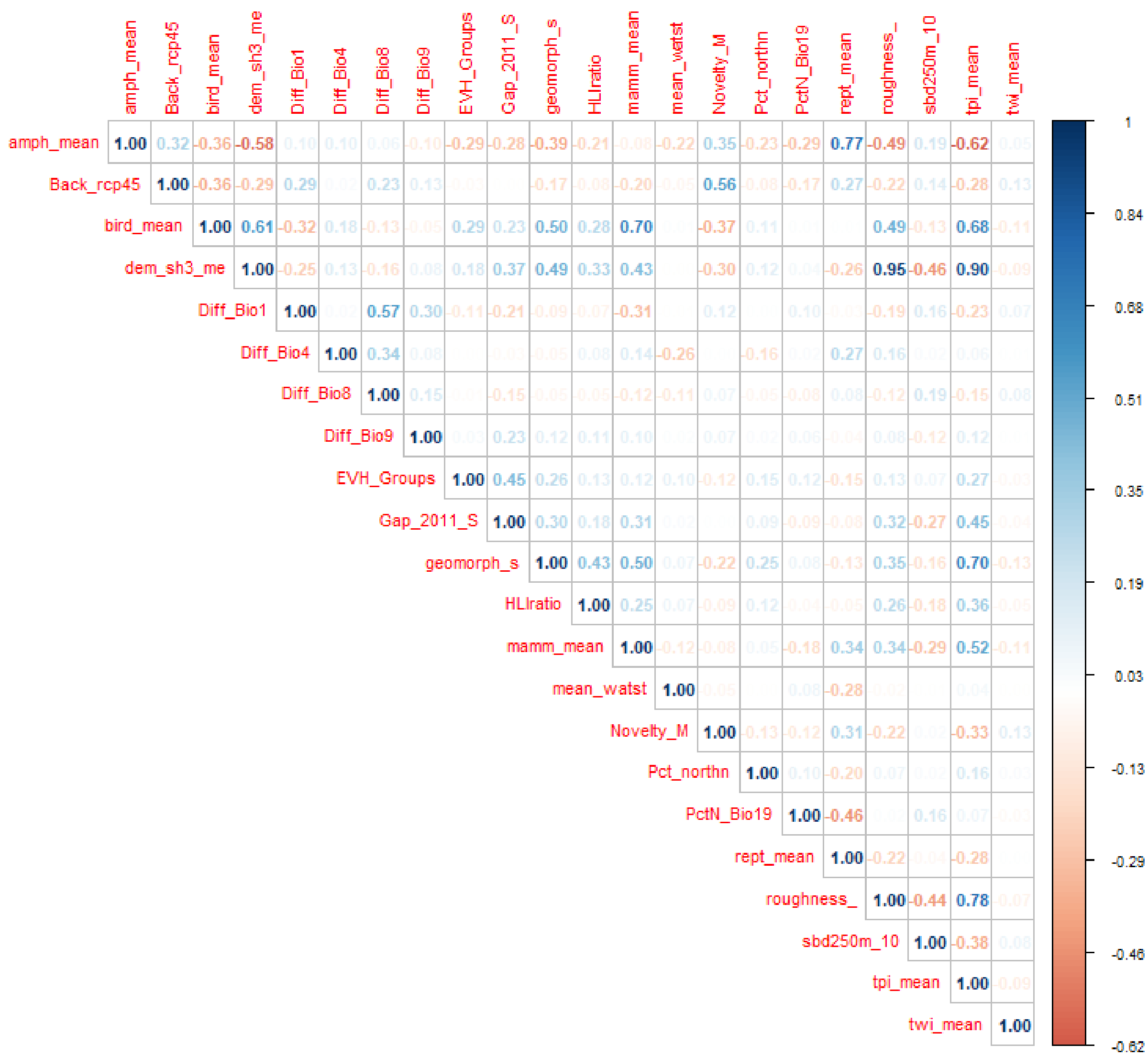


Table 2.1. Final optimized values for each variable used to estimate macro- and microrefugia.

Macrorefugia Indicator	Assigned Weights
Mean Pct normal Bio 18	0.204
Mean Diff in SMC	0.3
Mean Diff in HMI	0.238
Mean Diff Bio9	0.1
Mean Diff Bio8	0.05
Mean Diff Bio4	0.05
Mean Backwards Climate Velocity	0.05

	Assigned Weights			
Microrefugia Indicator	**Amphibian**	**Bird**	**Mammal**	**Reptile**
Mean Climate Novelty	0.27			0.195
Mean Elevation SDI		0.269		
Existing Vegetation Height Groups SDI				0.05
Mean Soil Bulk Density	0.155	0.167	0.05	0.089
Mean Topographic Position Index				0.3
Mean Topographic Wetness Index	0.3			0.259
Mean USNVC Macrogroups SDI			0.25	
Mean Water Storage (50 cm)		0.3	0.3	
Pct Northern Aspect		0.087	0.05	
Ratio of Low:High Heat Load Index	0.272	0.175	0.05	0.1
Mean Roughness			0.3	

Supplemental 3. State and COA Averages values for variables assessed in an analysis of climate macro- or microrefugia in New Mexico.

Table 3.1. Topographic and landscape metrics used to calculate microrefugia. Values represent the mean, minimum, maximum and standard deviation (STDEV) values calculated for HUC12 in New Mexico. Shannon Diversity Index (SDI) calculated on 3x3 window.

Variable Name (resolution)	Mean	Min	Max	STDEV
Aspect SDI (30m)				
CTI (30m)	9.58	3.04	37.45	2.75
Curve (30m)	0.00	-0.10	0.09	0.00
DEM (30m)	1760.00	859.46	4007.64	454.73
Geomorph SDI (30m)	0.63	0.00	2.20	0.46
HLI (30m)	0.81	0.11	1.12	0.08
Pct_northness	--	--	--	--
SBD (100m)	1.51	0.89	2.00	0.05
Slope stdev3 (30m)	2.46	0.00	166.51	3.69
Slope stdev9 (30m)	4.11	0.00	124.62	5.23
TPI (30m)	0.15	-91.00	82.00	1.18
TWI (30m)				
VRM (30m)	0.00	0.00	0.42	0.01
Slope_percent	9.38	0.00	488.18	13.82
Roughness	16.17	0.00	12495.21	49.72
DEM SDI	0.04	0.00	1.37	0.14
Aspect (30m)	172.58	-1.00	360.00	99.93

Table 3.2. Mean CI values for each group for 2025 COA.

COA Name	Amphibians	Birds	Mammals	Reptiles	Macrorefugia
Apache Box	0.1	0.33	0.34	0.09	0.77
Big Hatchet Mountains	0.1	0.24	0.27	0.13	0.6
Black Range Mountains	0.14	0.42	0.39	0.07	0.56
Bootheel	0.08	0.29	0.28	0.1	0.74
Conchas Reservoir	0.5	0.24	0.21	0.55	0.56
Eagle Nest Lake	0.24	0.43	0.36	0.22	0.74
Guadalupe Mountains	0.18	0.44	0.53	0.14	0.13
Jemez Mountains	0.17	0.56	0.54	0.1	0.56
Lower Gila River	0.12	0.34	0.37	0.09	0.63
Lower Pecos and Black Rivers	0.28	0.26	0.22	0.32	0.49
Lower Rio Grande	0.17	0.21	0.24	0.14	0.43
Lower Rio Grande - Caballo Reservoir	0.34	0.29	0.26	0.3	0.39
Middle San Juan River	0.13	0.26	0.35	0.17	0.45
Middle Pecos River	0.18	0.23	0.27	0.27	0.5
Middle Rio Grande	0.21	0.22	0.21	0.22	0.44
Mimbres River	0.09	0.28	0.27	0.07	0.49
Northern Sacramento & Capitan Mountains	0.14	0.53	0.58	0.1	0.76
Organ Mountains	0.17	0.33	0.41	0.16	0.38
Pecos River - Lake Sumner	0.09	0.19	0.24	0.17	0.49
Pecos River Headwaters	0.15	0.27	0.23	0.18	0.53
Rio Chama	0.17	0.43	0.44	0.15	0.66
Rio Puerco	0.13	0.4	0.4	0.1	0.76
San Francisco River	0.13	0.39	0.34	0.09	0.7
San Mateo Mountains	0.14	0.45	0.45	0.09	0.58
Santa Fe River	0.15	0.51	0.48	0.16	0.64
Southern Sacramento Mountains	0.16	0.57	0.54	0.1	0.69
Upper Gila River	0.12	0.4	0.37	0.08	0.65
Upper Rio Grande	0.11	0.33	0.32	0.09	0.47

Upper San Juan River	0.26	0.3	0.28	0.26	0.65
Vermejo River	0.24	0.09	0.08	0.32	0.66

Table 3.3. Mean Values of Climate metrics for 2025 COA.

The following data is broken into three parts (tables) for better visualization. Part I contains Percent of Normal Precipitation (Pct Norm) for Bio19, 18, 15, 14, 13, 12; Part II contains Magnitude Change in Temperature (Diff) for Bio 1-5, 7-9; Part III contains Climate Dissimilarity, Backward Climate Velocity, and Estimated Change in HMI and SMC. See main text for description of individual data.

Part I. Percent of Normal Precipitation (Pct Norm) for Bio19, 18, 15, 14, 13, 12.

COA_Name	Pct Norm Bio19	Pct Norm Bio18	Pct Norm Bio15	Pct Norm Bio14	Pct Norm Bio13	Pct Norm Bio12
Apache Box	39.66 (0.82-54.62)	44.80 (0.95-61.65)	44.84 (0.98-61.42)	33.85 (0.72-46.80)	45.68 (0.97-0.00)	41.98 (0.90-57.67)
Big Hatchet Mountains	12.80 (1.07-19.12)	15.22 (1.24-22.53)	16.48 (1.36-24.24)	10.60 (0.87-15.63)	15.59 (1.28-0.00)	14.12 (1.16-20.76)
Black Range Mountains	62.41 (0.40-103.04)	65.63 (0.44-106.83)	64.39 (0.43-103.02)	62.67 (0.42-104.80)	69.39 (0.46-0.00)	62.44 (0.41-100.53)
Bootheel	60.53 (0.00-85.13)	72.72 (0.00-100.54)	75.76 (0.00-106.49)	52.18 (0.00-72.57)	72.79 (0.00-0.00)	67.49 (0.00-92.98)
Conchas Reservoir	54.74 (0.09-82.28)	45.88 (0.08-67.95)	46.66 (0.08-69.03)	50.91 (0.08-76.77)	49.24 (0.08-0.00)	46.59 (0.08-69.25)
Eagle Nest Lake	24.62 (0.01-36.29)	25.29 (0.01-37.16)	29.93 (0.01-44.80)	22.88 (0.01-33.11)	26.30 (0.01-0.00)	23.70 (0.01-34.35)
Guadalupe Mountains	16.87 (0.78-41.47)	22.36 (0.83-59.36)	36.46 (1.01-107.41)	14.60 (0.85-31.36)	19.81 (0.74-0.00)	20.02 (0.81-52.66)
Jemez Mountains	50.70 (4.75-94.87)	49.78 (4.35-93.09)	54.70 (5.39-102.25)	44.99 (4.18-80.43)	52.05 (4.96-0.00)	49.91 (4.77-92.99)
Lower Gila River	32.84 (0.33-56.83)	37.20 (0.39-64.95)	37.77 (0.40-65.09)	28.56 (0.33-48.65)	38.75 (0.41-0.00)	34.93 (0.37-60.51)
Lower Pecos and Black Rivers	29.38 (0.03-44.96)	30.81 (0.03-46.35)	31.65 (0.03-46.97)	32.93 (0.03-47.18)	27.05 (0.03-0.00)	30.18 (0.03-44.98)
Lower Rio Grande	19.70 (0.71-26.46)	21.57 (0.76-28.72)	23.79 (0.80-31.43)	18.13 (0.66-24.62)	21.87 (0.78-0.00)	21.11 (0.73-28.16)
Lower Rio Grande - Caballo Reservoir	23.71 (0.09-30.43)	25.79 (0.10-32.96)	28.46 (0.11-36.56)	29.42 (0.12-37.95)	27.00 (0.11-0.00)	24.80 (0.10-31.97)
Middle San Juan River	27.32 (0.59-47.62)	28.13 (0.65-46.77)	31.54 (0.78-52.21)	24.70 (0.56-40.84)	29.39 (0.66-0.00)	26.81 (0.59-45.74)
Middle Pecos River	29.00 (0.02-56.06)	26.57 (0.02-50.57)	28.01 (0.02-52.88)	28.39 (0.03-54.23)	27.10 (0.02-0.00)	26.61 (0.02-50.54)
Middle Rio Grande	20.47 (0.01-45.62)	21.58 (0.01-46.39)	22.81 (0.02-46.68)	20.72 (0.01-44.36)	22.13 (0.02-0.00)	20.80 (0.01-45.35)

COA_Name	Pct Norm Bio19	Pct Norm Bio18	Pct Norm Bio15	Pct Norm Bio14	Pct Norm Bio13	Pct Norm Bio12
Mimbres River	36.85 (0.00-66.00)	39.83 (0.00-71.91)	39.88 (0.00-73.83)	37.54 (0.00-69.66)	42.16 (0.00-0.00)	37.84 (0.00-68.41)
Northern Sacramento and Capitan Mountains	44.18 (0.02-90.25)	50.46 (0.02-94.57)	58.03 (0.02-102.17)	41.60 (0.02-82.34)	53.48 (0.02-0.00)	46.58 (0.02-88.71)
Organ Mountains	28.58 (0.02-55.07)	31.41 (0.02-60.24)	35.11 (0.02-67.10)	24.64 (0.01-45.92)	31.42 (0.02-0.00)	29.53 (0.02-55.99)
Pecos River - Lake Sumner	17.41 (0.30-29.56)	17.39 (0.30-30.31)	19.47 (0.33-34.07)	15.31 (0.27-25.94)	17.52 (0.30-0.00)	17.14 (0.29-29.74)
Pecos River Headwaters	26.01 (0.73-42.94)	26.34 (0.76-43.43)	29.96 (0.84-49.78)	23.49 (0.65-39.05)	27.22 (0.78-0.00)	25.75 (0.75-42.40)
Rio Chama	35.43 (0.00-84.87)	32.73 (0.00-68.17)	35.81 (0.00-71.57)	32.09 (0.00-81.66)	33.33 (0.00-0.00)	32.72 (0.00-70.53)
Rio Puerco	34.39 (0.01-49.82)	31.16 (0.01-44.01)	36.07 (0.01-52.63)	29.41 (0.01-42.37)	34.00 (0.01-0.00)	33.11 (0.01-47.96)
San Francisco River	54.90 (0.24-106.35)	55.14 (0.25-104.60)	54.63 (0.24-102.15)	48.17 (0.20-97.31)	56.74 (0.25-0.00)	53.76 (0.24-103.56)
San Mateo Mountains	37.58 (0.26-89.63)	38.70 (0.28-92.39)	37.92 (0.30-90.35)	39.96 (0.28-100.82)	41.12 (0.29-0.00)	37.70 (0.27-90.26)
Santa Fe River	20.86 (4.02-36.39)	21.48 (4.24-37.97)	22.14 (4.40-39.08)	21.56 (4.61-39.04)	22.23 (4.49-0.00)	21.68 (4.29-38.59)
Southern Sacramento Mountains	73.95 (0.30-98.37)	75.32 (0.31-98.12)	85.19 (0.33-108.97)	55.36 (0.24-69.70)	78.42 (0.32-0.00)	69.79 (0.30-90.80)
Upper Gila River	62.86 (0.01-102.22)	67.44 (0.01-108.81)	66.12 (0.01-106.14)	56.92 (0.01-93.28)	70.71 (0.01-0.00)	63.83 (0.01-102.83)
Upper Rio Grande	24.49 (0.01-42.23)	23.89 (0.01-41.45)	24.23 (0.00-40.24)	24.50 (0.01-44.05)	24.62 (0.01-0.00)	24.08 (0.01-42.26)
Upper San Juan River	25.60 (4.35-49.28)	25.98 (4.29-49.63)	29.06 (4.70-55.15)	23.63 (3.90-45.23)	26.09 (4.31-0.00)	25.14 (4.23-48.29)
Vermejo River	32.86 (0.01-41.11)	31.26 (0.01-39.28)	31.71 (0.01-39.84)	30.65 (0.01-37.45)	32.00 (0.01-0.00)	31.19 (0.01-39.26)

Part II. Magnitude change in Temperature (Diff) for Bio 1-5, 7-9.

COA_Name	Diff Bio9	Diff Bio8	Diff Bio7	Diff Bio4	Diff Bio5	Diff Bio3	Diff Bio2	Diff Bio1
Apache Box	0.60 (0.02-0.78)	0.69 (0.02-0.91)	0.78 (0.02-1.03)	6.69 (0.13-8.81)	0.96 (0.03-1.27)	-0.56 (-0.83--0.01)	0.27 (0.01-0.32)	0.58 (0.02-0.77)
Big Hatchet Mountains	0.33 (0.03-0.57)	0.36 (0.03-0.51)	0.54 (0.04-0.83)	0.33 (0.00-0.53)	0.69 (0.06-1.02)	0.16 (0.01-0.31)	0.35 (0.03-0.55)	0.35 (0.03-0.50)
Black Range Mountains	2.34 (0.01-4.30)	1.66 (0.01-2.65)	1.95 (0.01-3.35)	16.96 (0.11-32.64)	2.57 (0.02-4.27)	0.10 (-0.56-0.67)	1.09 (0.00-2.00)	1.46 (0.01-2.36)
Bootheel	0.57 (0.00-1.14)	1.29 (0.00-2.04)	1.68 (0.00-3.20)	-3.31 (-11.51-10.53)	2.49 (0.00-3.87)	-0.85 (-1.53-0.08)	0.63 (-0.01-1.38)	1.47 (0.00-2.27)
Conchas Reservoir	0.99 (0.00-1.41)	1.22 (0.00-1.72)	0.46 (0.00-0.74)	-2.00 (-2.97-0.11)	1.46 (0.00-2.14)	-0.25 (-0.36-0.00)	0.19 (0.00-0.31)	1.20 (0.00-1.73)
Eagle Nest Lake	0.73 (0.00-1.05)	0.60 (0.00-0.93)	0.01 (-0.18-0.18)	-6.04 (-8.99-0.00)	0.65 (0.00-1.02)	0.33 (0.00-0.43)	0.18 (0.00-0.32)	0.60 (0.00-0.87)
Guadalupe Mountains	1.03 (0.04-1.92)	1.05 (0.03-3.12)	0.76 (0.01-2.24)	-6.45 (-28.61--0.08)	1.21 (0.03-3.44)	0.80 (-0.18-3.61)	0.64 (-0.03-2.27)	0.82 (0.03-2.26)
Jemez Mountains	1.65 (0.09-3.06)	1.16 (0.12-2.29)	0.01 (-0.78-0.86)	-7.37 (-21.15-2.70)	1.38 (0.16-3.07)	0.27 (0.00-0.72)	0.20 (-0.18-0.80)	1.17 (0.11-2.30)
Lower Gila River	0.63 (0.01-1.13)	0.89 (0.01-1.68)	0.80 (0.01-1.90)	7.18 (0.06-17.19)	1.20 (0.01-2.38)	-0.25 (-0.75-0.08)	0.37 (0.00-1.04)	0.75 (0.01-1.44)
Lower Pecos and Black Rivers	0.87 (0.00-1.60)	0.77 (0.00-1.35)	0.17 (-0.17-0.64)	-1.83 (-10.63-5.00)	0.98 (0.00-1.50)	-0.62 (-1.11-0.00)	-0.09 (-0.32-0.15)	0.84 (0.00-1.32)
Lower Rio Grande	0.92 (0.01-1.15)	0.59 (0.02-0.75)	0.75 (0.03-0.94)	5.16 (0.21-6.05)	0.83 (0.03-1.04)	-0.06 (-0.12-0.01)	0.37 (0.01-0.46)	0.48 (0.01-0.61)
Lower Rio Grande - Caballo Reservoir	1.10 (0.00-1.56)	0.80 (0.00-1.09)	0.50 (0.00-0.81)	3.33 (0.00-5.27)	1.03 (0.00-1.39)	-0.30 (-0.48-0.00)	0.16 (-0.05-0.36)	0.72 (0.00-0.96)
Middle San Juan River	0.72 (0.02-1.22)	1.15 (0.03-2.02)	0.31 (0.01-0.65)	-3.83 (-10.37-0.14)	0.87 (0.02-1.45)	-0.05 (-0.32-0.40)	0.16 (0.00-0.41)	0.69 (0.02-1.16)
Middle Pecos River	0.72 (0.00-1.41)	0.76 (0.00-1.43)	0.36 (0.00-0.91)	-2.58 (-5.67-4.46)	0.87 (0.00-1.71)	0.04 (-0.22-0.32)	0.24 (0.00-0.57)	0.70 (0.00-1.28)
Middle Rio Grande	0.68 (0.00-1.39)	0.57 (0.00-1.25)	0.22 (0.00-0.50)	-0.32 (-11.71-2.77)	0.70 (0.00-1.46)	-0.20 (-0.57-0.16)	0.06 (-0.06-0.29)	0.57 (0.00-1.20)
Mimbres River	1.28 (0.00-2.22)	0.97 (0.00-1.66)	1.05 (0.00-1.59)	10.43 (0.00-18.24)	1.53 (0.00-2.50)	-0.29 (-1.05-0.02)	0.46 (0.00-0.76)	0.86 (0.00-1.45)

COA_Name	Diff Bio9	Diff Bio8	Diff Bio7	Diff Bio4	Diff Bio5	Diff Bio3	Diff Bio2	Diff Bio1
Northern Sacramento and Capitan Mountains	1.10 (-0.36-3.28)	0.80 (0.00-1.70)	0.39 (-0.17-1.32)	-8.62 (-19.25-4.29)	1.10 (0.00-2.64)	0.52 (-0.38-1.72)	0.42 (-0.03-1.26)	0.78 (0.00-1.70)
Organ Mountains	1.31 (0.00-2.59)	0.89 (0.00-1.76)	1.11 (0.00-2.22)	6.86 (0.00-10.24)	1.34 (0.00-2.66)	0.25 (-0.12-0.93)	0.64 (0.00-1.42)	0.75 (0.00-1.50)
Pecos River - Lake Sumner	0.29 (0.01-0.40)	0.59 (0.01-0.99)	0.28 (0.00-0.55)	1.83 (-0.28-5.35)	0.64 (0.01-1.10)	-0.17 (-0.35-0.00)	0.10 (0.00-0.18)	0.46 (0.01-0.77)
Pecos River Headwaters	0.39 (0.01-0.70)	0.84 (0.02-1.40)	0.39 (0.01-0.60)	1.05 (-0.55-2.30)	0.91 (0.02-1.51)	-0.07 (-0.13-0.06)	0.20 (0.00-0.32)	0.66 (0.02-1.10)
Rio Chama	1.00 (0.00-2.34)	0.57 (0.00-1.25)	0.06 (-0.45-0.75)	-5.72 (-23.65-5.08)	0.74 (0.00-1.60)	0.07 (-0.27-0.43)	0.12 (-0.05-0.40)	0.65 (0.00-1.29)
Rio Puerco	1.78 (0.00-2.94)	0.62 (0.00-0.91)	-0.22 (-0.28-0.00)	-5.61 (-6.79-0.00)	0.76 (0.00-1.15)	-0.09 (-0.21-0.04)	-0.07 (-0.15-0.02)	0.69 (0.00-0.99)
San Francisco River	0.72 (0.00-1.90)	1.13 (0.00-2.89)	1.13 (0.00-3.10)	9.67 (-1.26-33.70)	1.43 (0.00-3.87)	0.03 (-0.41-0.34)	0.70 (0.00-1.75)	0.98 (0.00-2.38)
San Mateo Mountains	1.39 (0.01-3.31)	0.95 (0.01-2.24)	1.17 (0.00-3.24)	12.04 (0.01-34.98)	1.46 (0.01-3.59)	-0.11 (-0.37-0.27)	0.58 (-0.02-1.78)	0.83 (0.01-1.87)
Santa Fe River	-0.03 (-0.39-0.14)	0.56 (0.10-1.05)	-0.34 (-0.68-0.03)	-5.18 (-9.72-1.28)	0.44 (0.08-0.78)	-0.17 (-0.28-0.06)	-0.17 (-0.32-0.02)	0.55 (0.10-1.02)
Southern Sacramento Mountains	3.50 (0.01-4.98)	1.64 (0.01-2.26)	1.54 (0.01-2.25)	4.26 (-2.58-12.60)	2.54 (0.01-3.73)	0.14 (-0.99-0.93)	0.83 (0.00-1.37)	1.49 (0.01-2.14)
Upper Gila River	1.27 (0.00-4.09)	1.52 (0.00-2.57)	1.58 (0.00-2.83)	12.16 (0.00-29.82)	2.17 (0.00-3.70)	0.22 (-0.65-0.94)	0.98 (0.00-1.83)	1.36 (0.00-2.35)
Upper Rio Grande	0.44 (-0.21-0.95)	0.54 (0.00-1.08)	-0.13 (-0.46-0.03)	-6.87 (-14.62-0.00)	0.57 (0.00-1.12)	0.18 (-0.03-0.66)	0.06 (-0.11-0.33)	0.58 (0.00-1.02)
Upper San Juan River	0.60 (0.10-1.16)	0.94 (0.08-1.86)	0.28 (0.01-0.80)	-5.36 (-12.55-0.88)	0.60 (0.09-1.20)	0.06 (-0.05-0.17)	0.19 (0.01-0.49)	0.48 (0.08-0.86)
Vermejo River	0.54 (0.00-0.82)	0.82 (0.00-1.06)	0.44 (0.00-0.61)	3.50 (-0.04-6.65)	0.97 (0.00-1.22)	-0.26 (-0.40-0.00)	0.16 (0.00-0.20)	0.74 (0.00-0.99)

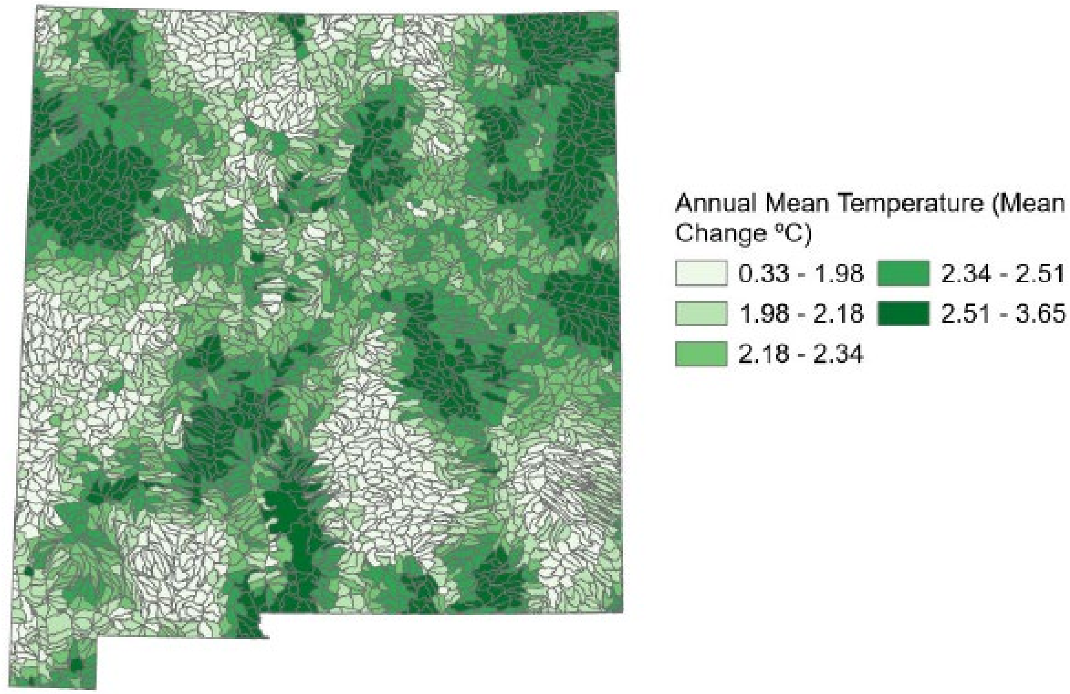
Part III. Climate Dissimilarity, Backward Climate Velocity, and Estimated Change in HMI and SMC.

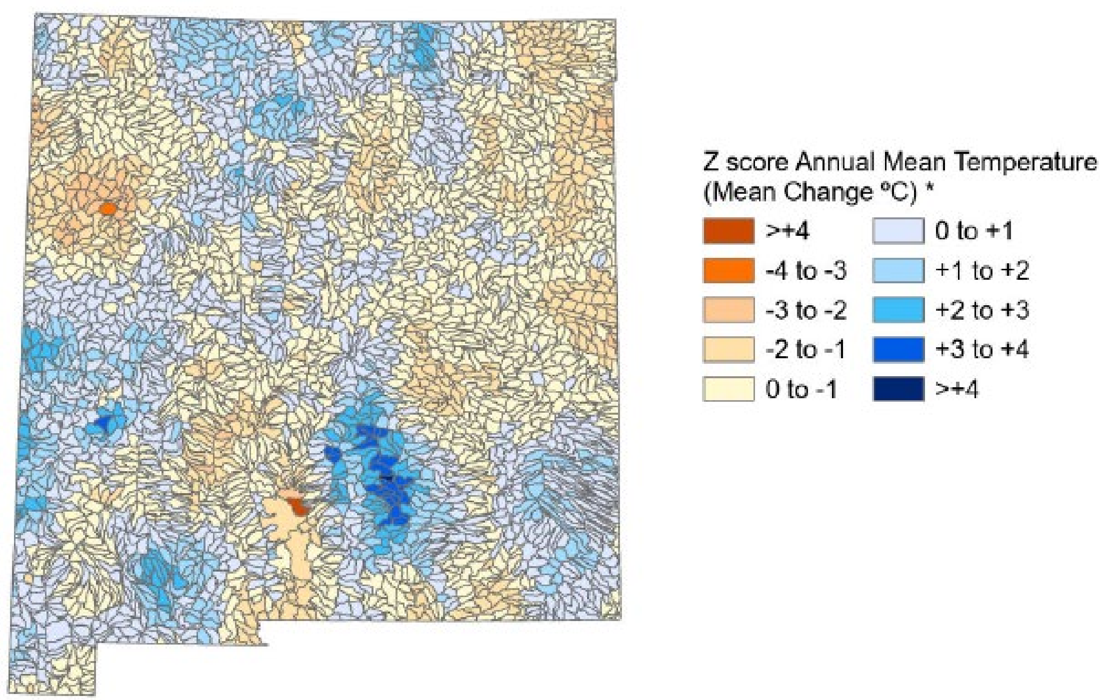
COA_Name	Dissimilarity (2050)	Backward Velocity (1995-2055)	Diff HMI	Diff SMC
Apache Box	0.20 (0.00-0.27)	0.17 (0.01-0.25)	1.16 (0.06-1.47)	-0.22 (-0.30-0.00)
Big Hatchet Mountains	0.07 (0.01-0.10)	0.18 (0.01-0.26)	2.02 (0.18-2.93)	0.03 (0.00-0.05)
Black Range Mountains	0.32 (0.00-0.51)	0.30 (0.00-0.83)	3.47 (0.02-6.76)	0.04 (-0.25-0.67)
Bootheel	0.32 (0.00-0.45)	0.68 (0.00-1.03)	5.57 (0.00-9.70)	0.33 (0.00-0.66)
Conchas Reservoir	0.24 (0.00-0.36)	2.02 (0.00-3.10)	5.19 (0.01-7.74)	0.29 (0.00-0.44)
Eagle Nest Lake	0.16 (0.00-0.24)	0.07 (0.00-0.12)	2.02 (0.00-3.26)	0.52 (0.00-0.65)
Guadalupe Mountains	0.16 (0.00-0.47)	0.34 (0.01-0.50)	18.16 (0.35-52.84)	0.22 (0.01-0.45)
Jemez Mountains	0.27 (0.03-0.50)	0.62 (0.07-1.78)	3.77 (0.26-6.61)	0.14 (-0.13-0.56)
Lower Gila River	0.17 (0.00-0.29)	0.31 (0.00-0.57)	2.24 (0.02-4.05)	-0.11 (-0.29-0.06)
Lower Pecos and Black Rivers	0.14 (0.00-0.21)	0.83 (0.00-1.42)	5.82 (0.01-8.81)	0.02 (-0.11-0.18)
Lower Rio Grande	0.10 (0.00-0.14)	0.48 (0.03-0.64)	3.90 (0.09-4.83)	-0.18 (-0.21-0.00)
Lower Rio Grande - Caballo Reservoir	0.13 (0.00-0.16)	0.53 (0.00-0.64)	5.31 (0.02-7.28)	-0.11 (-0.15-0.00)
Middle San Juan River	0.14 (0.00-0.24)	0.68 (0.01-1.11)	3.62 (0.08-7.25)	-0.52 (-0.95-0.00)
Middle Pecos River	0.13 (0.00-0.24)	0.39 (0.00-0.80)	4.61 (0.00-8.47)	-0.04 (-0.09-0.01)
Middle Rio Grande	0.10 (0.00-0.22)	0.69 (0.00-3.34)	3.74 (0.00-7.46)	-0.09 (-0.17-0.00)
Mimbres River	0.19 (0.00-0.34)	0.34 (0.00-0.68)	2.20 (0.00-4.83)	-0.05 (-0.27-0.11)
Northern Sacramento and Capitan Mountains	0.27 (0.00-0.53)	0.38 (0.00-1.15)	4.73 (0.00-7.51)	0.58 (0.00-1.21)
Organ Mountains	0.16 (0.00-0.30)	1.21 (0.00-2.46)	6.28 (0.00-12.44)	-0.46 (-1.00-0.00)
Pecos River - Lake Sumner	0.10 (0.00-0.17)	0.45 (0.01-0.81)	3.12 (0.05-5.33)	0.00 (-0.02-0.01)
Pecos River Headwaters	0.14 (0.00-0.23)	0.73 (0.02-1.25)	4.45 (0.12-7.54)	0.06 (0.00-0.11)

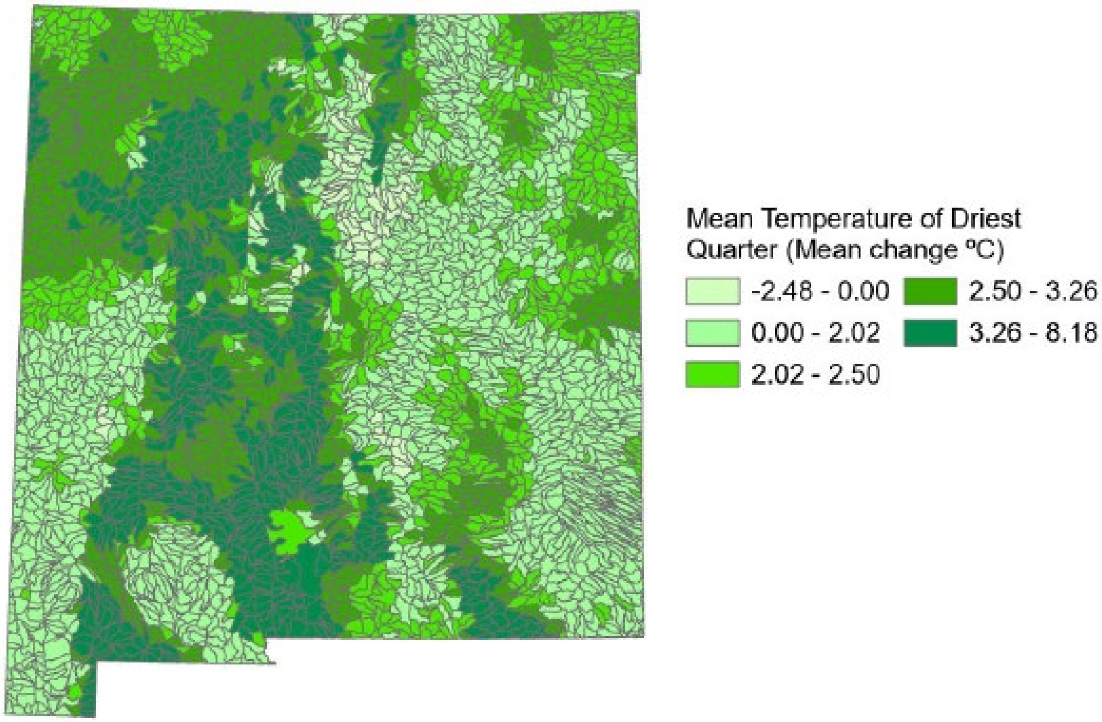
COA_Name	Dissimilarity (2050)	Backward Velocity (1995-2055)	Diff HMI	Diff SMC
Rio Chama	0.18 (0.00-0.37)	0.33 (0.00-0.92)	2.39 (0.00-5.47)	-0.04 (-0.25-0.60)
Rio Puerco	0.17 (0.00-0.25)	0.35 (0.00-0.69)	2.54 (0.00-3.57)	1.46 (-0.52-3.33)
San Francisco River	0.30 (0.00-0.54)	0.29 (0.00-0.85)	1.84 (-0.06-3.59)	0.16 (-0.17-0.65)
San Mateo Mountains	0.19 (0.00-0.45)	0.20 (0.00-0.69)	2.28 (0.03-4.97)	-0.06 (-0.22-0.01)
Santa Fe River	0.11 (0.02-0.21)	0.20 (0.02-0.35)	2.39 (0.35-4.26)	0.01 (-0.02-0.08)
Southern Sacramento Mountains	0.43 (0.00-0.58)	0.21 (0.00-0.35)	6.36 (0.03-10.12)	1.10 (0.00-1.62)
Upper Gila River	0.34 (0.00-0.60)	0.26 (0.00-0.58)	2.45 (0.00-4.85)	0.18 (-0.14-0.57)
Upper Rio Grande	0.13 (0.00-0.22)	0.33 (0.00-0.88)	2.22 (0.00-5.55)	-0.07 (-0.36-0.02)
Upper San Juan River	0.13 (0.02-0.26)	0.51 (0.05-0.97)	1.73 (0.26-2.94)	-0.03 (-0.10-0.03)
Vermejo River	0.19 (0.00-0.24)	0.52 (0.00-0.67)	2.82 (0.00-3.71)	0.32 (0.00-0.47)

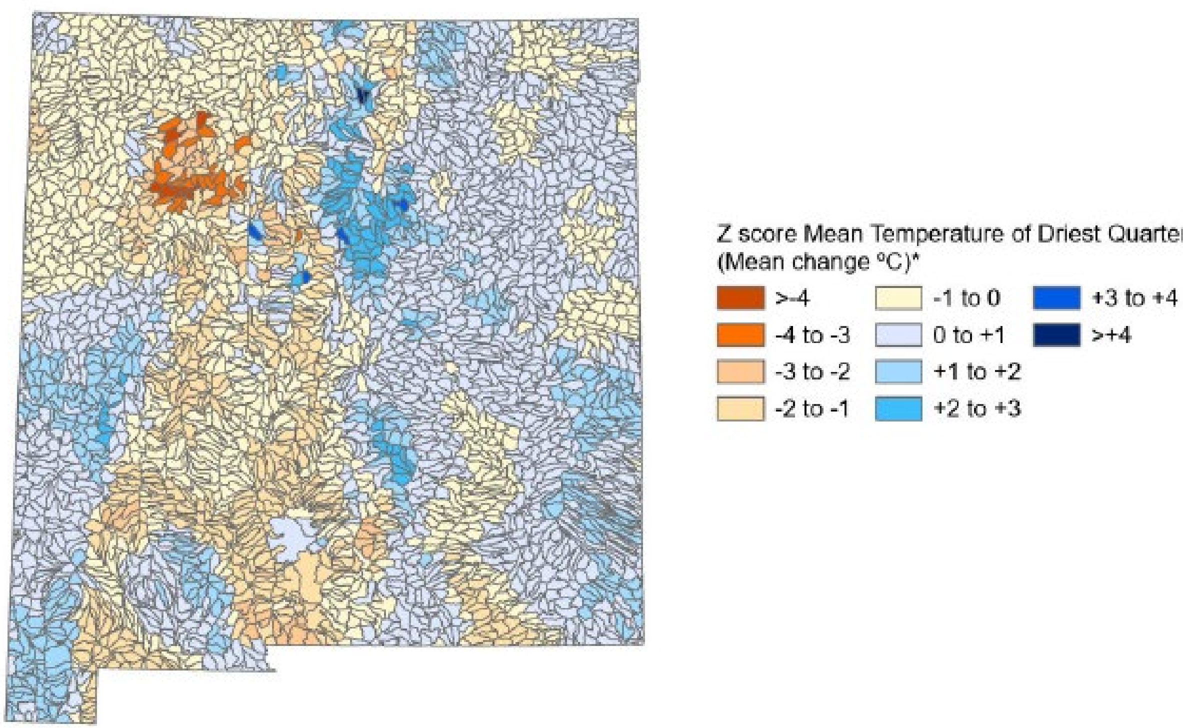
Supplemental 4. Distribution of final variables and corresponding Z-scores.

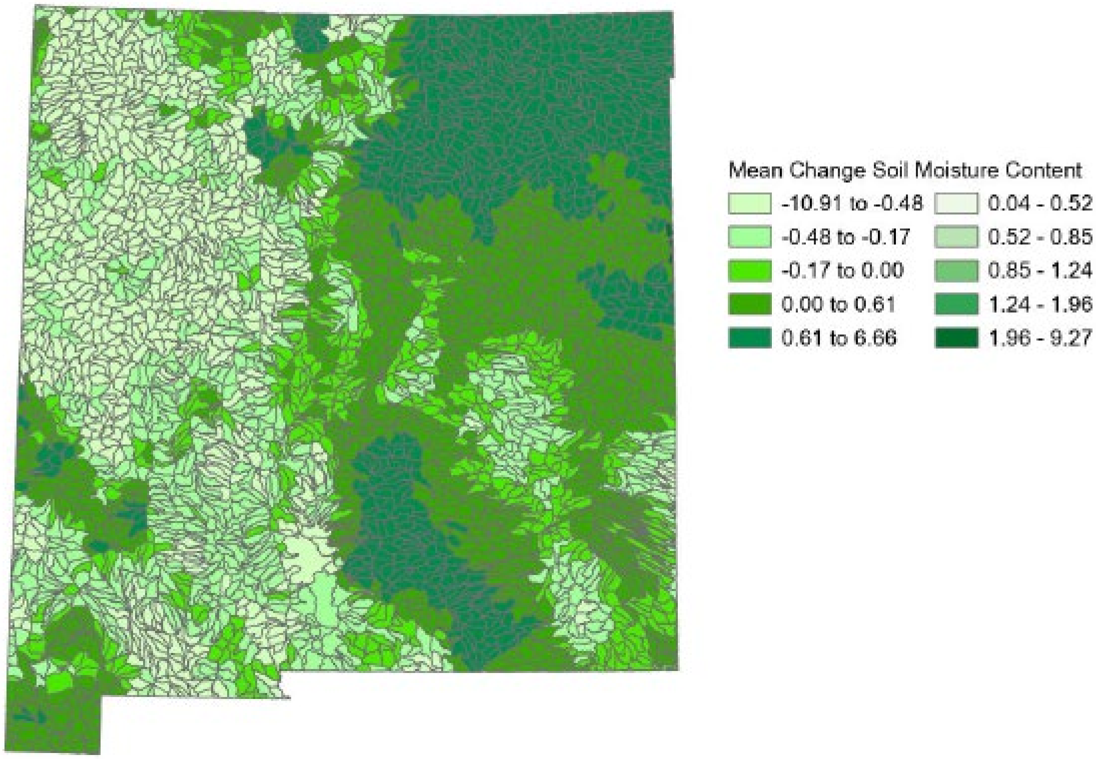
A. Climate variables

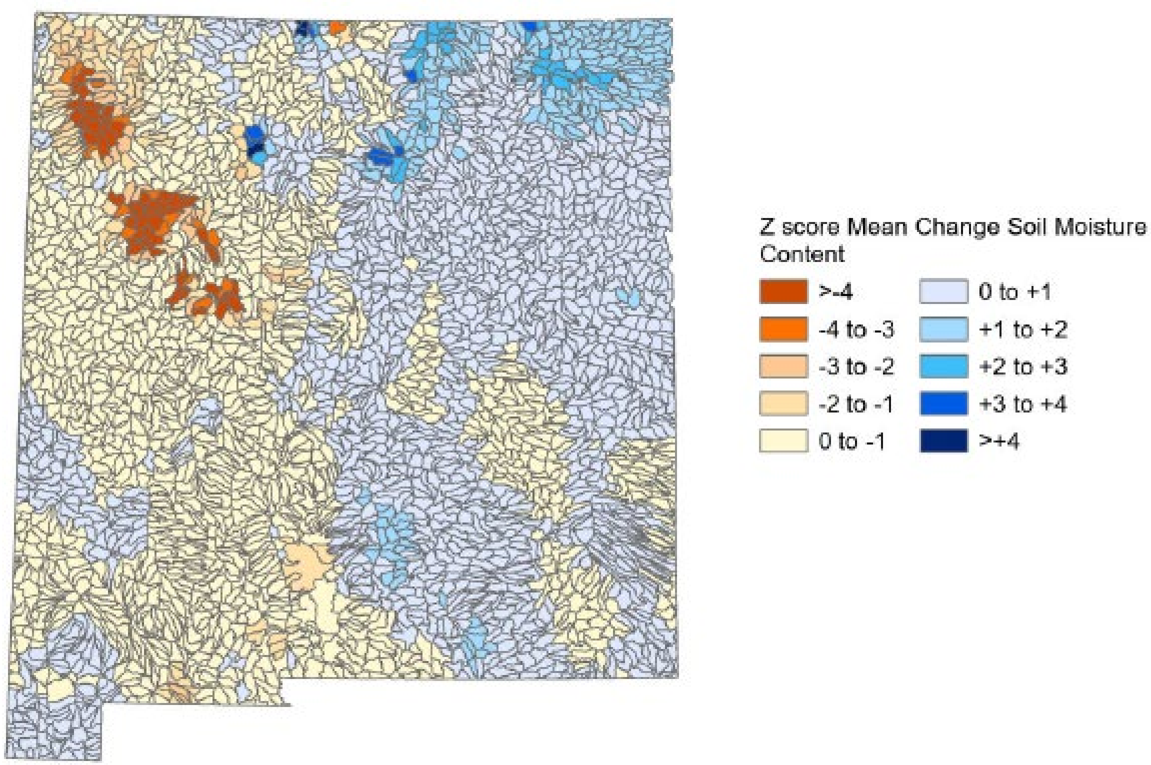


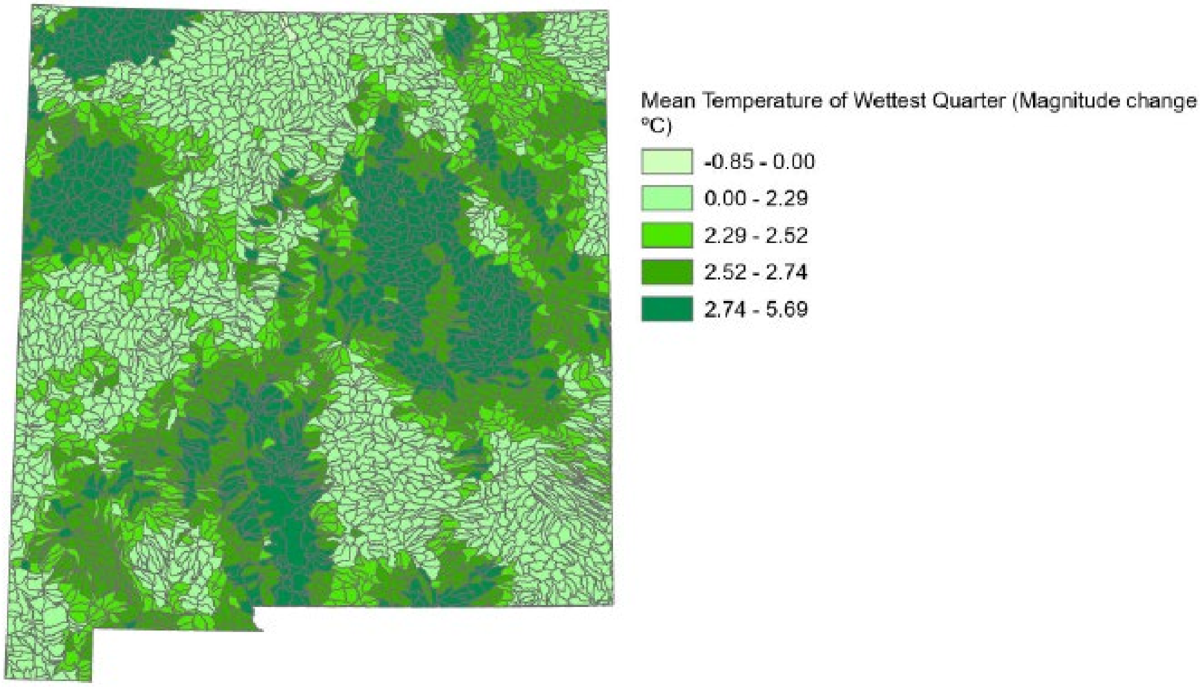


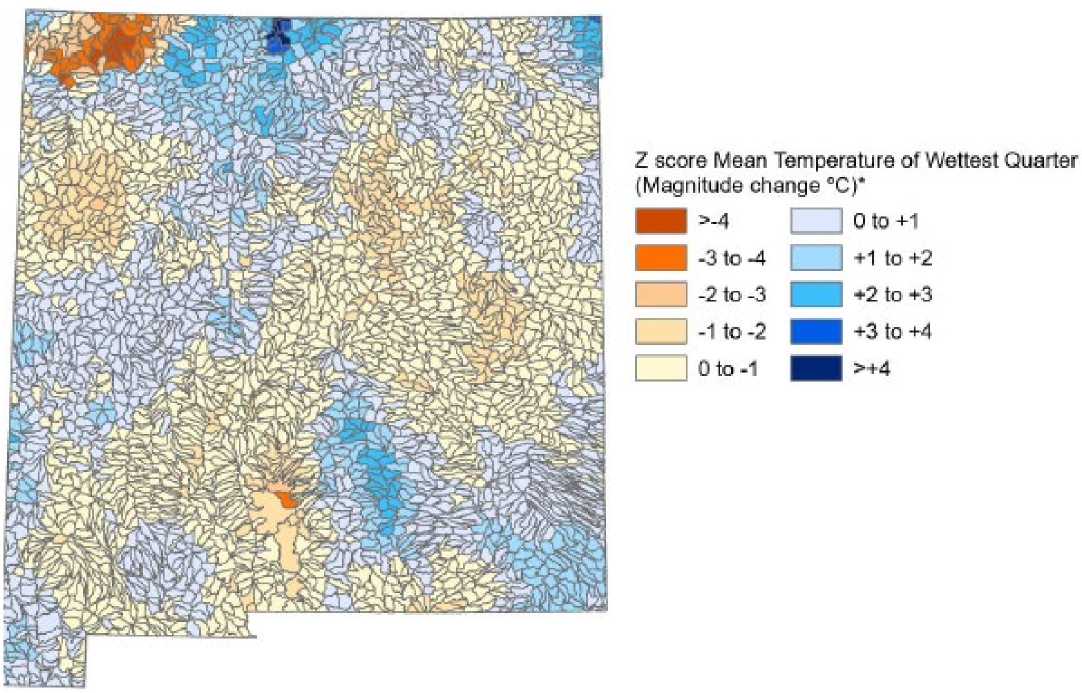

Mean Temperature of Driest Quarter (Mean change ºC)
-2.48 - 0.00
0.00 - 2.02
2.02 - 2.50
2.50 - 3.26
3.26 - 8.18

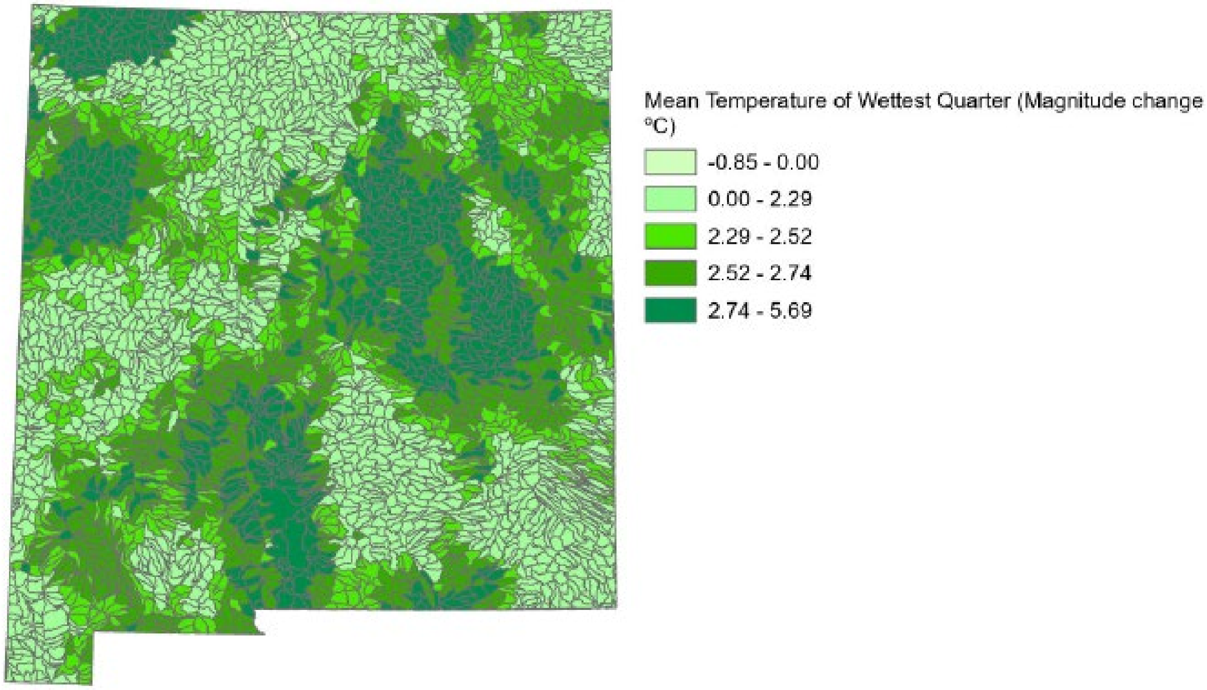

Z score Mean Temperature of Driest Quarter (Mean change ºC)*
>-4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

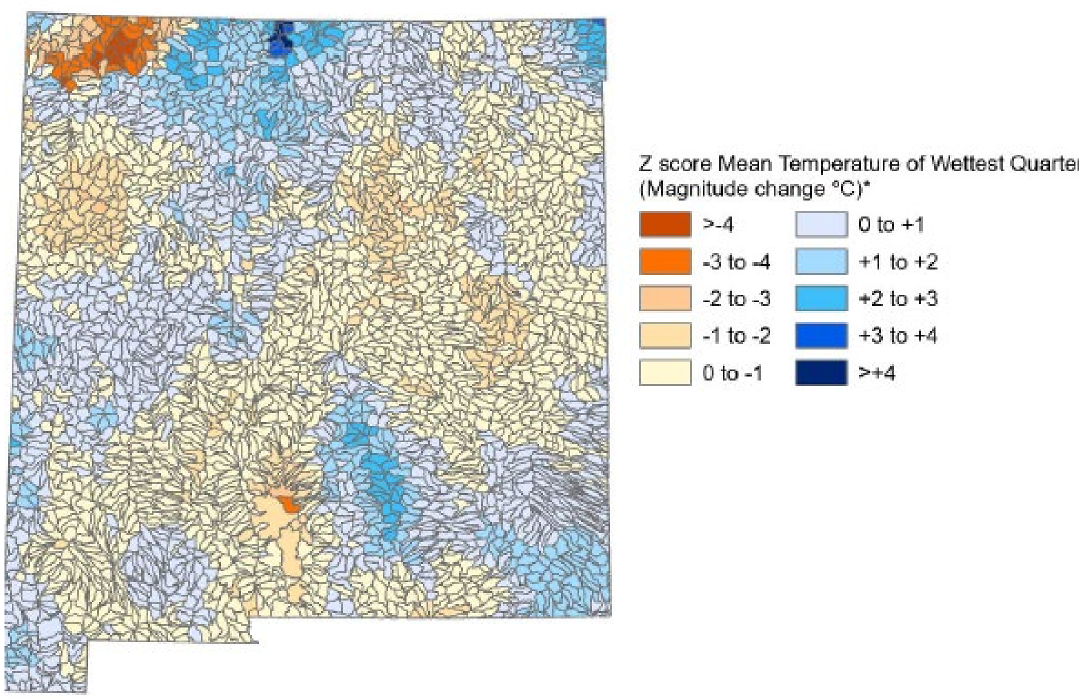

Mean Change Soil Moisture Content
-10.91 to -0.48
-0.48 to -0.17
-0.17 to 0.00
0.00 to 0.61
0.61 to 6.66
0.04 - 0.52
0.52 - 0.85
0.85 - 1.24
1.24 - 1.96
1.96 - 9.27

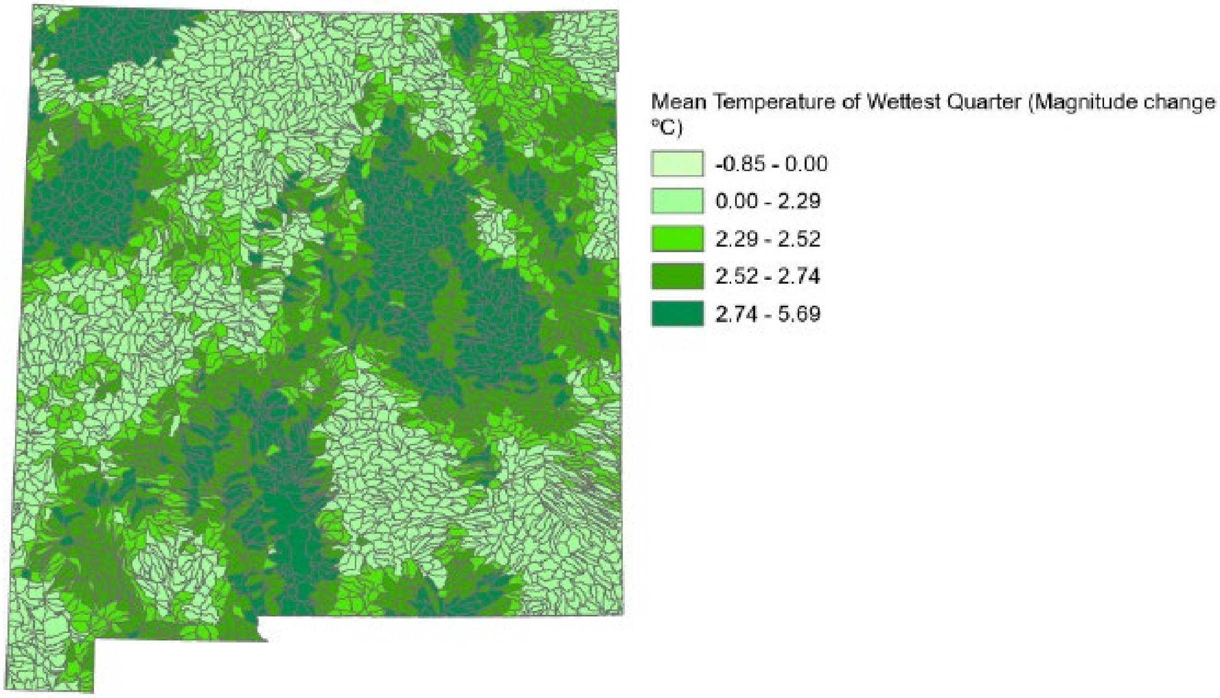

Z score Mean Change Soil Moisture Content
>-4
-4 to -3
-3 to -2
-2 to -1
0 to -1
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

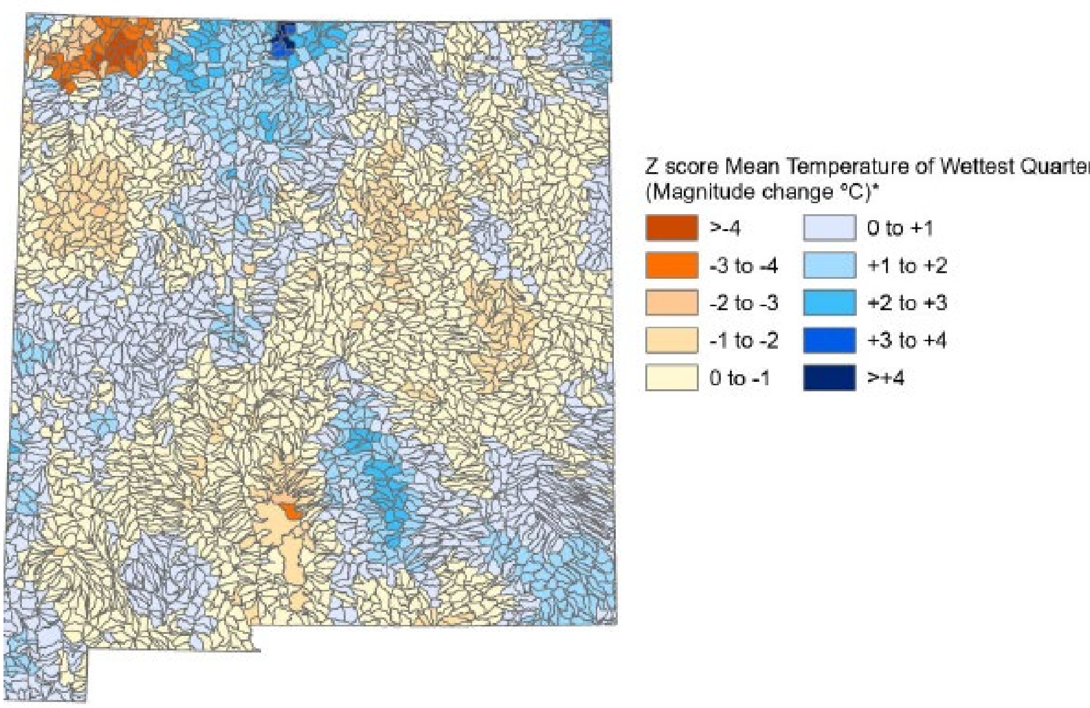

Mean Temperature of Wettest Quarter (Magnitude change °C)
-0.85 - 0.00
0.00 - 2.29
2.29 - 2.52
2.52 - 2.74
2.74 - 5.69

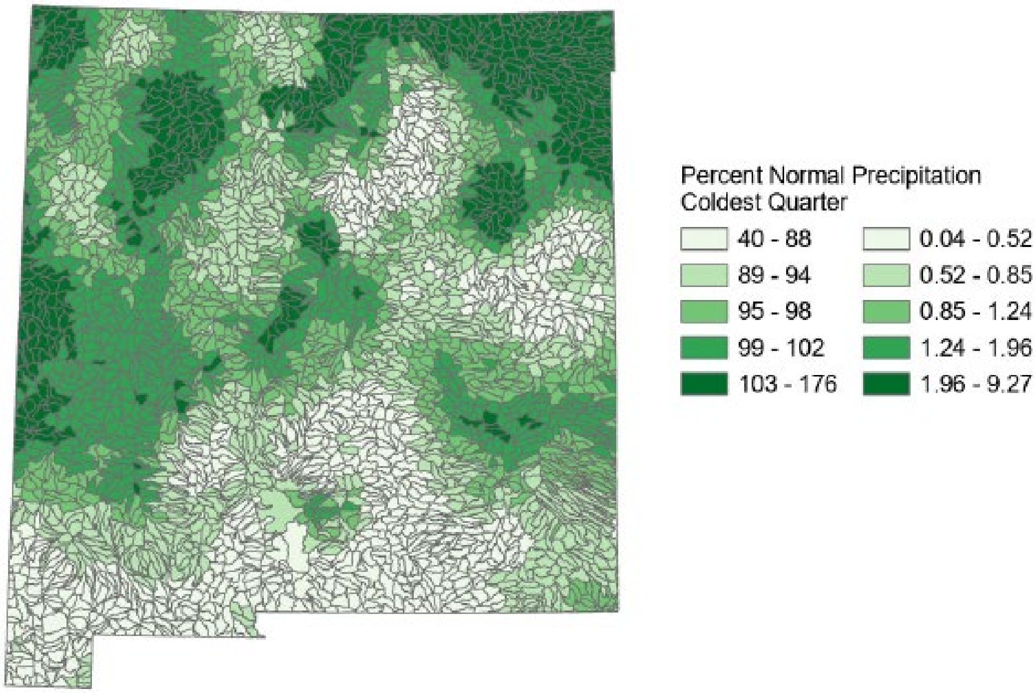

Z score Mean Temperature of Wettest Quarter (Magnitude change °C)*
>-4
-3 to -4
-2 to -3
-1 to -2
0 to -1
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

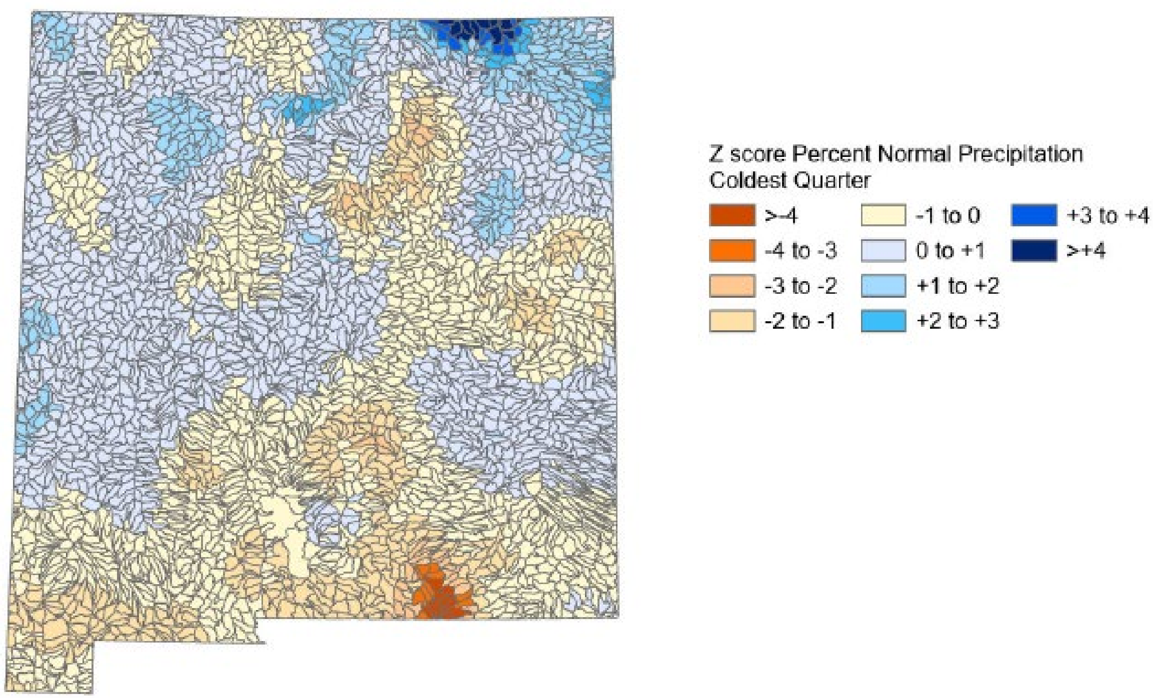

Mean Temperature of Wettest Quarter (Magnitude change °C)
-0.85 - 0.00
0.00 - 2.29
2.29 - 2.52
2.52 - 2.74
2.74 - 5.69

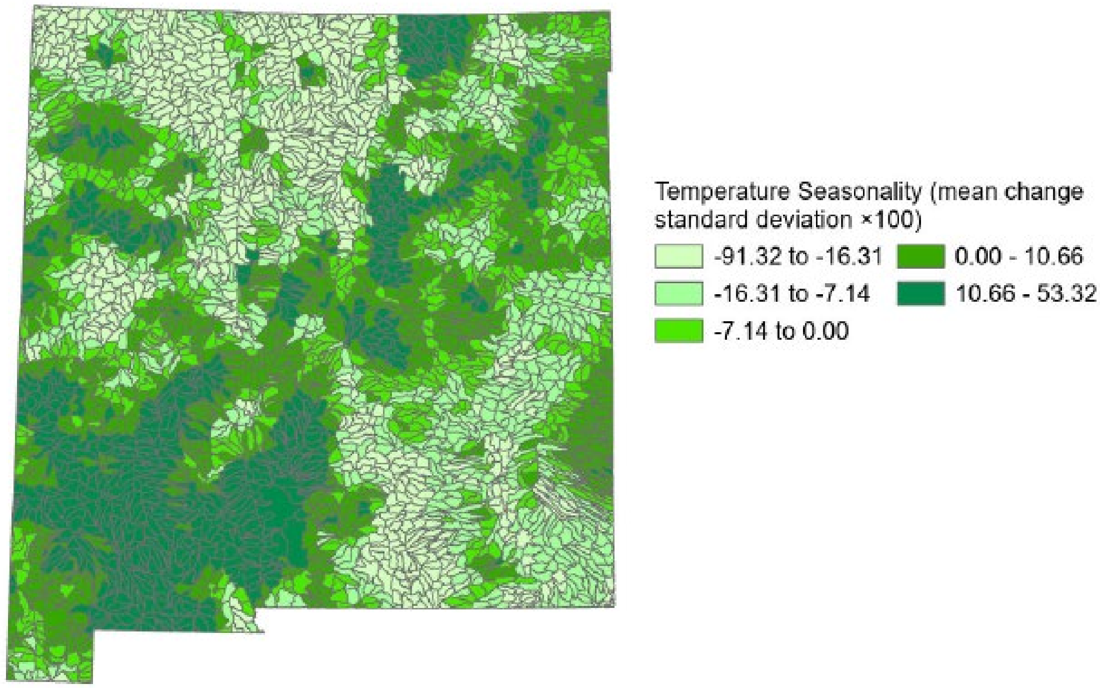

Z score Mean Temperature of Wettest Quarter (Magnitude change °C)*
>-4
-3 to -4
-2 to -3
-1 to -2
0 to -1
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

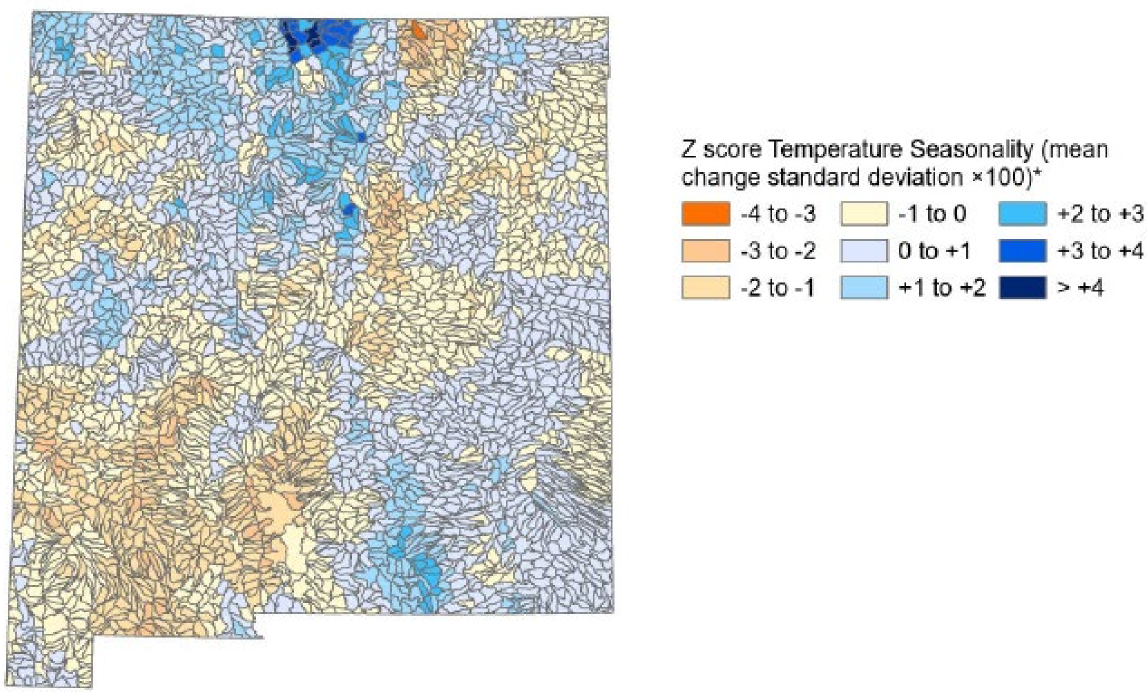

Mean Temperature of Wettest Quarter (Magnitude change °C)
-0.85 - 0.00
0.00 - 2.29
2.29 - 2.52
2.52 - 2.74
2.74 - 5.69

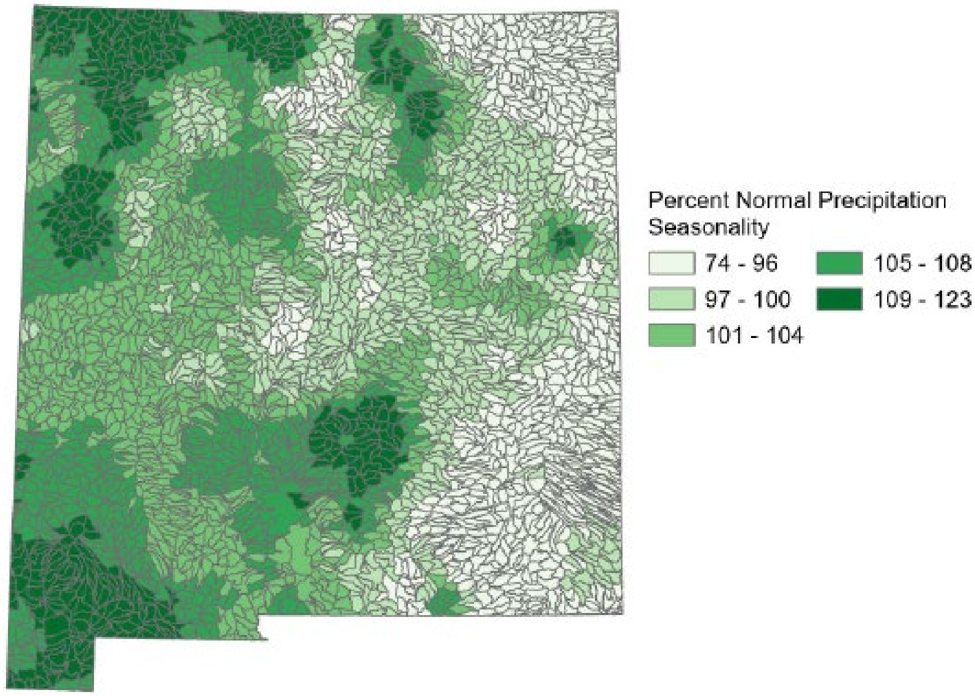

Z score Mean Temperature of Wettest Quarter (Magnitude change °C)*
>-4
-3 to -4
-2 to -3
-1 to -2
0 to -1
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

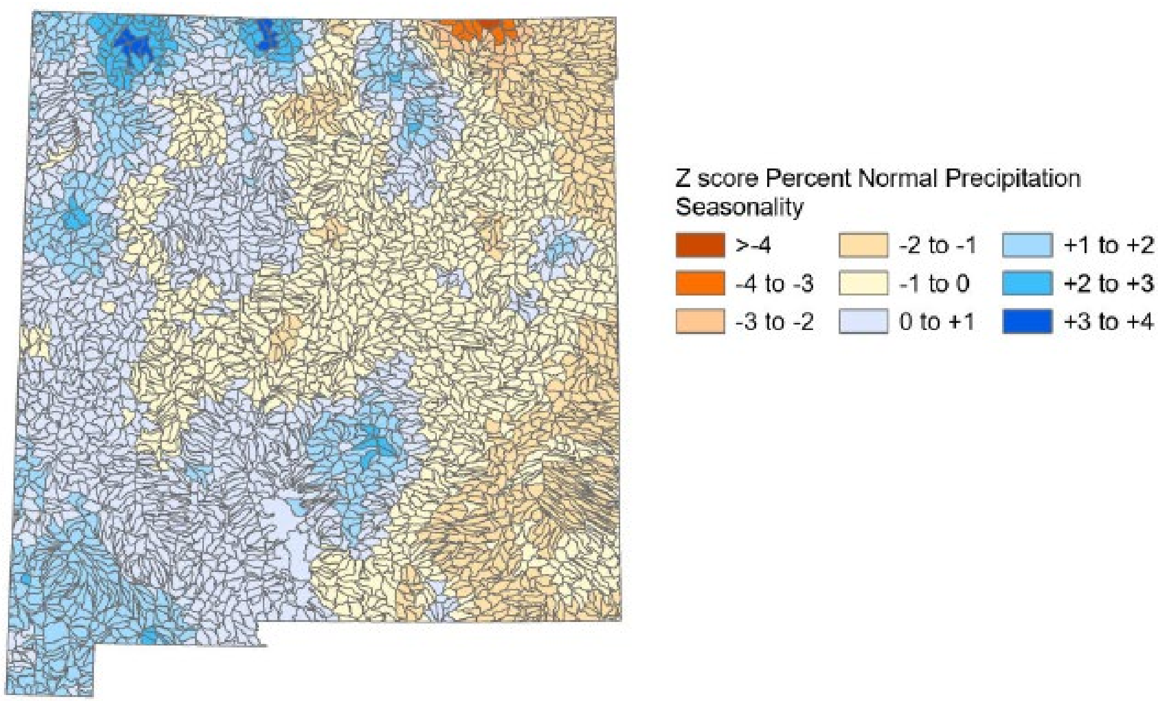

Percent Normal Precipitation
Coldest Quarter
40 - 88
89 - 94
95 - 98
99 - 102
103 - 176
0.04 - 0.52
0.52 - 0.85
0.85 - 1.24
1.24 - 1.96
1.96 - 9.27

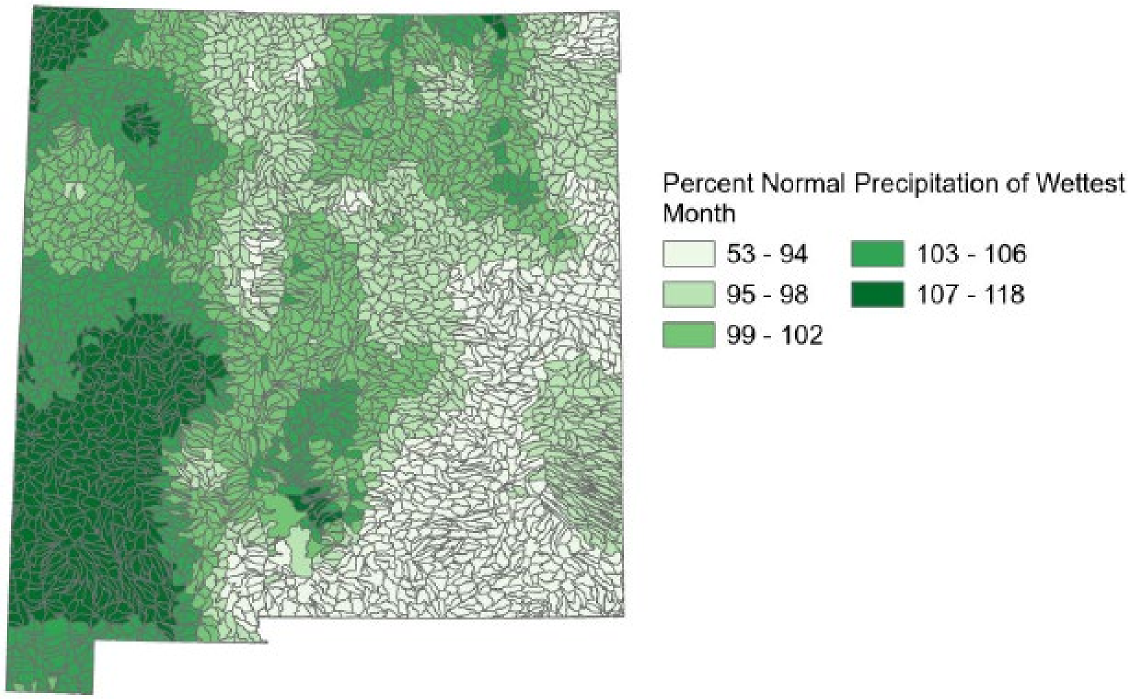

Z score Percent Normal Precipitation
Coldest Quarter
>-4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

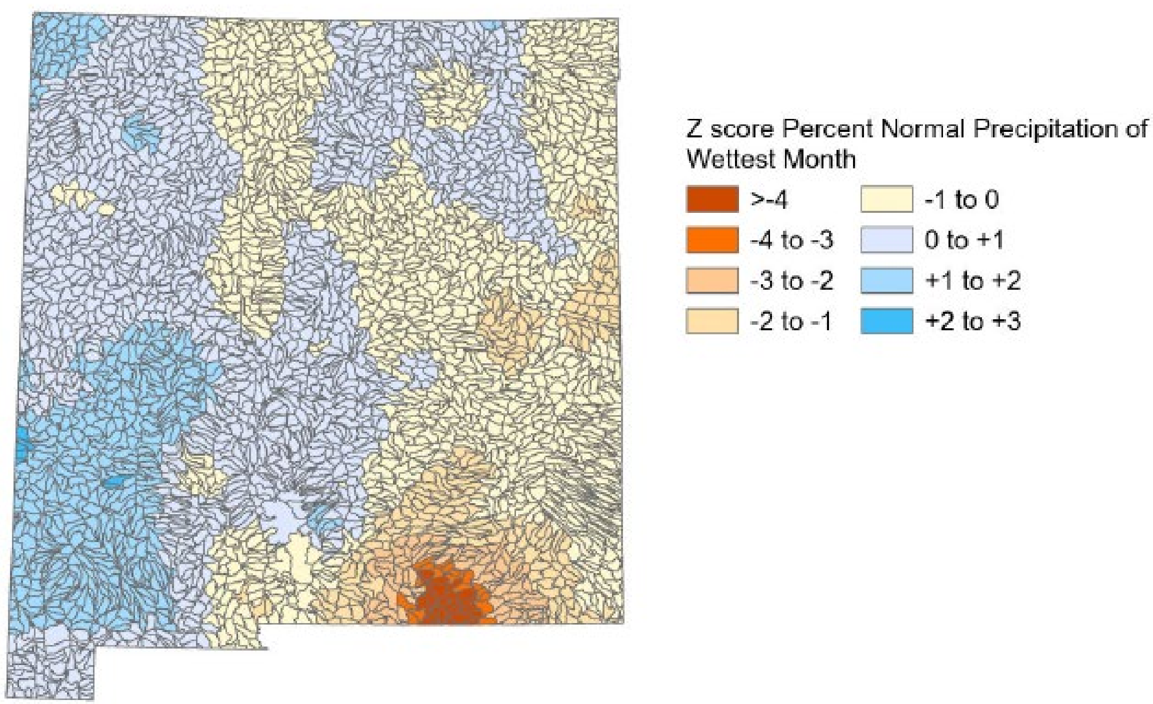

Temperature Seasonality (mean change standard deviation ×100)
-91.32 to -16.31
-16.31 to -7.14
-7.14 to 0.00
0.00 - 10.66
10.66 - 53.32

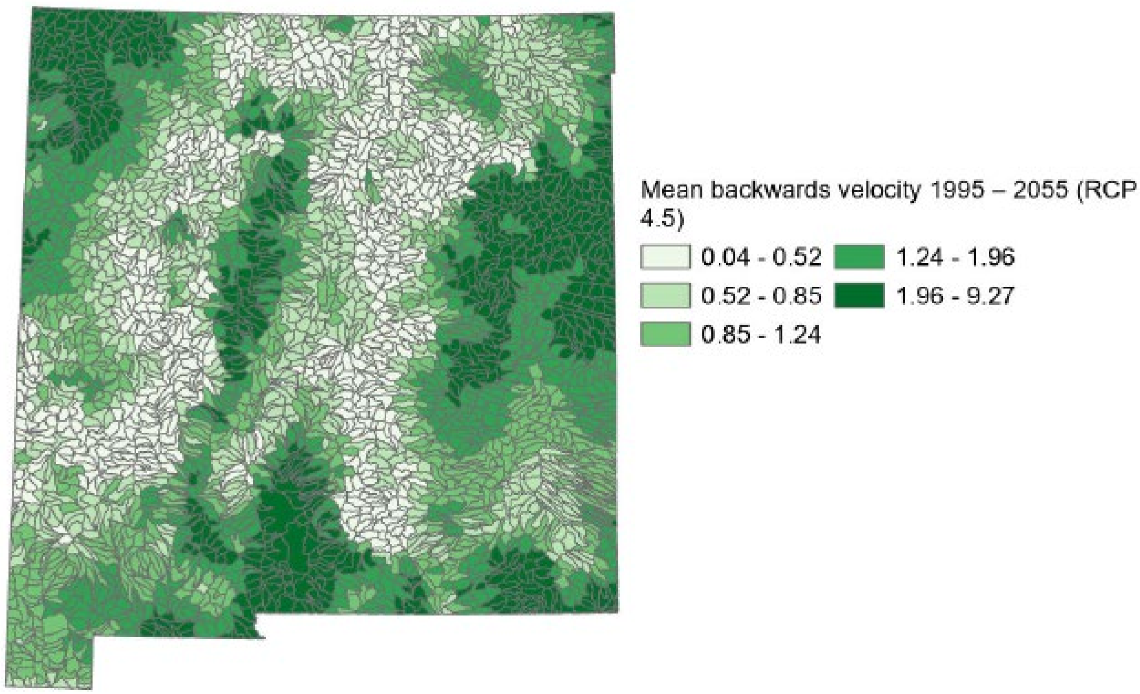

Z score Temperature Seasonality (mean change standard deviation ×100)*
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
> +4

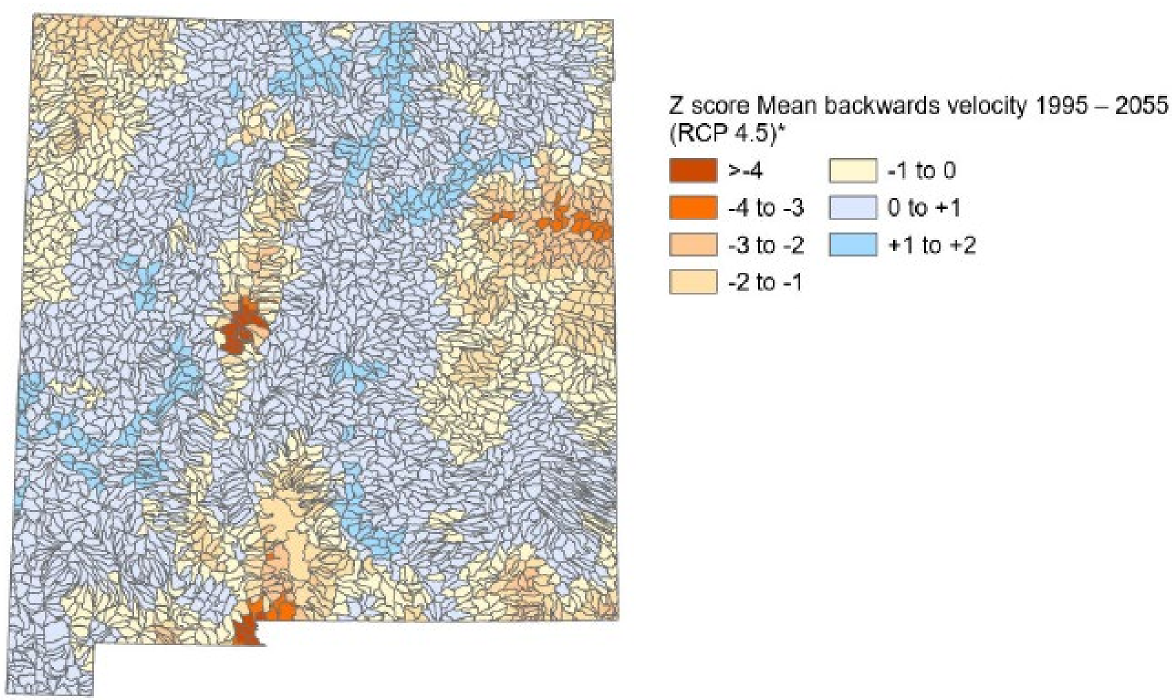

Percent Normal Precipitation
Seasonality
74 - 96
97 - 100
101 - 104
105 - 108
109 - 123

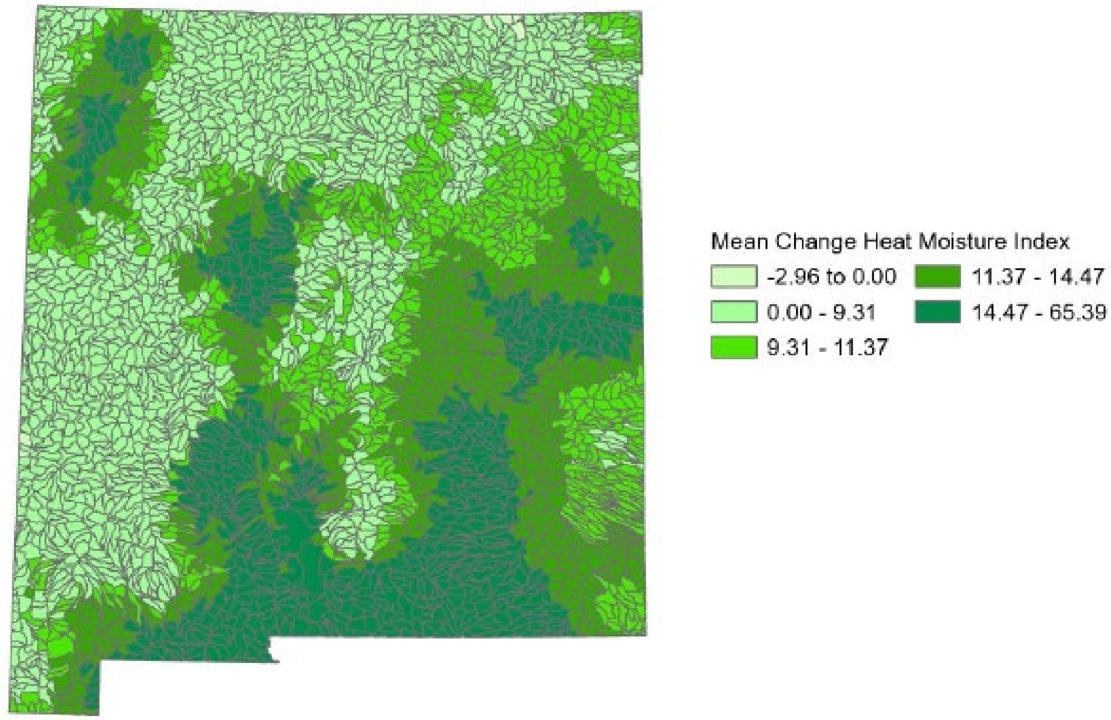

Z score Percent Normal Precipitation
Seasonality
>-4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4

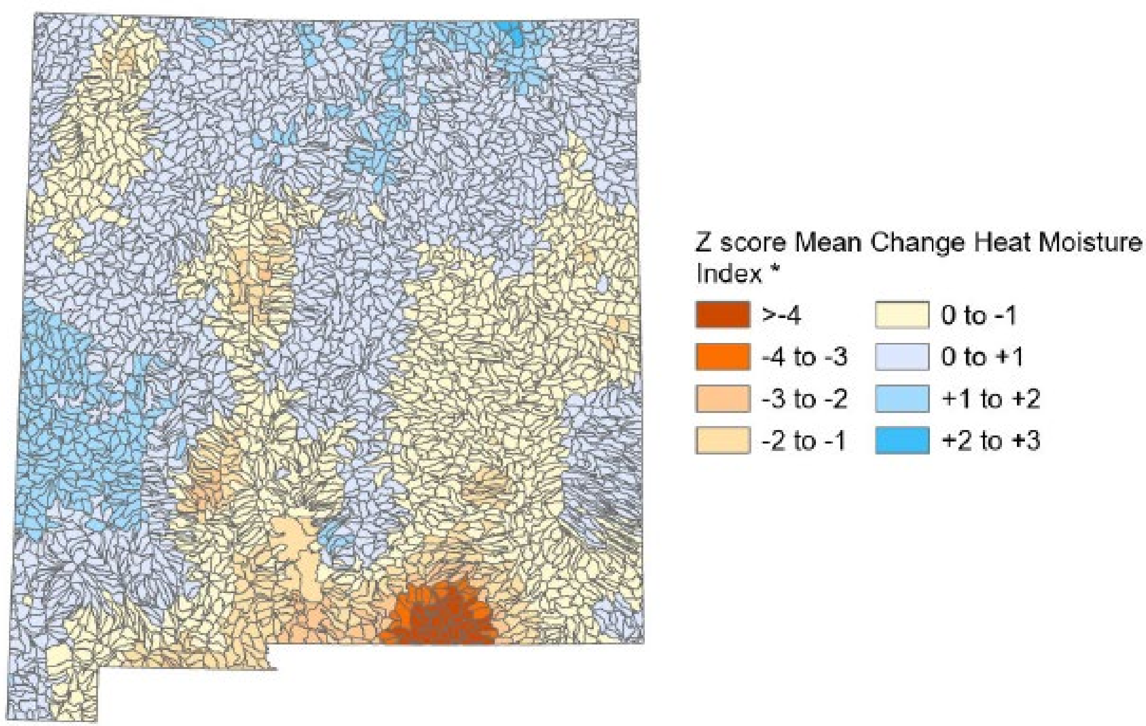

Percent Normal Precipitation of Wettest Month
53 - 94
95 - 98
99 - 102
103 - 106
107 - 118


Z score Percent Normal Precipitation of Wettest Month
>-4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3

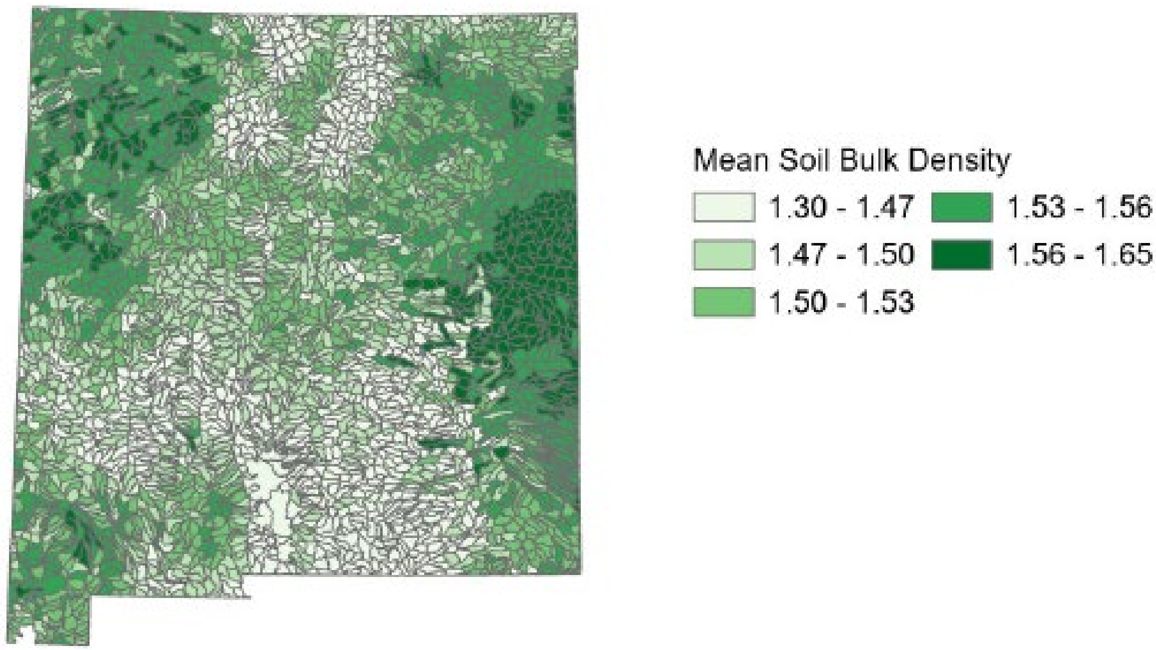

Mean backwards velocity 1995 – 2055 (RCP 4.5)
0.04 - 0.52
0.52 - 0.85
0.85 - 1.24
1.24 - 1.96
1.96 - 9.27

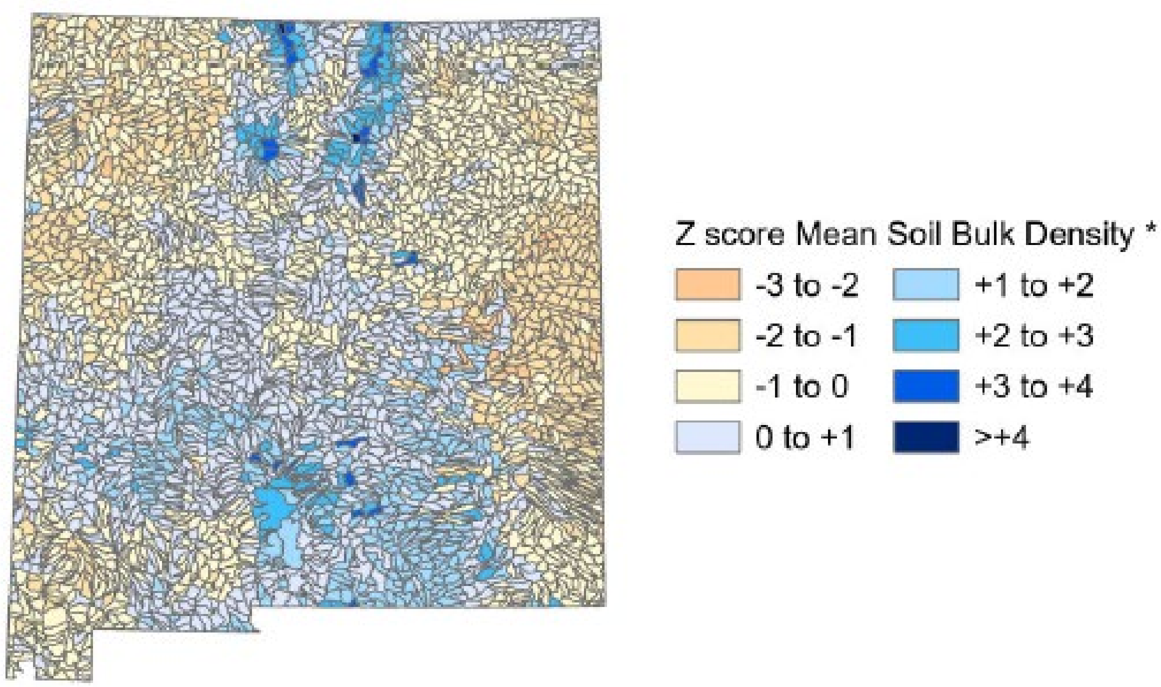

Z score Mean backwards velocity 1995 – 2055 (RCP 4.5)*
>-4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2

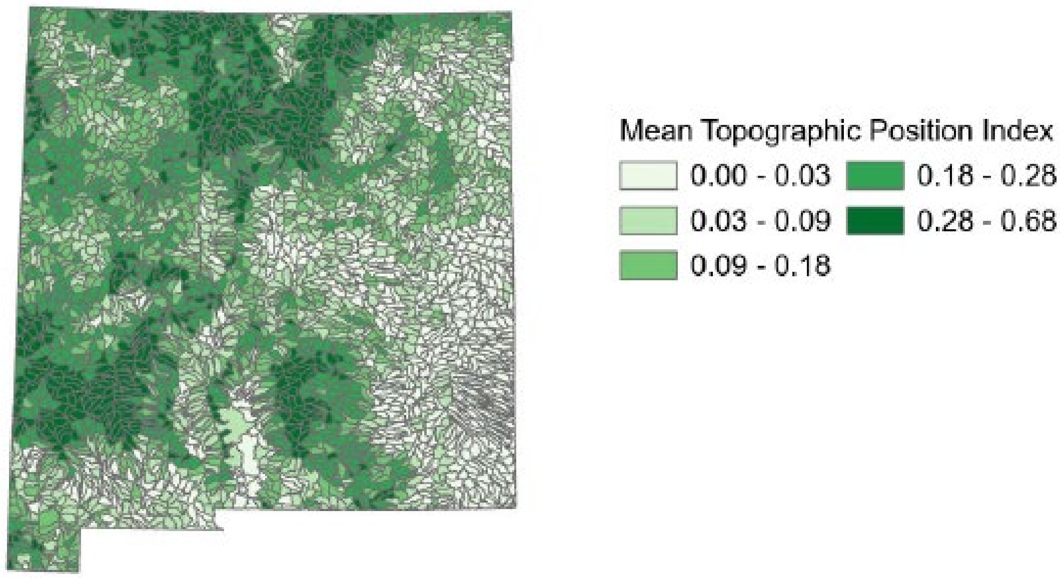

Mean Change Heat Moisture Index
-2.96 to 0.00
0.00 - 9.31
9.31 - 11.37
11.37 - 14.47
14.47 - 65.39

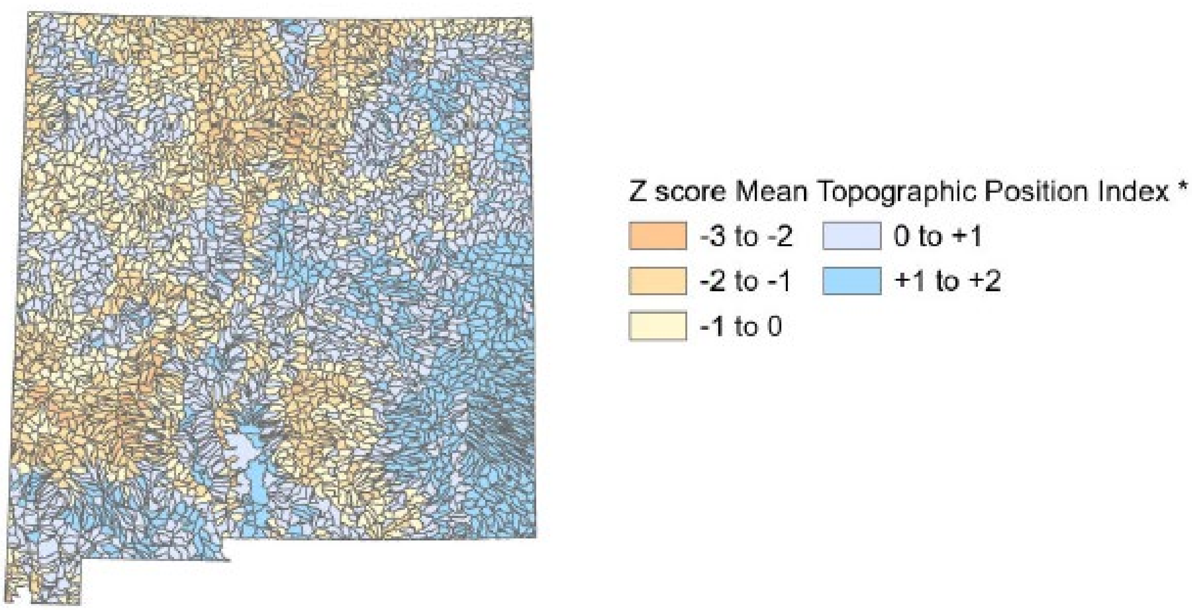

Z score Mean Change Heat Moisture Index *
>-4
-4 to -3
-3 to -2
-2 to -1
0 to -1
0 to +1
+1 to +2
+2 to +3

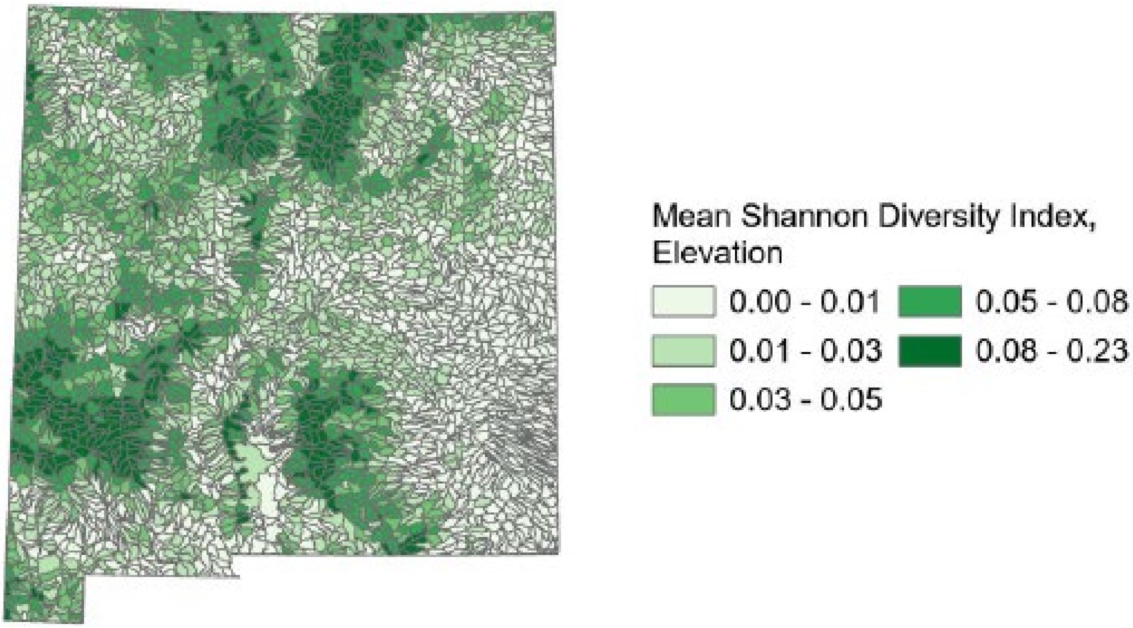
B . Topographic and Landscape Diversity Variables

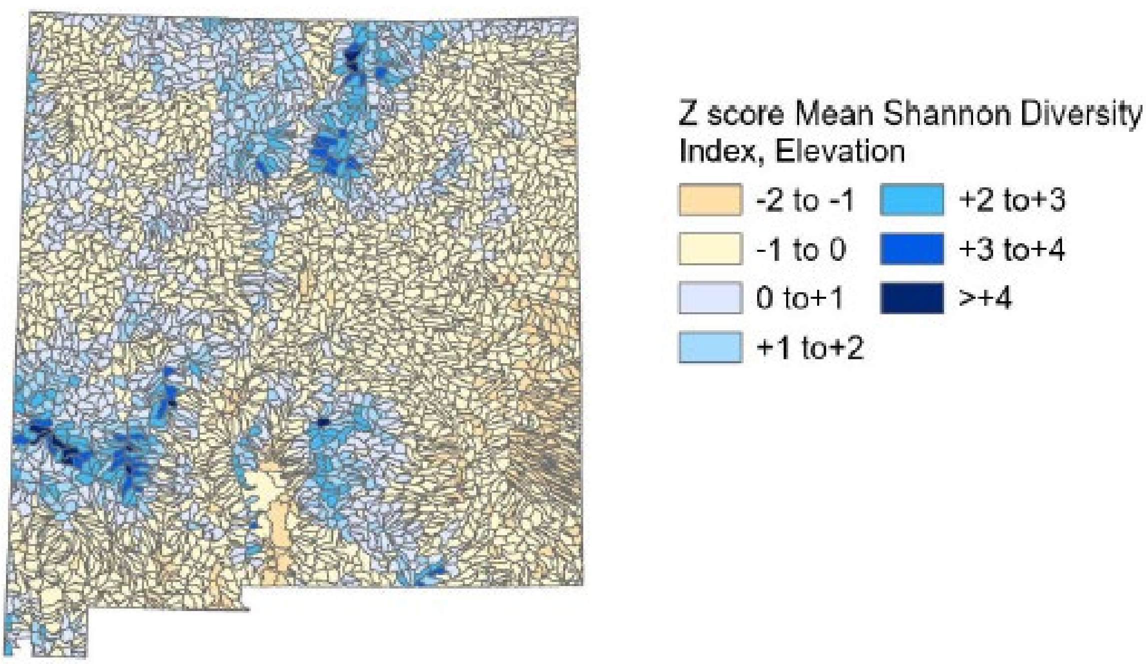


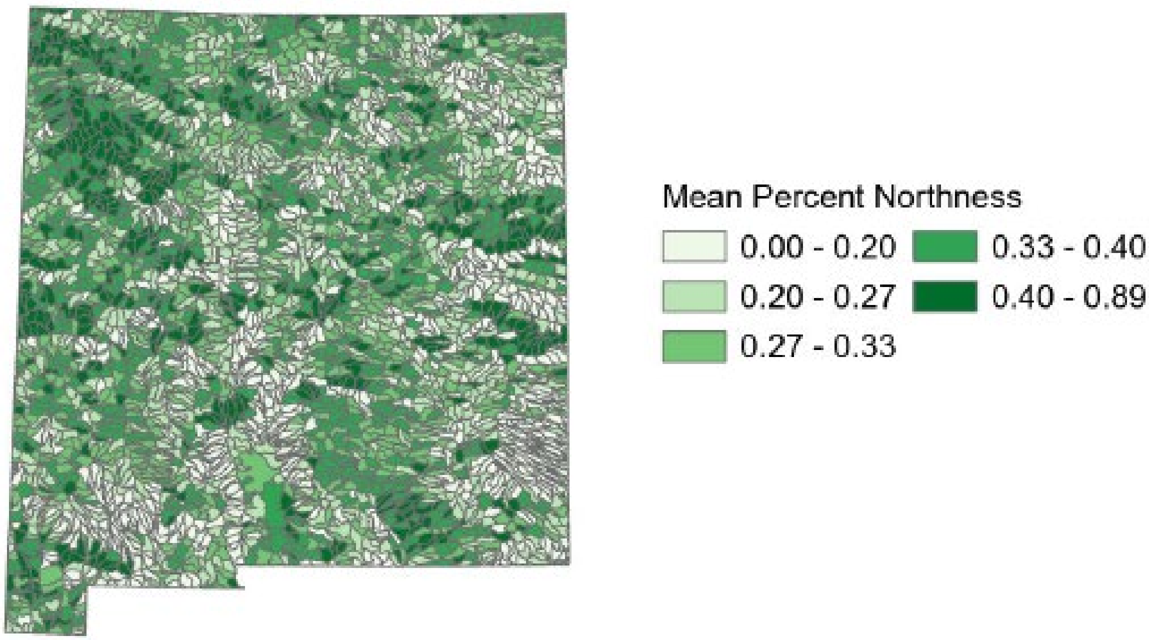


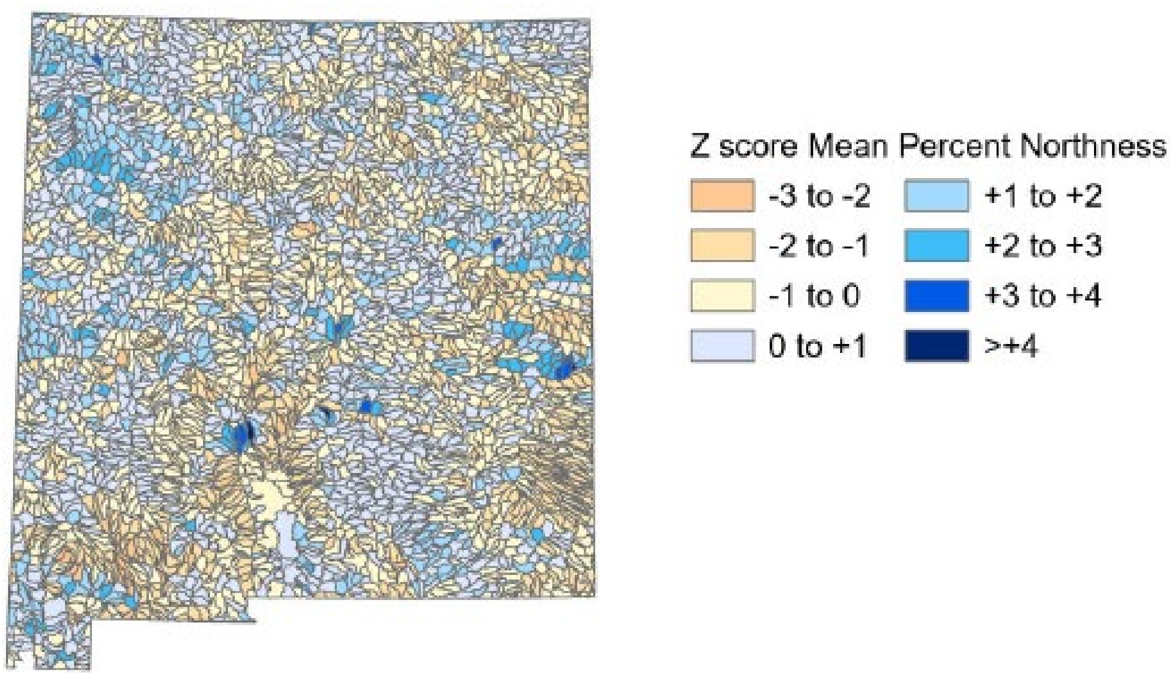

Mean Topographic Position Index
0.00 - 0.03
0.03 - 0.09
0.09 - 0.18
0.18 - 0.28
0.28 - 0.68

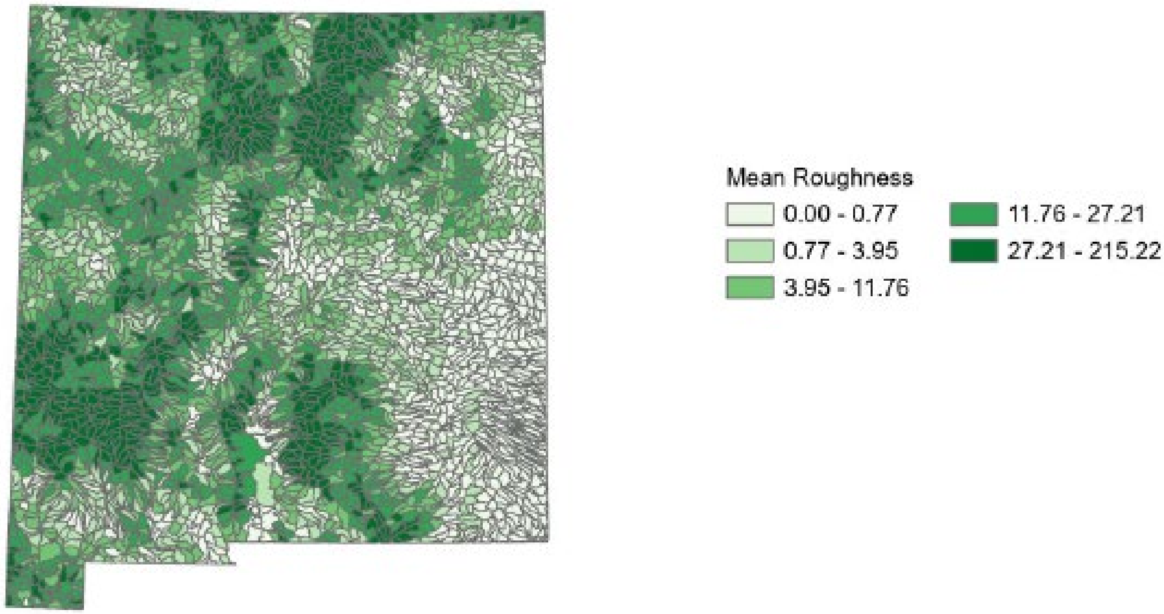

Z score Mean Topographic Position Index *
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2

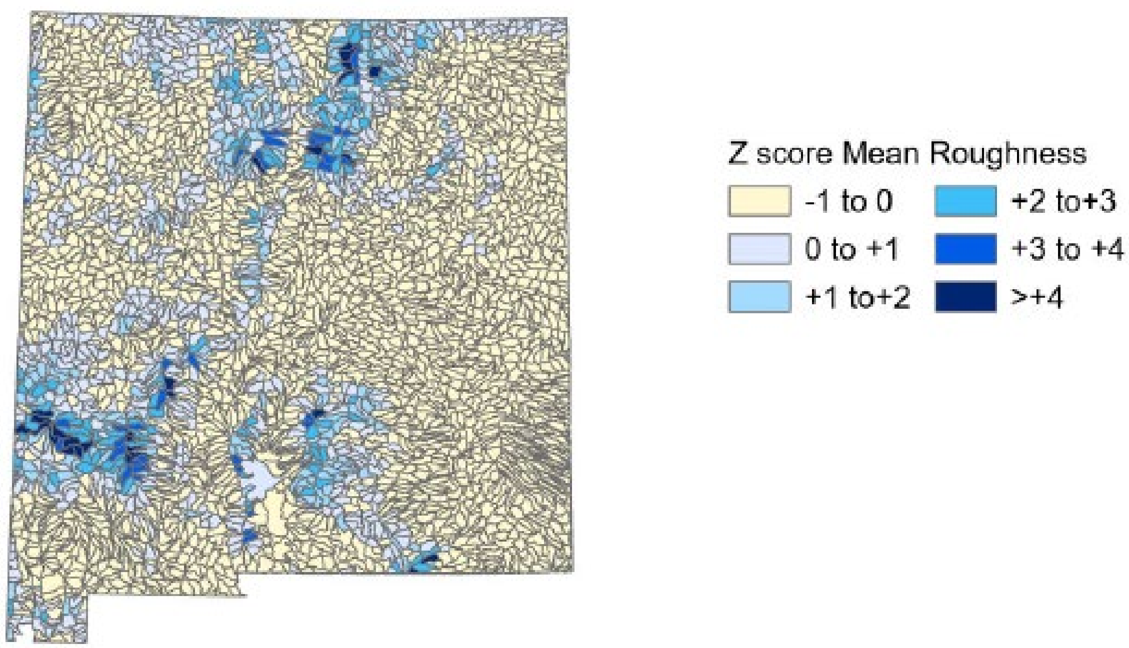

Mean Shannon Diversity Index, Elevation
0.00 - 0.01
0.01 - 0.03
0.03 - 0.05
0.05 - 0.08
0.08 - 0.23

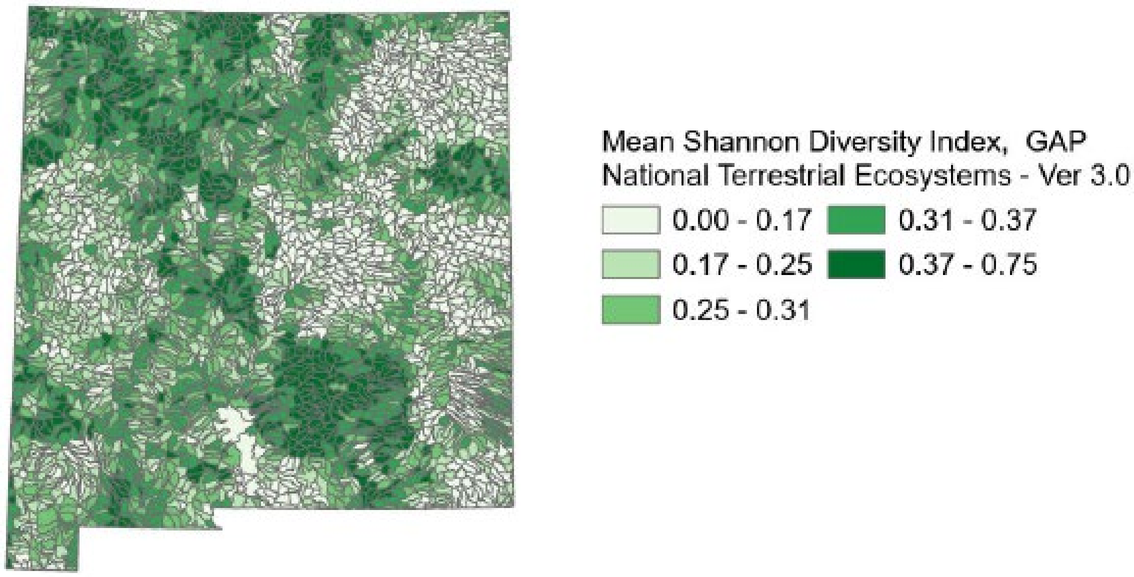

Z score Mean Shannon Diversity Index, Elevation
-2 to -1
-1 to 0
0 to+1
+1 to+2
+2 to+3
+3 to+4
>+4

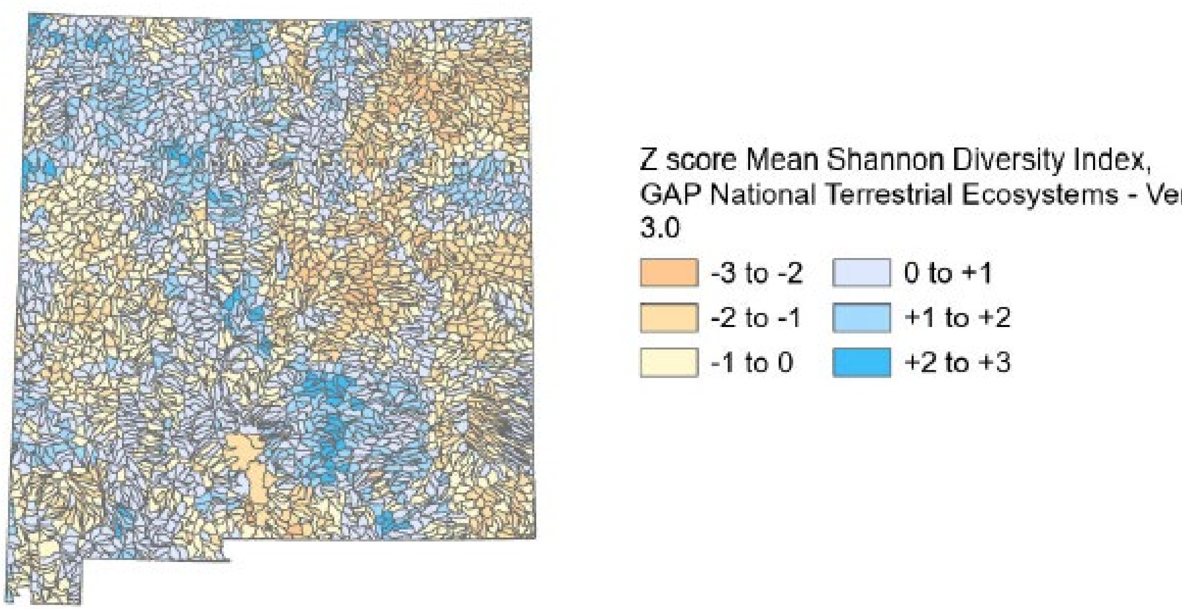

Mean Percent Northness
0.00 - 0.20
0.20 - 0.27
0.27 - 0.33
0.33 - 0.40
0.40 - 0.89

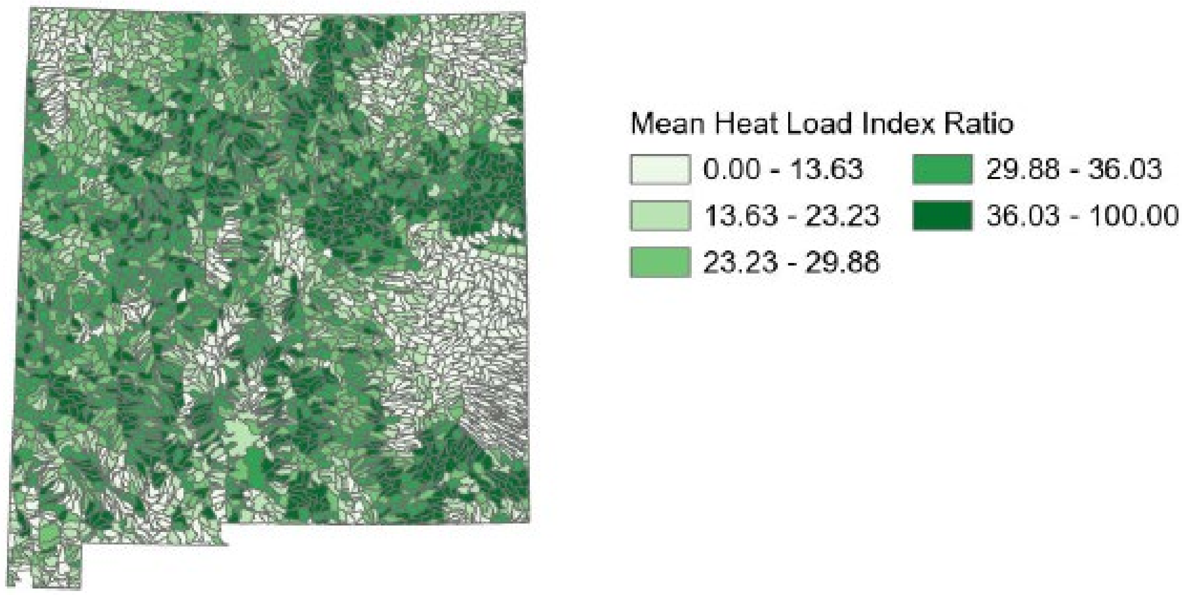

Z score Mean Percent Northness
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

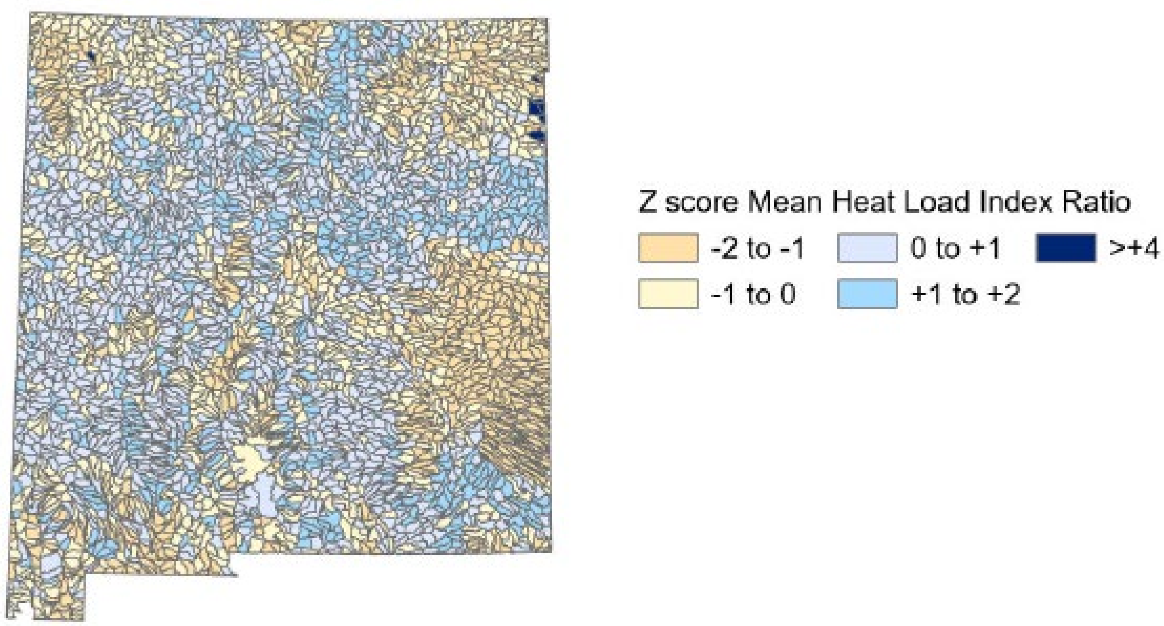

Mean Roughness
0.00 - 0.77
0.77 - 3.95
3.95 - 11.76
11.76 - 27.21
27.21 - 215.22

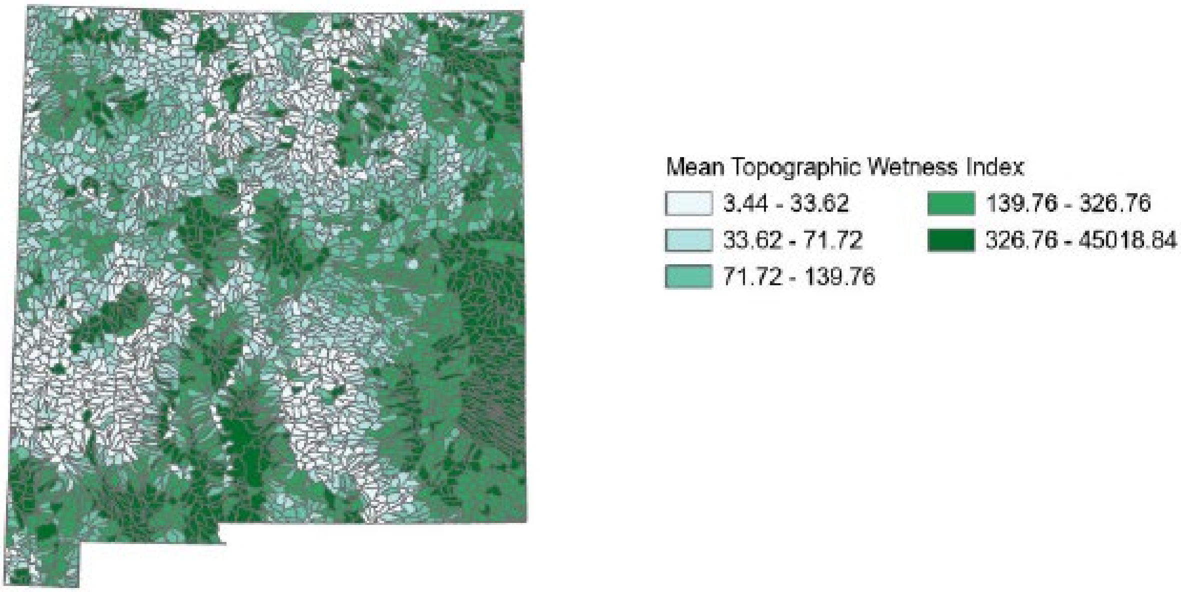

Z score Mean Roughness
-1 to 0
0 to +1
+1 to+2
+2 to+3
+3 to +4
>+4

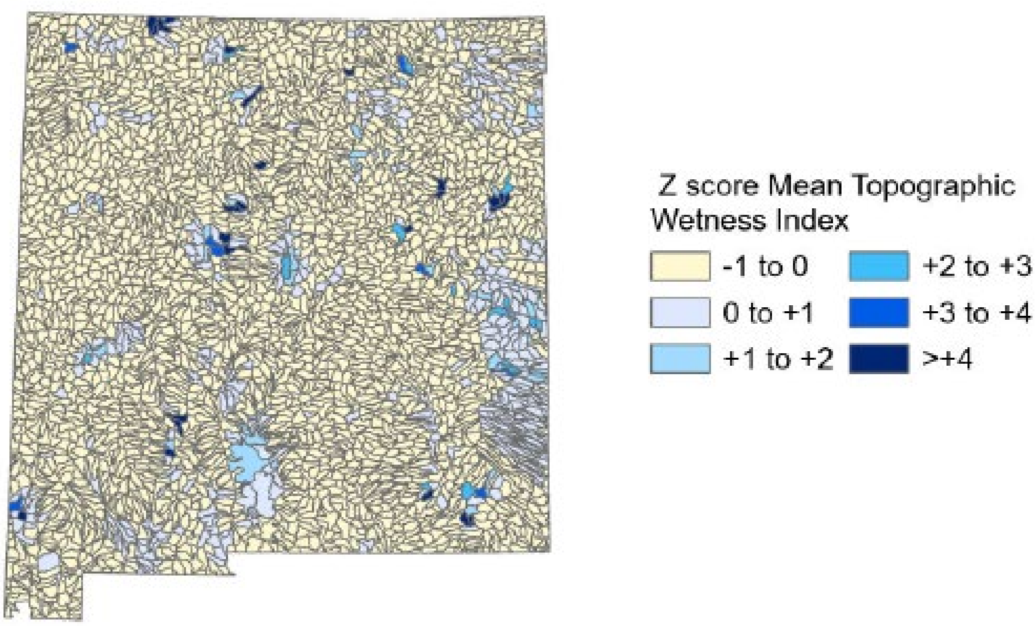

Mean Shannon Diversity Index, GAP National Terrestrial Ecosystems - Ver 3.0
0.00 - 0.17
0.17 - 0.25
0.25 - 0.31
0.31 - 0.37
0.37 - 0.75


Z score Mean Shannon Diversity Index, GAP National Terrestrial Ecosystems - Ver 3.0
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3


Mean Heat Load Index Ratio
0.00 - 13.63
13.63 - 23.23
23.23 - 29.88
29.88 - 36.03
36.03 - 100.00


Z score Mean Heat Load Index Ratio
-2 to -1
-1 to 0
0 to +1
+1 to +2
>+4


Mean Topographic Wetness Index
3.44 - 33.62
33.62 - 71.72
71.72 - 139.76
139.76 - 326.76
326.76 - 45018.84


Z score Mean Topographic Wetness Index
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
>+4

Supplemental Files 1-4 for Final Report Part II: Climate Change Refugia for Aquatic Species

Agreement # 23-CO-11221632-013

State Wildlife Grant # T-80-R-1

Prepared by D. Max Smith, Megan M. Friggens, and Karen Cooper Chaudry

Contents

Supplemental 1. Results of Literature Review.

Table 1.1. List of indicators identified in our review of the literature focused on climate change refugia. Papers that focused on the identification of climate change refugia are cited in this list. Indicators are listed as they are presented in each paper. Some studies focused on a concept in its entirety (landforms) and others focused on certain aspects of a concept (percent valleys). Some variables are specific to certain ecosystems. Importantly, this list does not include variables listed in papers assessing species distributions or analyzing climate resilience/resistance. However, papers covering those topics were considered during the final selection of refugia indicators.

Category	Metric	**Citations**
Watershed value		
	Species Richness	Carroll et al. 2017; Carroll and Noss 2021; Costelloe and Russell 2014; Ebersole et al. 2003
	Habitat Features	
Climate		
	Mean Annual Temperature	Carroll and Noss 2021; Dobrowski 2011; Haire et al. 2022; Rojas et al. 2022; Stark and Fridley 2022; Stralberg et al. 2018
	Mean Annual Maximum Temperature	
	Mean Annual Minimum Temperature	
	Mean Seasonal or Quarterly Temp	
	Macroclimate Mean Annual Temperature	
	Microclimate Mean Annual Temperature	
	Maximum Synoptic Temperature	
	Minimum Synoptic Temperature	
	Temperature (Hottest-Coldest) Difference	
	Total Precipitation Per Season or Quarter	
	Total Annual Precipitation	
Climate Extremes		
	Extreme Summer Temp	Ashcroft et al. 2012; Rojas et al. 2022
	Highest Mean Ann Temp	
	Lowest Mean Ann Temp	
	Frequency of Drought	
	Length of Drought	
	Number of Heat Waves	
	Snow vs. Rain Proportion	
Climate Index		
	Backward Climatic Velocity	Ashcroft et al. 2012; Carroll et al. 2017; Carroll and Noss 2021; Haire et al. 2022; Stralberg et al. 2018
	Forward Climatic Velocity	
	Climate Dissimilarity (Over Time)	
	Climate Stability	

Category Metric		Citations
	Climatic Isolation	
	Climatic Moisture Index (CMI)	
	Heat Moisture Index	
	Current Climate Diversity	
	Heat Load Index (HLI)	
Climate- Water Balance		
	Actual Evapotranspiration (AET)	Ackerley et al. 2020
	Climatic Water Deficit (CWD)	
	Potential Evapotranspiration (PET)	
	Soil Moisture Content (SMC)	
	Snow Water Equivalent (SWE)	
Climate-Streamflows		
	Streamflow Volume	Ebersole et al. 2003; Isaak et al. 2015; Peters-Lidard et al. 2021
	Stream Temperature	
Drought refugia		
	Elevation	Cartwright et al. 2020
	Soil Available Water Capacity	
	Soil Bulk Density	
Fire		
	Fire Regime Changes	Rojas et al. 2022
Land Cover Pattern/Landforms		
	Canyons	Carroll et al. 2017; Cartwright et al. 2018; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2015; Haire et al. 2022; Stralberg et al. 2018; Stark and Fridley 2022
	Catchment Area	
	Catchment Slope	
	Convergent Features	
	Landforms	
	Presence Of Debris-Covered Glaciers, Rock Glaciers and Boulder-Streams (For Alpine)	
	Presence Of Incised Valleys	
	Proportion Headwater	
	Stream Distance	
	Valley Bottoms Presence	
	Valley Bottoms Proportion	
	Valley Depth	
Land Use		
	Human Footprint	Carroll and Noss 2021; Rojas et al. 2022
	Human Use of Wildlands	
	Urban Expansion	

Category Metric		Citations
Soils		
	Moisture Holding Capacity	Ackerly et al. 2020; Carroll et al. 2017; Cartwright 2018; Cartwright et al. 2022;
	Presence of Slow-Infiltrating Soils	
	Presence Of Nonsaline Alluvial Soils	
	Soil Bulk Density	
	Soil Order	
Topography		
	Aspect	Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2015; Haire et al. 2022; Hoffren et al. 2022; Stralberg et al. 2018; Stark and Fridley 2022
	Elevation	
	Landform	
	Mid-Slope Position	
	North–South Corridor Potential	
	Slope	
Topographic Index		
	Annual Radiation	Carroll et al. 2017; Cartwright et al. 2020; Dobrowski 2011; Estevo et al. 2022; Gentili et al. 2015; Haire et al. 2022; Stralberg et al. 2018; Stark and Fridley 2022
	Compound Topographic Index (CTI) / Topographic Wetness Index (TPI)*	
	Daily Radiation	
	Heat Load Index (HLI)	
	Presence of North Facing Slope	
	Slope + Aspect (Southness)	
	Terrain Roughness/Terrain Roughness Index*	
	Terrain Ruggedness Index (TRI)*	
	Topographic Convergence Index	
	Topographic Position Index (TPI)*	
Topodiversity**		
	Aspect Diversity	Carroll et al. 2017; Carroll and Noss 2021; Malakoutinakhah et al. 2018
	Elevational Diversity	
	Heat Load Index (HLI) diversity	
	Land facet diversity	
	Topographic Diversity	
Topodiversity Index		
	Elevation + Topodiversity	Carroll et al. 2017; Carroll and Noss 2021
	Elevational and HLI Diversity	
Lithology		
	Presence of Karst	Ishiyama et al. 2023; Tague et al. 2007;
	Presence of Volcanic Aquifers	

Category Metric		**Citations**
	Presence of Unconsolidated Aquifers	Wang et al. 2009
	Aquifer Richness	
Vegetation		
	Marsh/Wet Meadow Vegetation	Baker and Bonar 2019; Colvin et al. 2019; DeWalle 2010; Haire et al. 2022; Turunen et al. 2021
	Riparian Woodlands	
	Tree Canopy in Stream Buffer	
	Riparian Canopy Height	
	Floodplain Shrub Cover	
	Floodplain Wetland Cover	
	Natural Cover in Stream Buffer	
*Variations exist in how these are calculated. Studies also employ these at different spatial scales, which are not elaborated on here.		
**Diversity metrics that include combinations of other diversity metrics are not noted here.		

Table 1.2. Candidate list of climate refugia indicators considered for inclusion in analysis of New Mexico landscapes. These data have been gathered (Available) or were derived from Elevation or Climate information (Calculated) and are currently stored in either a geodatabase or the collaborative ArcGIS Online.

Category (Metric)	Source (Available or Calculated)
Value Indicators	
1. Species Richness	Calculated
2. Density of Habitat Features	Calculated
Climate Indices	
3. Forward Velocity	Available
4. Backward Velocity	Available
5. Presence of Climate Corridors*	Available
6. Climate Dissimilarity (over time)	Available/Calculated
7. Current Climate Diversity	Calculated
8. Climate Stability	Calculated
9. Climatic Isolation	Calculated
10. Climatic Moisture Index (CMI)	Calculated
11. Heat Moisture Index (HMI)	Calculated
Derived Climate Variables (based on current and projected temperature and precipitation variables)	
12. Aridity Index (AI)	Available
13. Climatic Water Deficit (CWD)	Available
14. Mean Annual Temperature	Calculated
15. Annual Minimum Temperature	Calculated
16. Annual Maximum Temperature	Calculated
17. Interannual Range of Temperatures	Calculated
18. Interannual Range of Precipitation	Calculated
19. Mean Annual Isothermality	Calculated
20. SWE April	Calculated
21. Total Annual Precipitation	Calculated
22. Total Precipitation Warmest Quarter	Calculated
23. Potential Evapotranspiration (PET)	Calculated
24. Actual Evapotranspiration (AET)	Calculated
25. Summer Vapor Pressure Deficit (VPD)	Calculated
26. Spring AET	Calculated
27. Soil Moisture Content (SWC)	Calculated
28. Summer AET	Calculated
29. Spring PET	Calculated
30. Summer PET	Calculated
31. Mean Dry Degree Days	Available
Future Change	
32. Magnitude Change Mean Annual Temperature	Calculated
33. Magnitude Change Summer Maximum Temperature	Calculated
34. Magnitude Change in Winter Minimum Temperature	Calculated
35. Percent of Normal Future Annual Precipitation	Calculated
36. Percent of Normal Future Winter Precipitation	Calculated
37. Percent of Normal Future Spring Precipitation	Calculated
38. Percent of Normal Future Summer Precipitation	Calculated
39. Percent Change in June Streamflow	Available

Category (Metric)	Source (Available or Calculated)
40. Percent Change in August Stream Temperature	Available
Topography	
41. Elevation	Calculated
42. Slope	Calculated
43. Ruggedness	Calculated
44. Aspect (radians)	Calculated
45. Aspect (linear)	Calculated
Derived Topographic	
46. Landform	Calculated
47. Catchment Area	Calculated
48. Curve	Calculated
49. Mean Elevation	Calculated
Topographic Indices	
50. Heat Load Index (HLI)	Available
51. Terrain Ruggedness Index (TRI)	Calculated
52. Northness (cosine of aspect in radians)	Calculated
53. Eastness (sine of aspect in radian)	Calculated
54. Topographic Position Index (TPI)	Calculated
55. Compound Topographic Index (CTI)/Topographic Wetness Index (TWI)	Available/Calculated
56. Slope + Aspect (Southness)	Calculated
57. Topographic Convergence Index	Calculated
58. Vector Ruggedness Index	Calculated
59. Standard Deviation of Slope	Calculated
Land Cover Pattern/Landforms	
60. Topofacet Layer	Available
61. Facet ID values	Available
62. Convergent Features (e.g., catchments, valleys, headwaters, canyons)	Calculated
63. Presence of Ecotones	Calculated
64. Distance to Ecotone (e.g., Fir)	Calculated
65. Percent Cover (e.g., Forest)	Calculated
66. Stream Distance	Calculated
Topographic Diversity	
67. Aspect Diversity	Calculated
68. Elevational Diversity	Calculated
69. HLI diversity	Calculated
70. Land Facet Diversity	Calculated
71. Topographic Diversity	Calculated
Lithology	
72. Presence of Carbonate Karst	Available
73. Presence of Volcanic Aquifers	Available
74. Presence of Unconsolidated Aquifers	Available
75. Aquifer Richness	Calculated
Soils	
76. Percent Soil Bulk Density, 1m	Available/Calculated
77. Soil Water Storage/Available Water Capacity	Available
78. Available Soil Moisture	Available/Calculated
79. Mean Duration Dry Soil Intervals	Available
80. Presence of Shallow or Finer Textured Soils	Available/Calculated

Category (Metric)	Source (Available or Calculated)
81. Presence of Slow-Infiltrating Soils	Available
Vegetation	
82. Riparian Canopy Height	Calculated
83. Presence of Marsh/Wetland Vegetation	Available
84. Presence of Riparian Woodland	Available
85. Tree Canopy in Stream Buffer	Available
86. Natural Cover in Stream Buffer	Available
87. Floodplain Wetland Buffer	Available
88. Floodplain Shrub Cover	Available
*Climate corridors are areas that form the best route between current or future climate types.	

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Supplemental 2: Variable Selection and Standardization

Table 2.1. Final optimized values for each variable used to estimate macro- and hydrorefugia. Shannon Diversity Index (SDI) calculated on 3x3 window.

Indicator	**Assigned Weights**				
	Cold-Water Fish	**Perennial Streams**	**Amphibian and Reptile Habitat**	**Ephemeral Catchments**	**Springs**
Macrorefugia					
Pct Change Precip Wettest Month (Bio13)		0.16			
Pct Change Precip Driest Month (Bio14)				0.14	
Pct Change Precip Warmest Quarter (Bio18)	0.09		0.13	0.13	
Pct Change Precip Coldest Quarter (Bio19)	0.05	0.13	0.05		0.05
Change Soil Moisture Content (SMC)				0.24	
Change Snow Water Equivalent (SWE)	0.24	0.05	0.15		0.24
Pct Change June Streamflow Volume	0.06	0.06	0.14		
Backwards Climate Velocity	0.05		0.05	0.14	
Diff Mean Temp Wettest Quarter (Bio8)	0.11	0.22	0.05		0.26
Diff Mean Temp Driest Quarter (Bio9)	0.05	0.07	0.05	0.05	0.15
Diff Max Temp Warmest Month (Bio5)	0.05	0.15	0.17	0.05	
Change Evapotranspiration (ET)			0.21	0.26	
Change Potential Evapotranspiration of Natural Vegetation (PNV)	0.05	0.17			0.30
Pct Change August Stream Temp	0.25				
Hydrorefugia					
Mean Riparian Canopy Height	0.05		0.08		
Pct Marsh/Wet Meadow Vegetation	0.30	0.30	0.28		
Pct Riparian Woodland/Shrubland	0.05				
Pct Stream Buffer with Tree Canopy	0.05		0.05		
Mean Soil Water Storage			0.05		
Mean Compound Topographic Index			0.06	0.30	
Mean Elevation	0.05	0.09	0.05		
Mean SDI for Aspect	0.13		0.05	0.19	
geomorph_sh3_std	0.16		0.14	0.30	
Mean Vector Ruggedness					0.11

Indicator	Assigned Weights				
	Cold-Water Fish	Perennial Streams	Amphibian and Reptile Habitat	Ephemeral Catchments	Springs
Pct Carbonate Karst	0.05	0.11	0.05		0.18
Pct Volcanic Aquifers	0.05	0.30			0.27
Pct Unconsolidated Aquifers		0.05			
Aquifer Richness		0.06			0.05
Mean Heat Load Index	0.05		0.05	0.05	0.08
Mean Soil Bulk Density	0.05	0.10	0.14		0.30
Pct Slow-Infiltrating Soils				0.17	

Supplemental 3. Variables Assessed for their Potential Role in Predicting Macro or Hydrorefugia for Taxa in New Mexico.

Table 3.1. Topographic and landscape metrics used to calculate macro- and hydrorefugia for cold-water fish habitat. Values represent the number of HUC12 included, in addition to the mean, minimum, maximum and standard deviation values calculated for each HUC12. Shannon Diversity Index (SDI) calculated on 3x3 window.

	Count	Mean	Min	Max	STD
Macrorefugia	542				
Pct Change Precip Warmest Quarter (Bio18)		-1.5	-40.6	10.7	6.01
Pct Change Precip Coldest Quarter (Bio19)		-2.8	-58.5	76.1	10.7
Change Snow Water Equivalent (SWE)		-0.2	-6.7	2.2	0.9
Pct Change June Streamflow Volume		-9.3	-60.7	103.5	18.1
Backwards Climate Velocity		0.8	0.1	3.5	0.6
Diff Mean Temp Wettest Quarter (Bio8)		2.2	-0.9	4.6	0.6
Diff Mean Temp Driest Quarter (Bio9)		2.3	-2.5	5.9	1.3
Diff Max Temp Warmest Month (Bio5)		2.8	0.7	4.8	0.7
Change Potential Evapotranspiration of Natural Vegetation (PNV)		-1.3	-2.3	-0.1	0.5
Pct Change August Stream Temp		3.1	0.3	8.0	0.8
Hydrorefugia	542				
Mean Riparian Canopy Height		6.8	0	25.8	6.1
Pct Marsh/Wet Meadow Vegetation		0.6	0	11.3	1.2
Pct Riparian Woodland/Shrubland		1.5	0	7.4	1.3
Pct Stream Buffer with Tree Canopy		20.6	0.6	47.7	11.5
Mean Elevation		2291.2	1447.9	3428.5	351.9
Mean SDI for Aspect		0.6	0.4	0.9	0.1
Mean SDI for Geomorphology		0.4	0.3	0.5	0.02
Pct Carbonate Karst		11.5	0	76.4	15.4
Pct Volcanic Aquifers		4.1	0	39.7	6.7
Mean Heat Load Index		0.8	0.7	0.9	0.03
Mean Soil Bulk Density		1.5	1.3	1.5	0.1

Table 3.2. Topographic and landscape metrics used to calculate macro- and hydrorefugia for perennial streams. Values represent the number of HUC12 included, in addition to the mean, minimum, maximum and standard deviation values calculated for each HUC12. Shannon Diversity Index (SDI) calculated on 3x3 window.

	Count	Mean	Min	Max	STD
Macrorefugia	1,022				
Pct Change Precip Wettest Month (Bio13)		-0.1	-21.0	12.3	6.2
Pct Change Precip Coldest Quarter (Bio19)		-3.3	-23.1	47.0	8.1
Change Snow Water Equivalent (SWE)		-0.1	-2.3	0.5	0.4
Pct Change June Streamflow Volume		-7.0	-60.7	103.5	14.3
Diff Mean Temp Wettest Quarter (Bio8)		2.3	1.0	4.4	0.4
Diff Mean Temp Driest Quarter (Bio9)		2.3	1.1	5.1	0.7
Diff Max Temp Warmest Month (Bio5)		2.8	1.5	4.1	0.5
Change Potential Evapotranspiration of Natural Vegetation (PNV)		-0.9	-1.6	0.01	0.4
Hydrorefugia	1,022				
Mean Riparian Canopy Height		0.3	0	2.7	0.4
Mean Elevation		1937.0	896. 3	3428.5	497.3
Pct Carbonate Karst		11.5	0	89.2	13.7
Pct Volcanic Aquifers		2.7	0	42.5	5.1
Pct Unconsolidated Aquifers		19.9	0	100.0	24.4
Aquifer Richness		3.3	0	5	0.9
Mean Soil Bulk Density		1.5	1.4	1.6	0.03

Table 3.3. Topographic and landscape metrics used to calculate macro- and hydrorefugia for perennial water amphibian and reptile habitat. Values represent the number of HUC12 included, in addition to the mean, minimum, maximum and standard deviation values calculated for each HUC12. Shannon Diversity Index (SDI) calculated on 3x3 window.

	Count	Mean	Min	Max	STD
Macrorefugia	2,750				
Pct Change Precip Warmest Quarter (Bio18)		-3.3	-17.4	6.9	5.3
Pct Change Precip Coldest Quarter (Bio19)		-4.5	-23.1	47.0	8.3
Change Snow Water Equivalent (SWE)		-0.03	-2.3	0.5	0.3
Pct Change June Streamflow Volume		-4.0	-60.7	103.5	10.7
Backwards Climate Velocity		1.2	0.04	6. 1	0.8
Diff Mean Temp Wettest Quarter (Bio8)		2.4	1.0	4.4	0.4
Diff Mean Temp Driest Quarter (Bio9)		2.4	1.1	5.1	0.8
Diff Max Temp Warmest Month (Bio5)		2.9	1.5	4.1	0.5
Change Evapotranspiration (ET)		-0.2	-0.6	0.02	0.1
Hydrorefugia	2,750				
Mean Riparian Canopy Height		2.0	0	29.9	4.1
Pct Marsh/Wet Meadow Vegetation		0.2	0	13.9	0.8
Pct Stream Buffer with Tree Canopy		7.6	0	47.7	10.1
Mean Soil Water Storage		0.2	0.001	1. 5	0.2
Mean Compound Topographic Index		9.3	6.6	17.0	1.2
Mean Elevation		1817.3	896.3	3428.5	430.6
Mean SDI for Aspect		0.6	0.2	1.3	0.1
Mean SDI for Geomorphology		0.4	0.1	0.6	0.03
Pct Carbonate Karst		12.6	0	89.2	17.6
Mean Heat Load Index		0.8	0.7	0.9	0.03
Mean Soil Bulk Density		1.5	1.3	1.6	0.05

Table 3.4. Topographic and landscape metrics used to calculate macro- and hydrorefugia for ephemeral catchments. Values represent the number of HUC12 included, in addition to the mean, minimum, maximum and standard deviation values calculated for each HUC12. Shannon Diversity Index (SDI) calculated on 3x3 window.

	Count	Mean	Min	Max	STD
Macrorefugia	3,177				
Pct Change Precip Driest Month (Bio14)		-11.0	-69.3	55.3	11.0
Pct Change Precip Warmest Quarter (Bio18)		-3.7	-41.5	11.6	6.2
Change Soil Moisture Content (SMC)		-0.08	-10.9	6.7	1.4
Backwards Climate Velocity		1.3	0.04	6.1	0.8
Diff Mean Temp Driest Quarter (Bio9)		2.3	-2.5	8.2	1.2
Diff Max Temp Warmest Month (Bio5)		2.9	0.5	5.4	0.6
Change Evapotranspiration (ET)		-0.2	-1.4	0. 2	0.1
Hydrorefugia	3,177				
Mean Compound Topographic Index		9.5	6.6	17.6	1.4
Mean SDI for Aspect		0.6	0.2	1.3	0.1
Mean SDI for Geomorphology		0.4	0.03	0.7	0.05
Mean Heat Load Index		0.8	0.7	0.9	0.03
Pct Slow-Infiltrating Soils		51.6	0	100	36.4

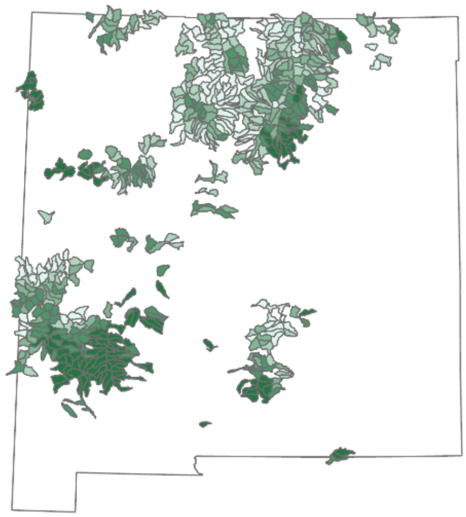
Table 3.5. Topographic and landscape metrics used to calculate macro- and hydrorefugia for springs. Values represent the number of HUC12 included, in addition to the mean, minimum, maximum and standard deviation values calculated for each HUC12. Shannon Diversity Index (SDI) calculated on 3x3 window.

	Count	Mean	Min	Max	STD
Macrorefugia	3,168				
Pct Change Precip Coldest Quarter (Bio19)		-4.7	-23.1	47.0	8.2
Change Snow Water Equivalent (SWE)		-0.02	-2.3	0.5	0.3
Diff Mean Temp Wettest Quarter (Bio8)		2.4	1.0	4.4	0.4
Diff Mean Temp Driest Quarter (Bio9)		2.3	1.1	5.1	0.8
Change Potential Evapotranspiration of Natural Vegetation (PNV)		-0.7	-1.6	0.01	0.4
Hydrorefugia	3,168				
Mean Vector Ruggedness		0.002	0	0.02	0.002
Pct Carbonate Karst		12.0	0	89.2	16.9
Pct Volcanic Aquifers		2.2	0	42.5	5.5
Aquifer Richness		3.1	0	5	1.0
Mean Heat Load Index		0.8	0.7	0.9	0.03
Mean Soil Bulk Density		1.5	1.4	1.6	0.03

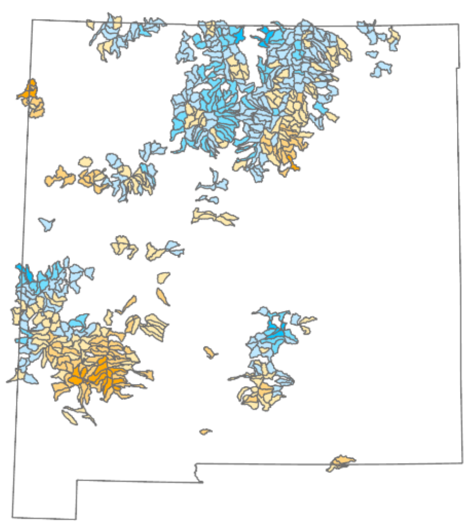
Supplemental 4. Distribution of Final Variables and Corresponding Z-Scores

Macrorefugia Variables

Cold-Water Fish Habitat

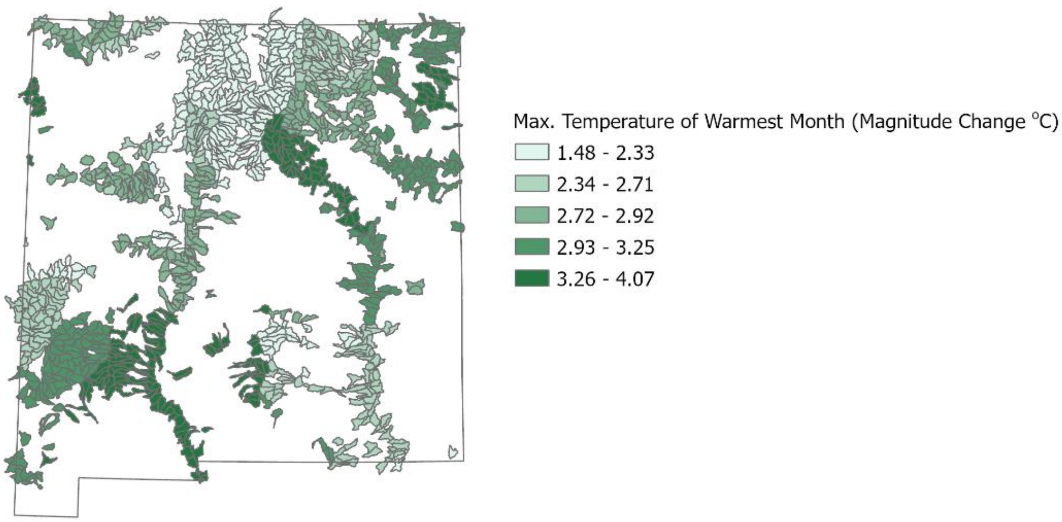


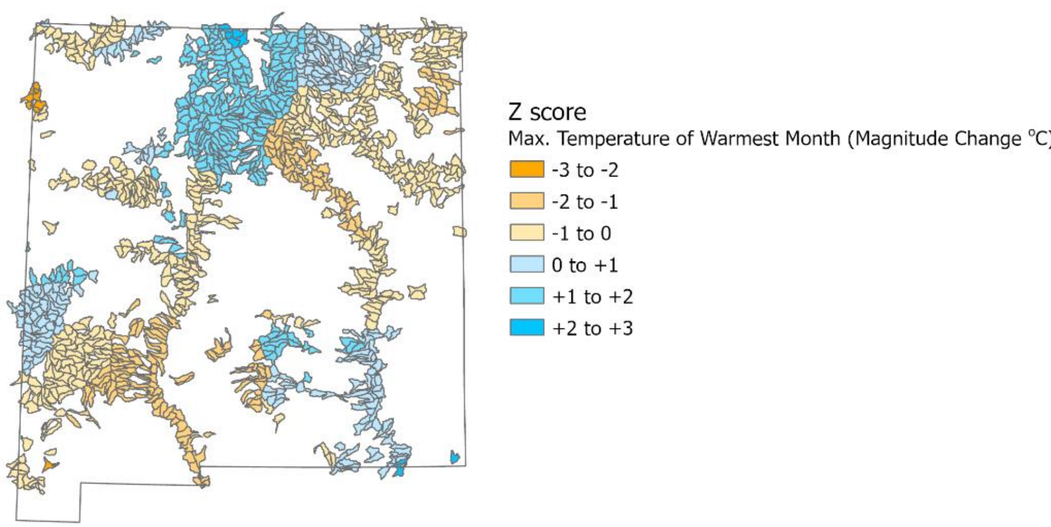
Max. Temperature of Warmest Month (Magnitude Change °C)
- 0.70 - 2.16
- 2.17 - 2.51
- 2.52 - 2.89
- 2.90 - 3.45
- 3.46 - 4.81



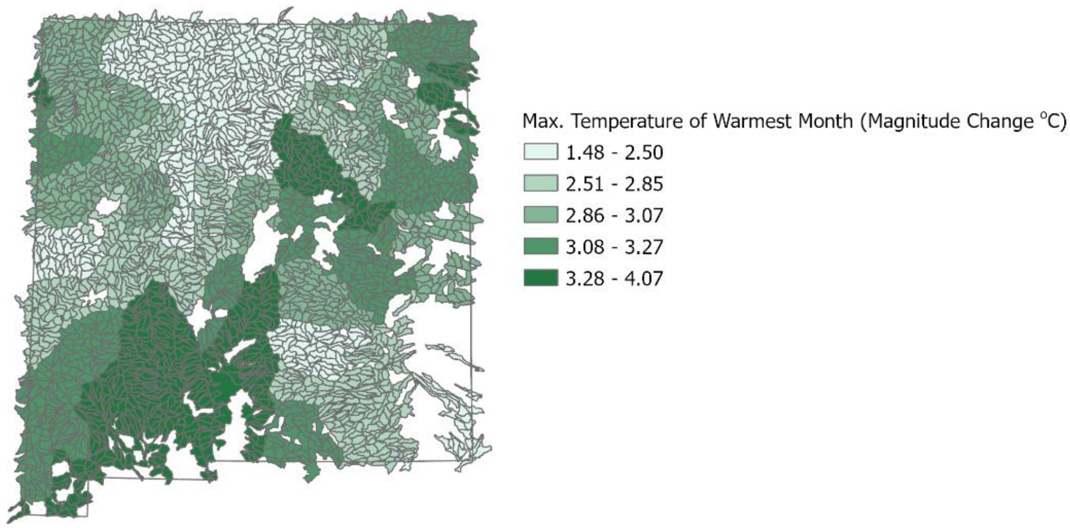
Z score
Max. Temperature of Warmest Month (Magnitude Change °C)
- -3 to -2
- -2 to -1
- -1 to 0
- 0 to +1
- +1 to +2
- +2 to +3

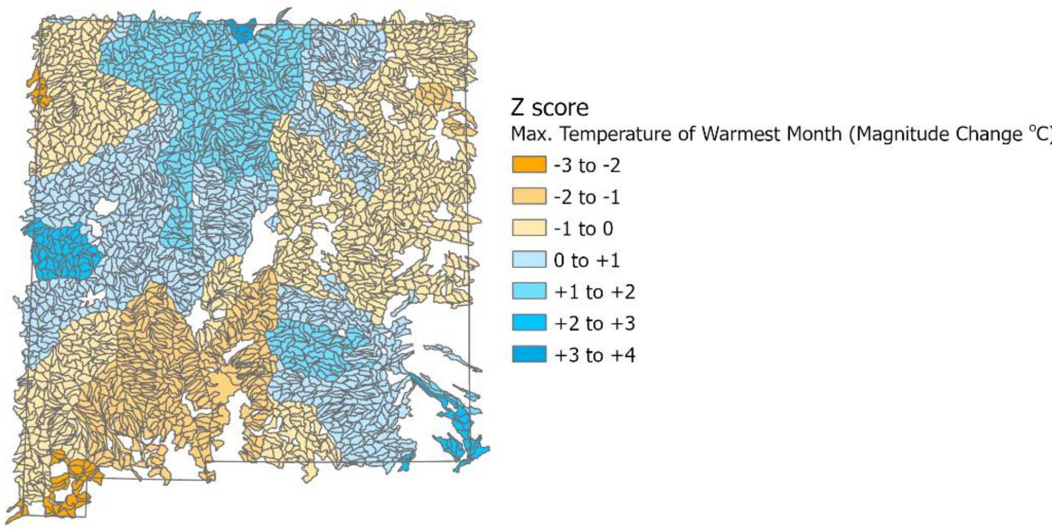
Perennial Streams



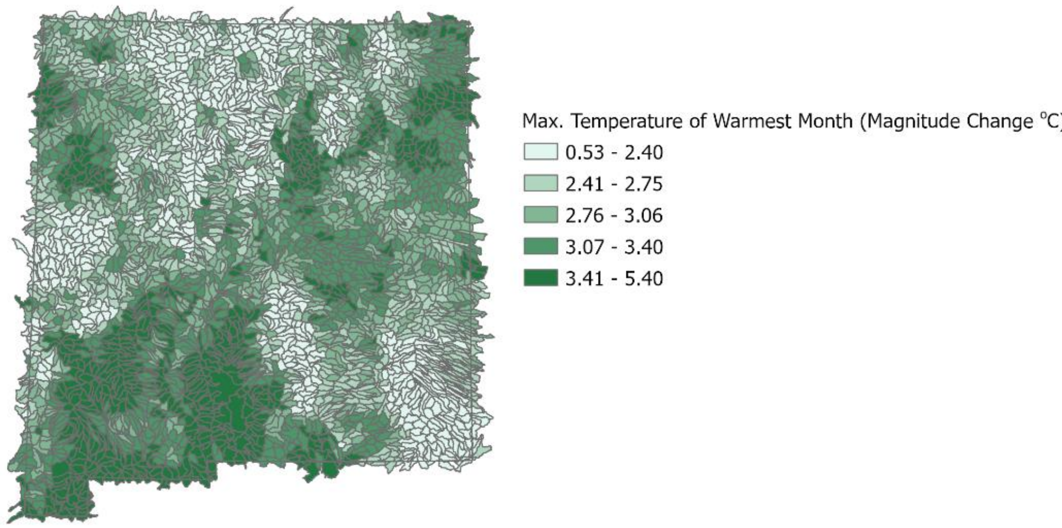


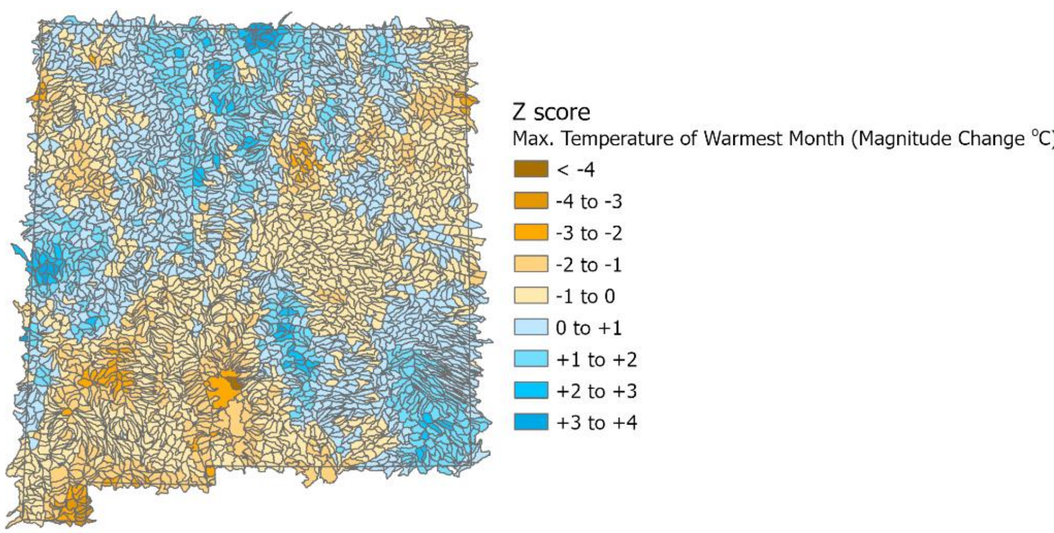
Amphibian and Reptile Habitat



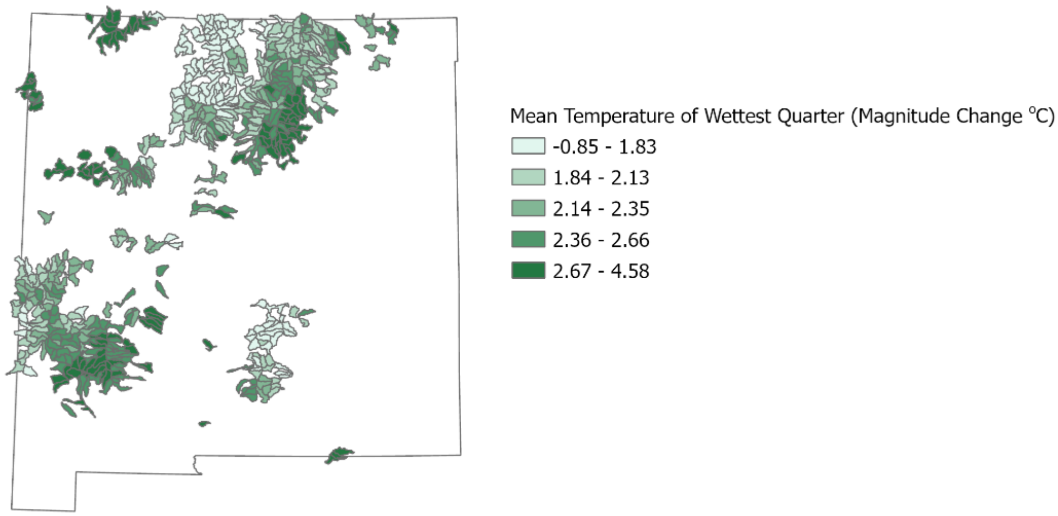


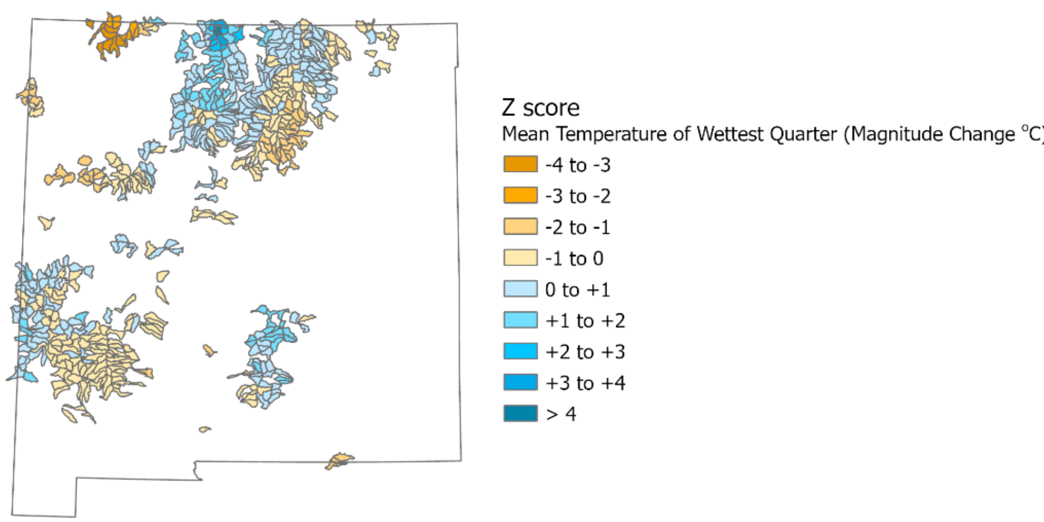
Ephemeral Catchments



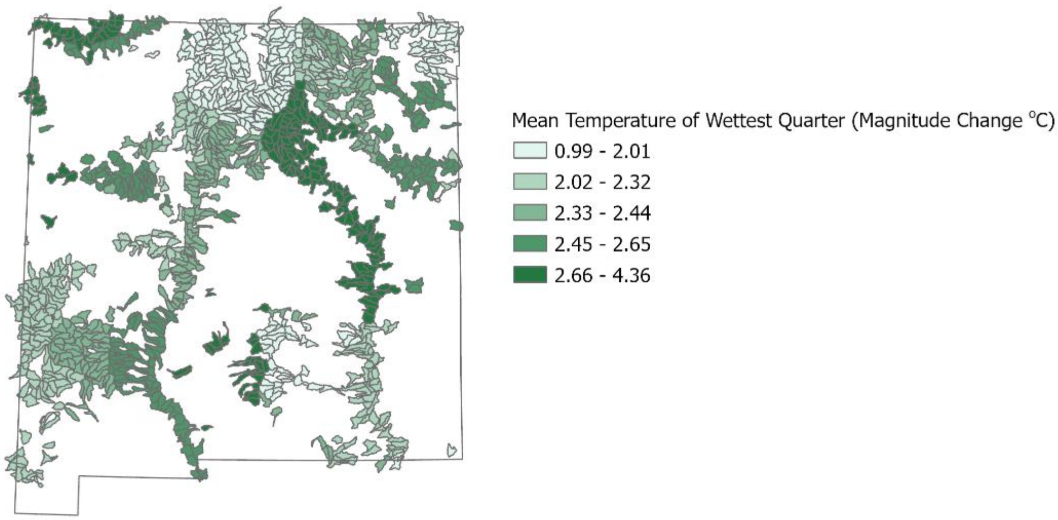


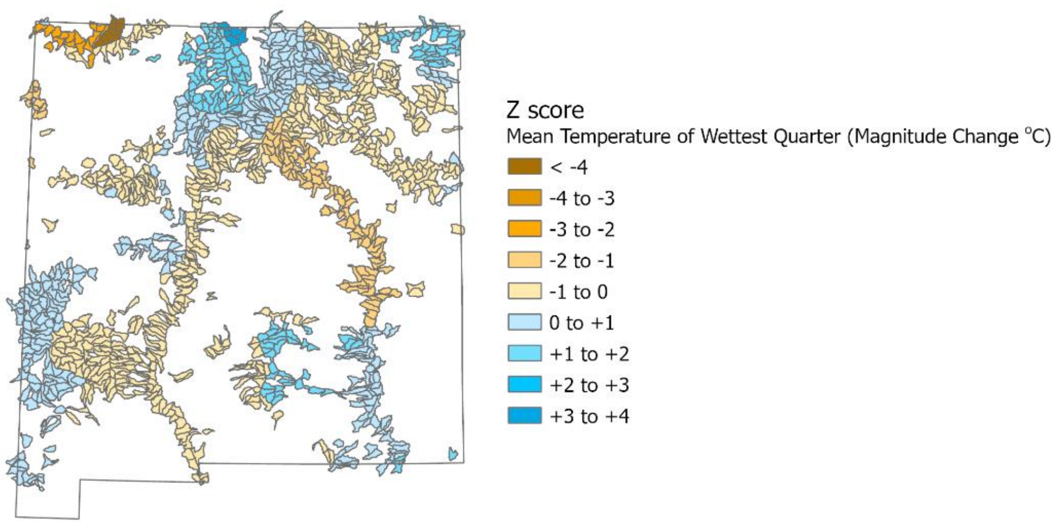
Cold-Water Fish Habitat



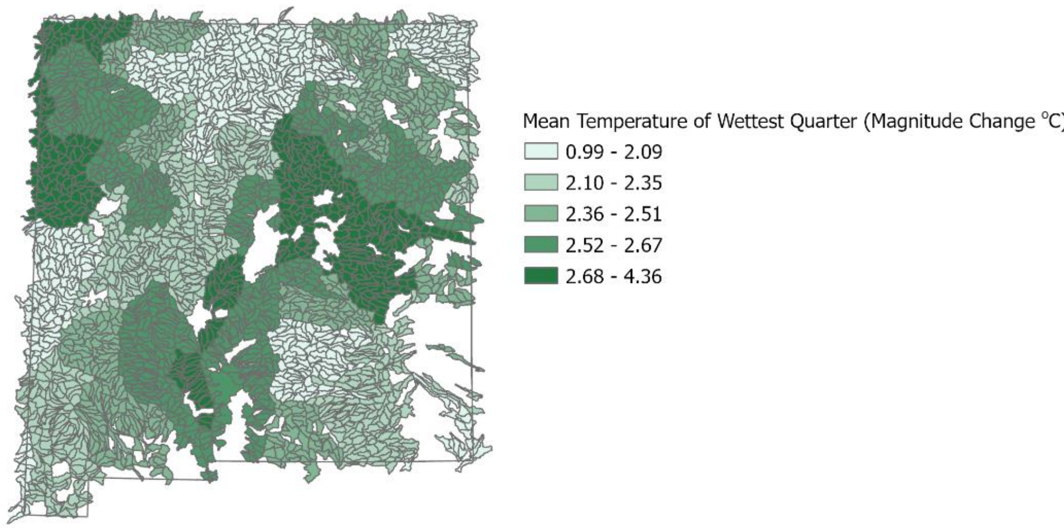


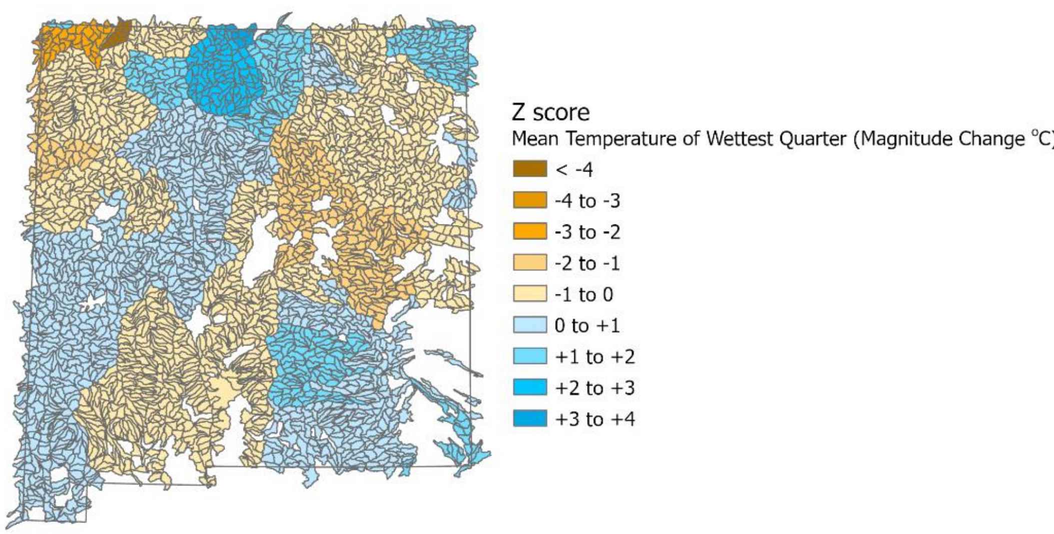
Perennial Streams



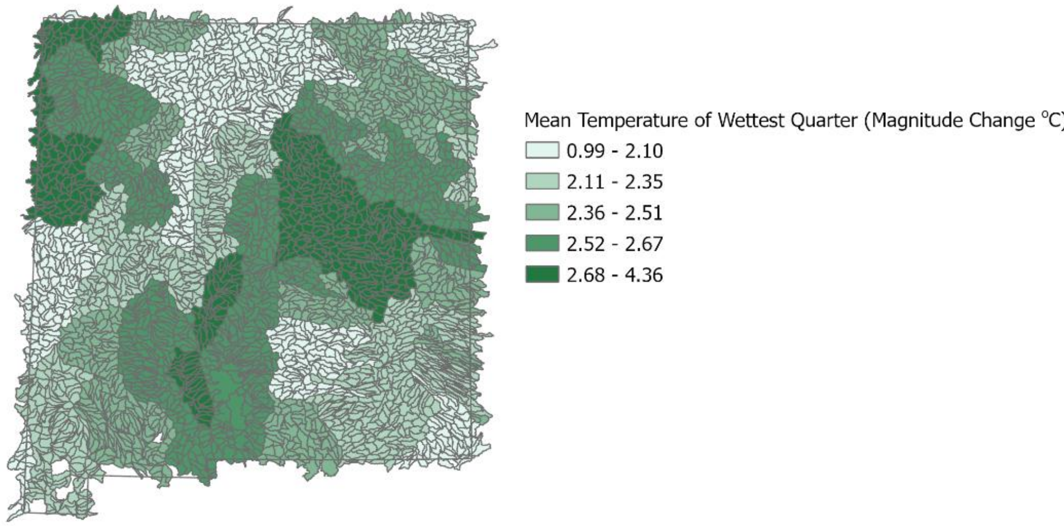


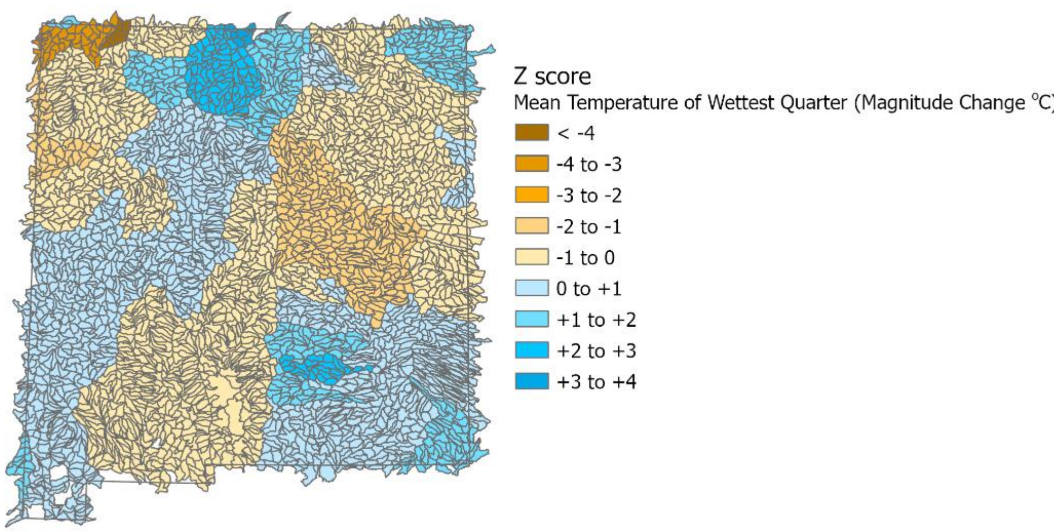
Amphibian and Reptile Habitat



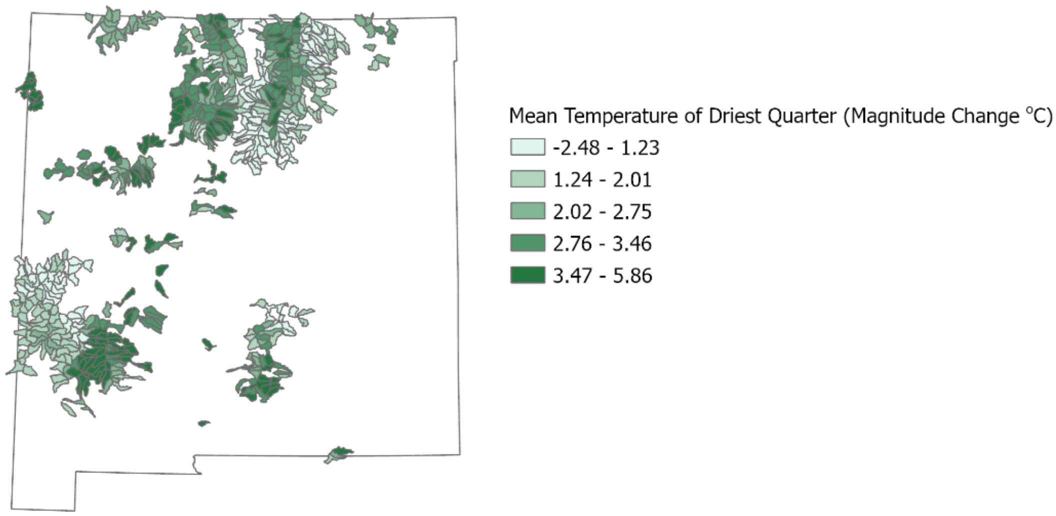


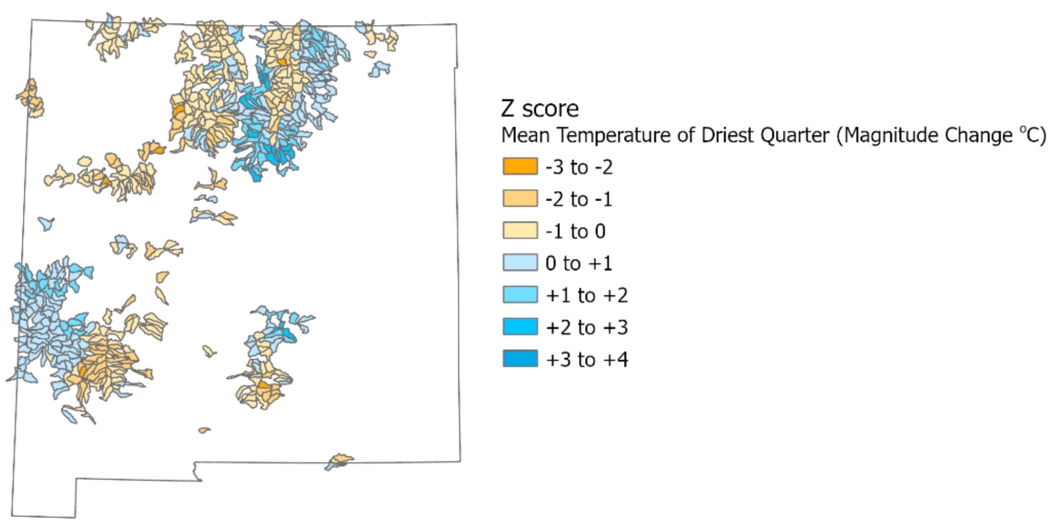
Springs


Mean Temperature of Wettest Quarter (Magnitude Change °C)
0.99 - 2.10
2.11 - 2.35
2.36 - 2.51
2.52 - 2.67
2.68 - 4.36

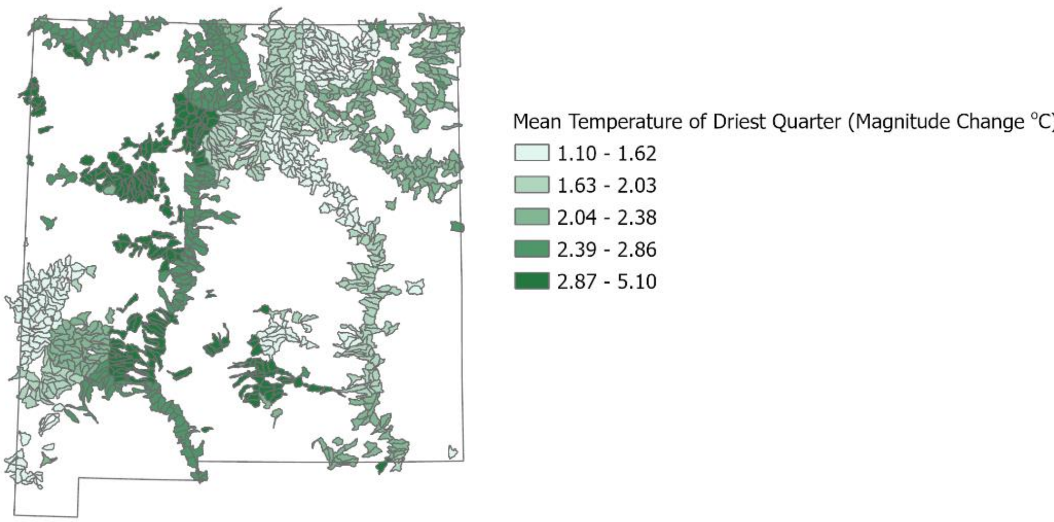

Z score
Mean Temperature of Wettest Quarter (Magnitude Change °C)
< -4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4

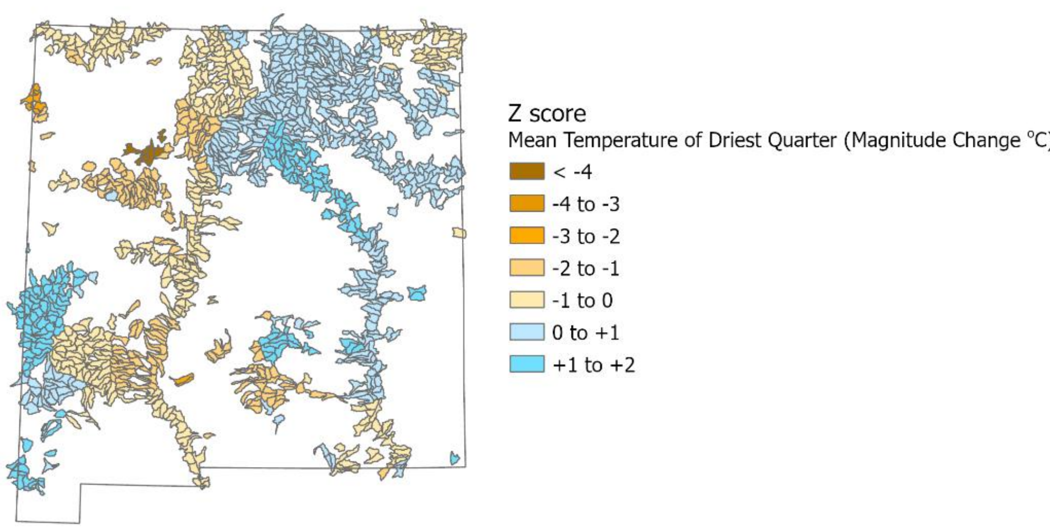
Cold-Water Fish Habitat



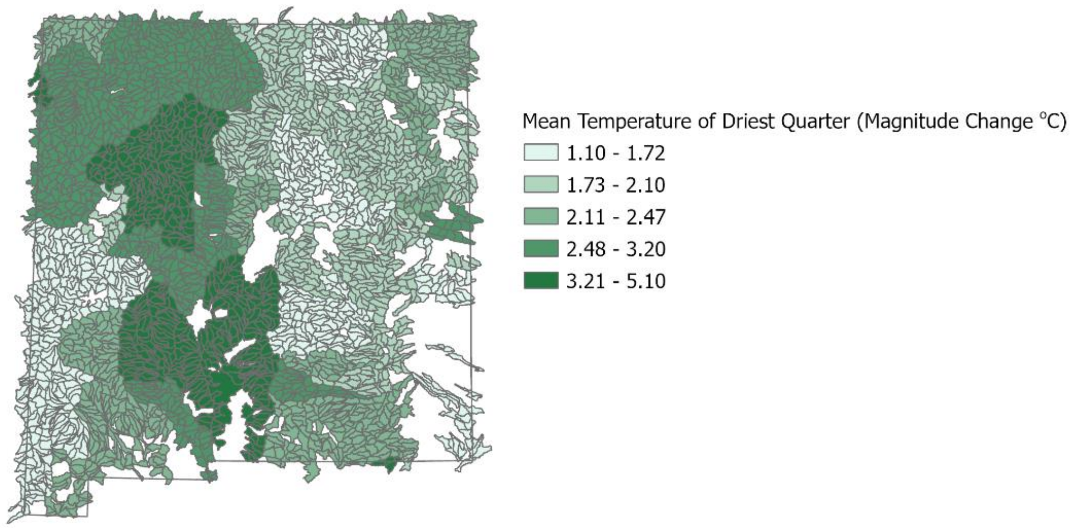


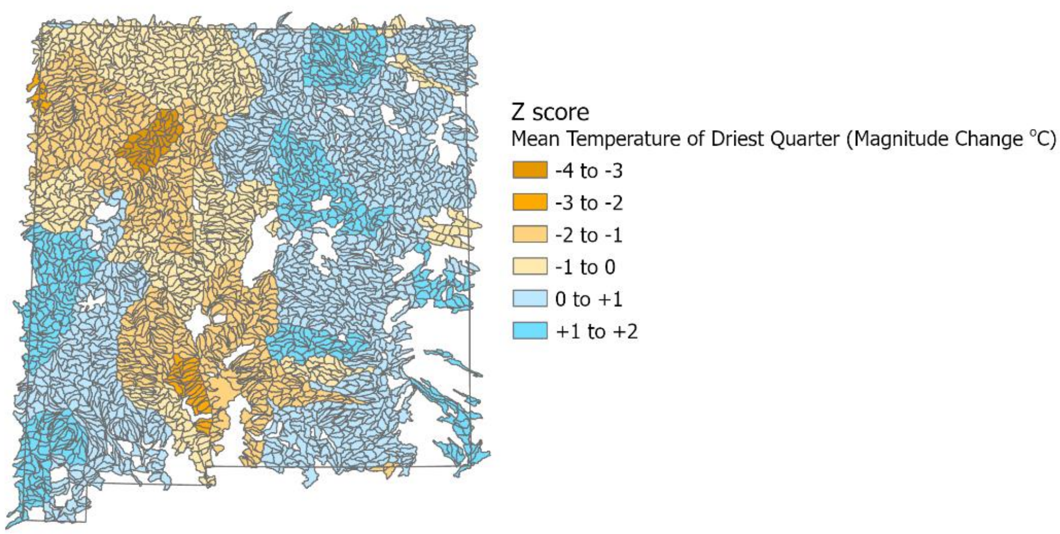
Perennial Streams



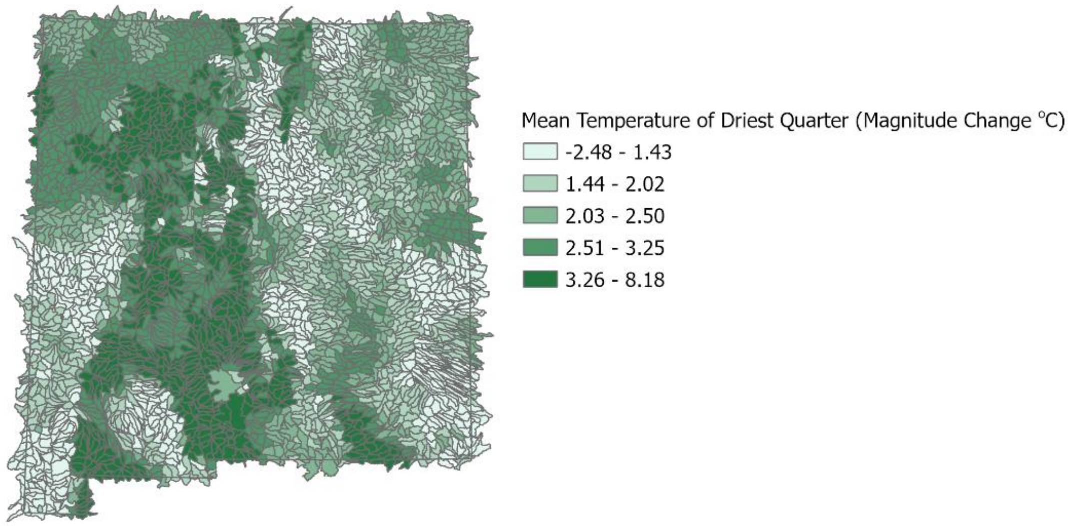


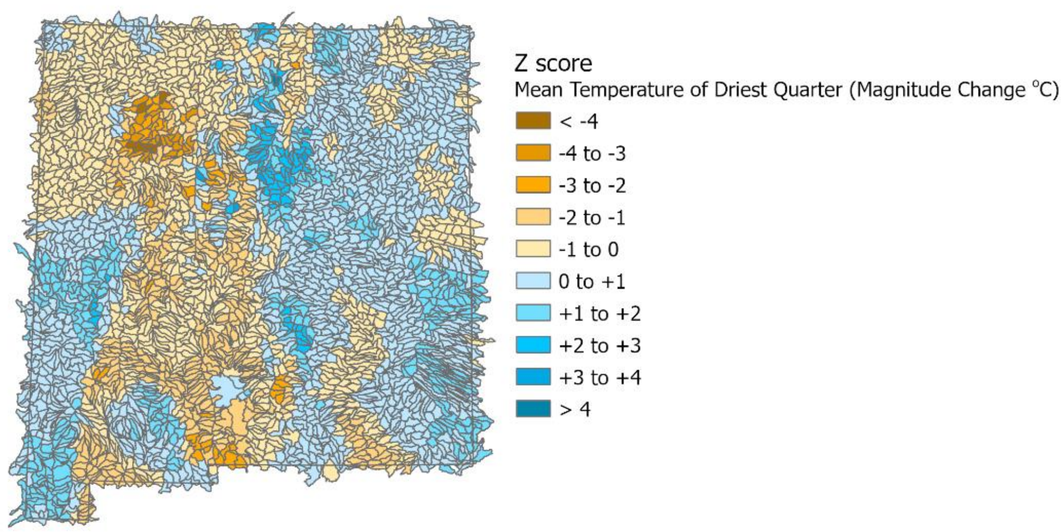
Amphibian and Reptile Habitat



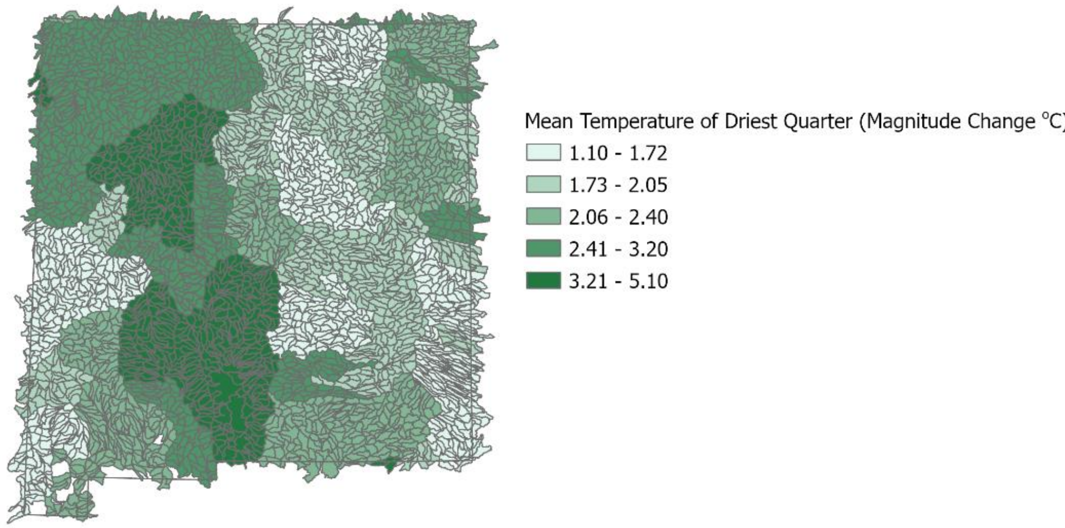


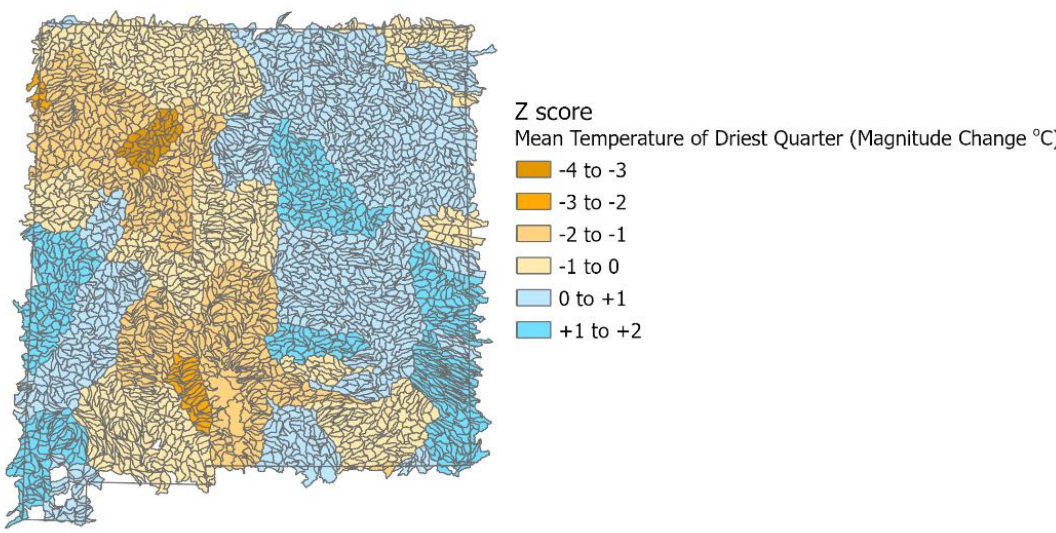
Ephemeral Catchments



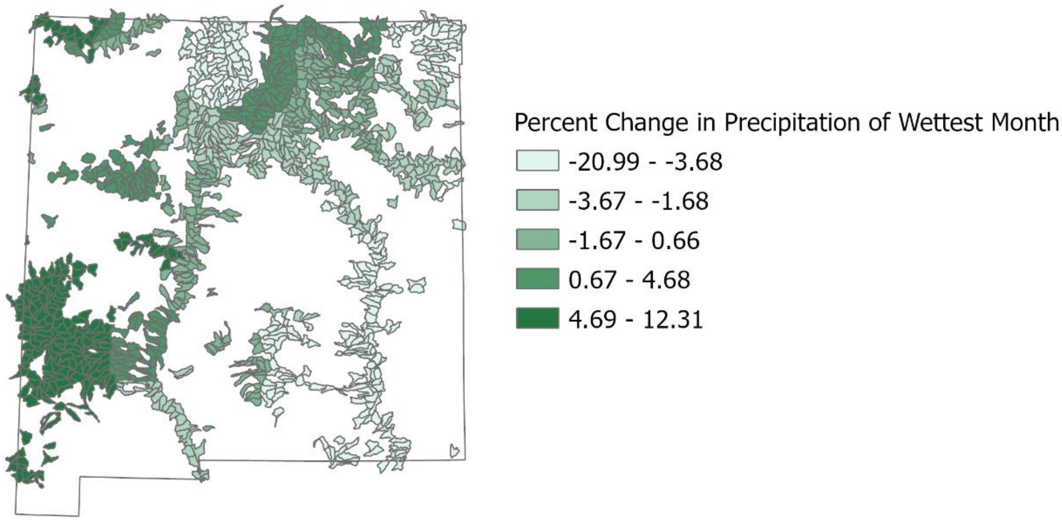


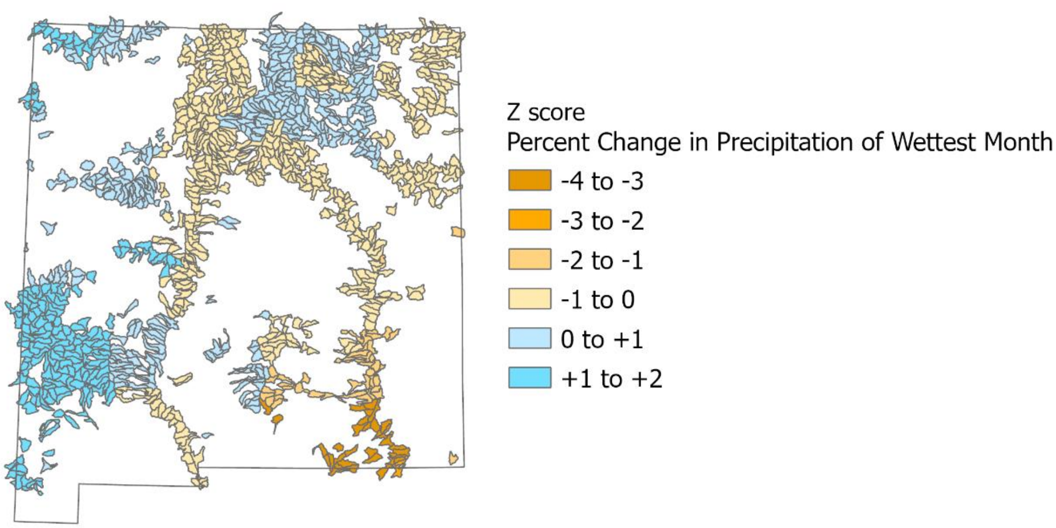
Springs


Mean Temperature of Driest Quarter (Magnitude Change °C)
1.10 - 1.72
1.73 - 2.05
2.06 - 2.40
2.41 - 3.20
3.21 - 5.10

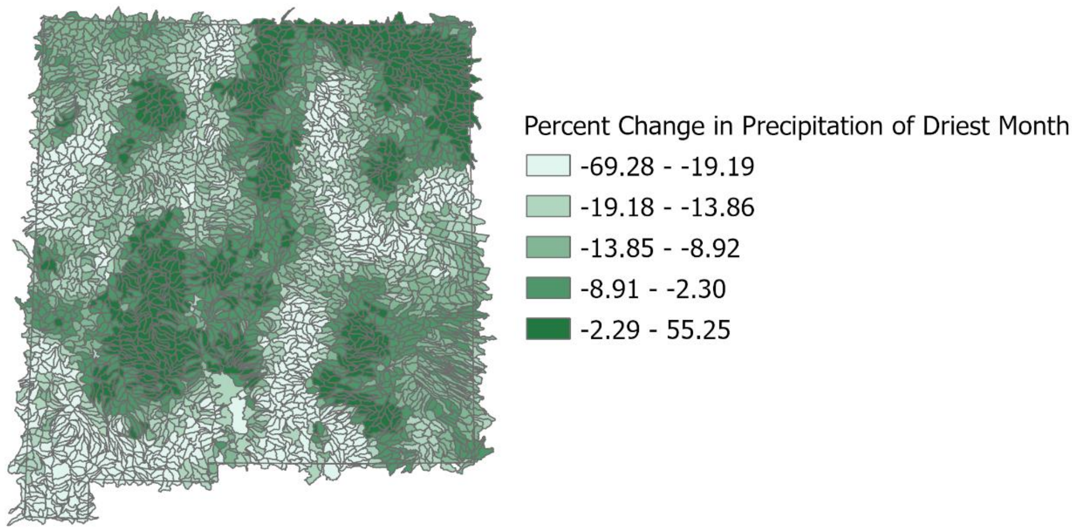

Z score
Mean Temperature of Driest Quarter (Magnitude Change °C)
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2

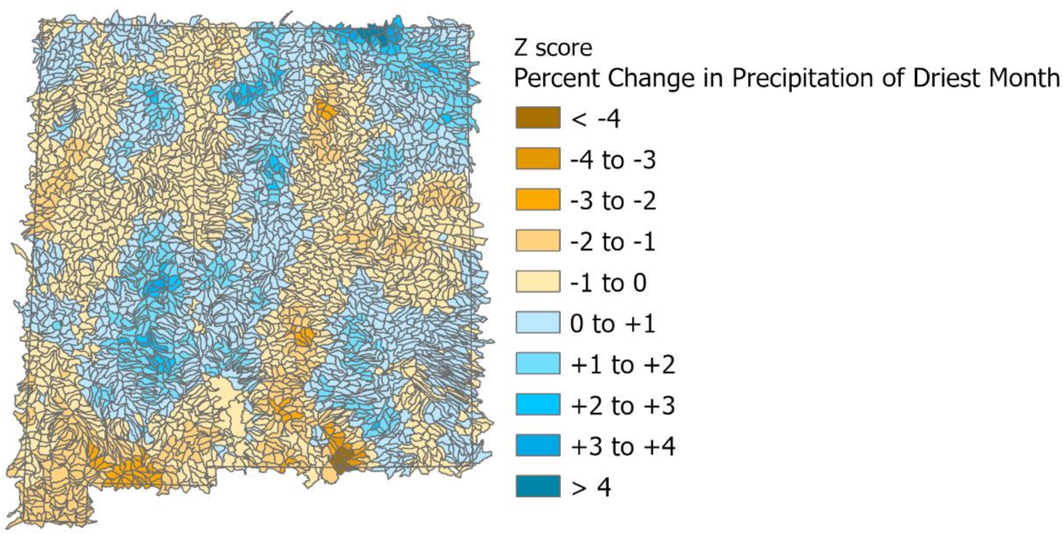
Perennial Streams



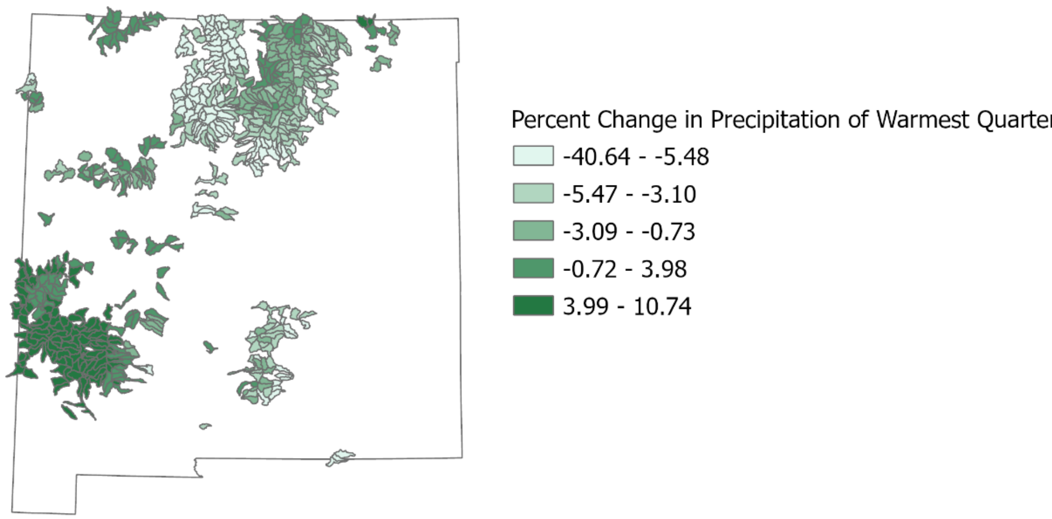


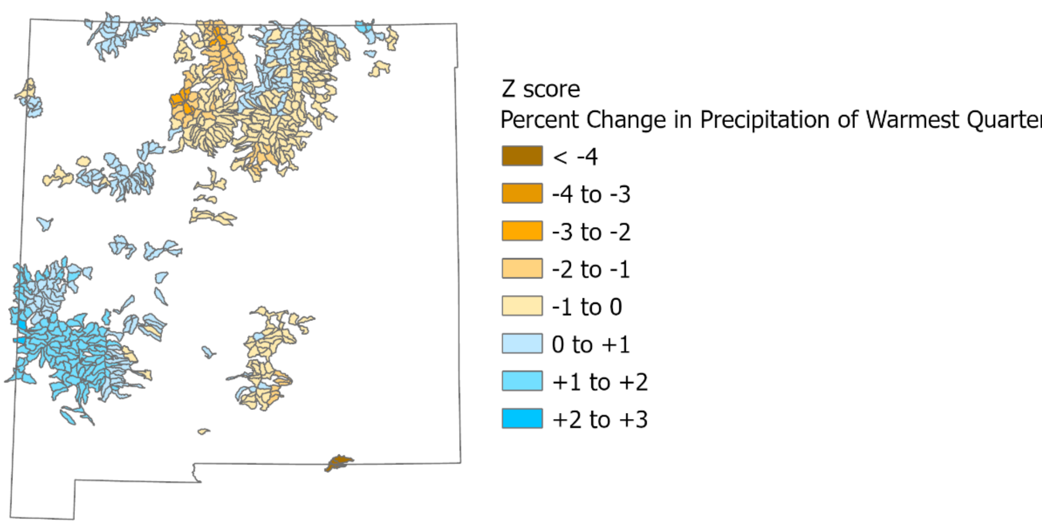
Ephemeral Catchments



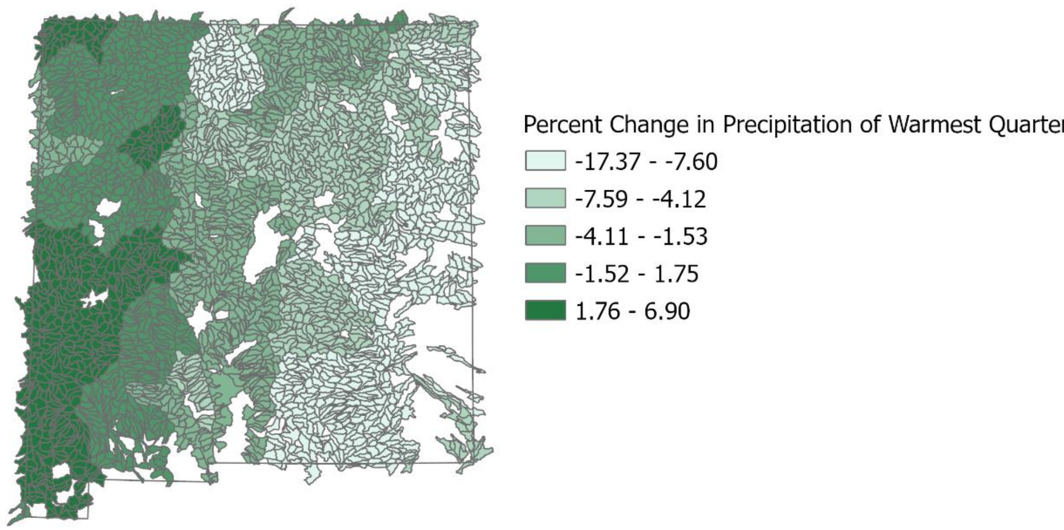


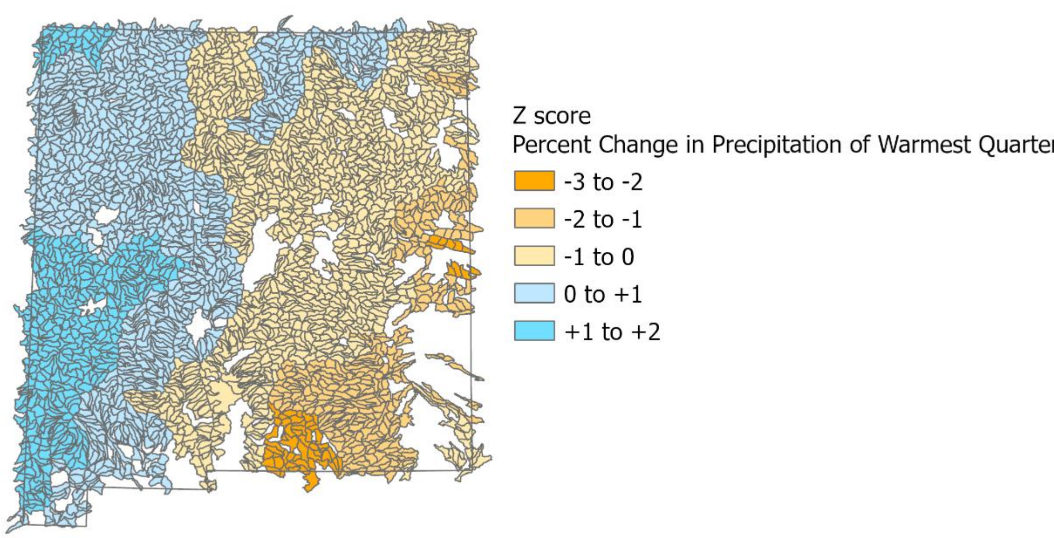
Cold-Water Fish Habitat



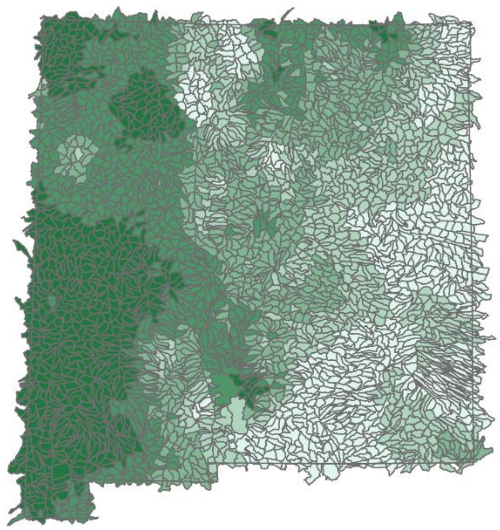


Amphibian and Reptile Habitat

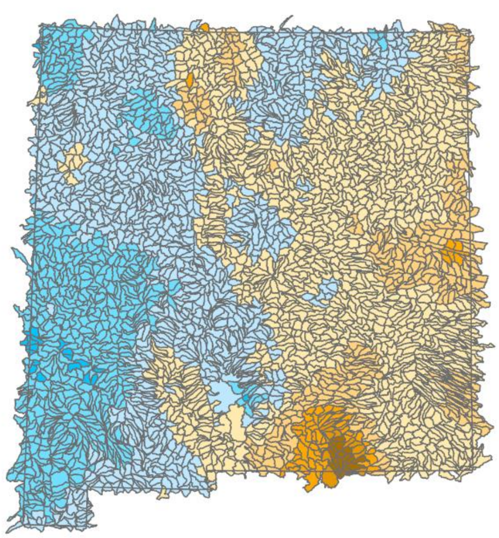




Ephemeral Catchments

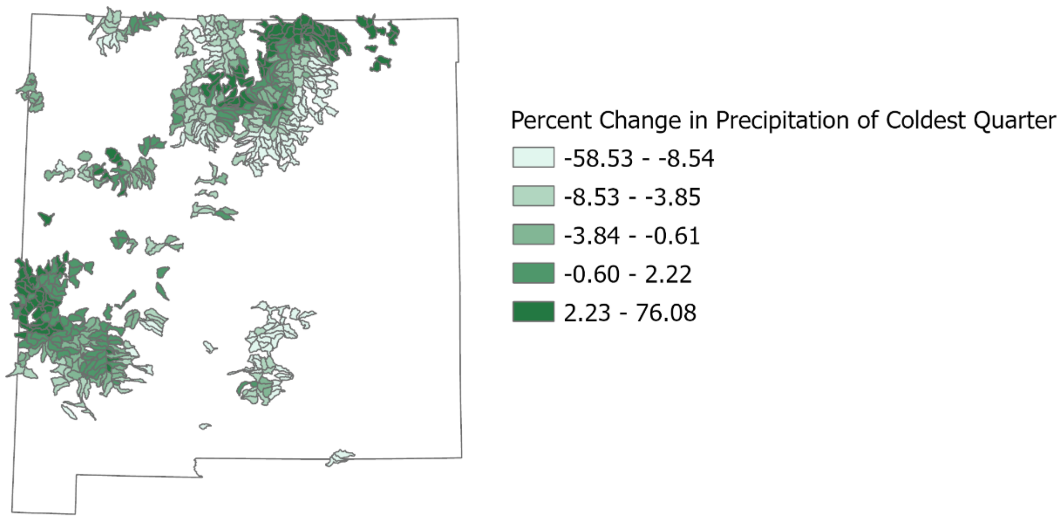


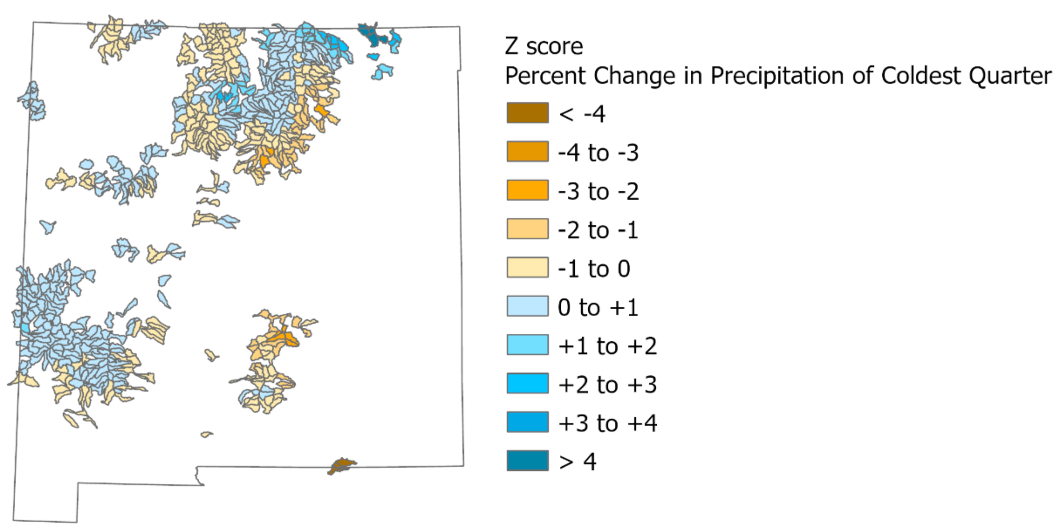
Percent Change in Precipitation of Warmest Quarter
- -41.47 - -8.36
- -8.35 - -5.18
- -5.17 - -2.20
- -2.19 - 1.74
- 1.75 - 11.59



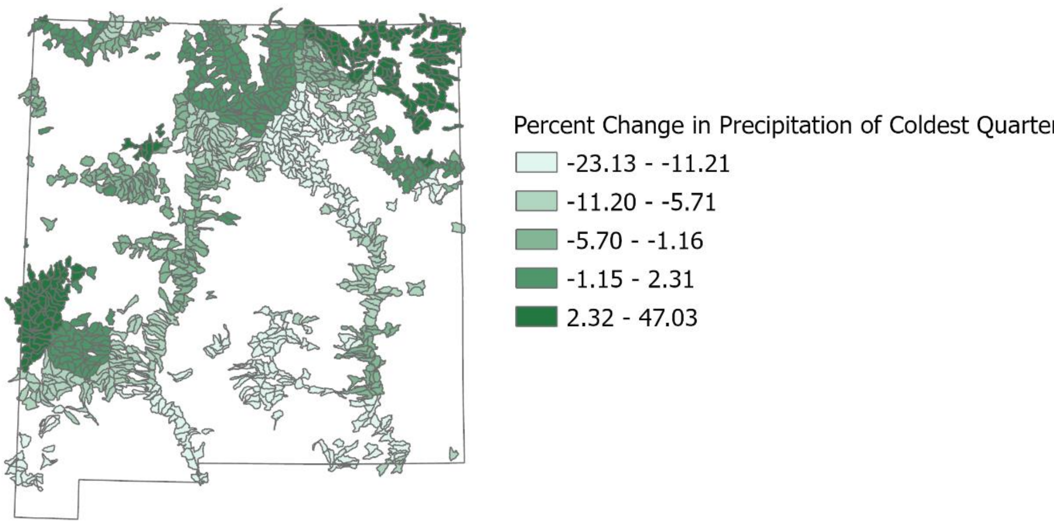
Z score
Percent Change in Precipitation of Warmest Quarter
- < -4
- -4 to -3
- -3 to -2
- -2 to -1
- -1 to 0
- 0 to +1
- +1 to +2
- +2 to +3

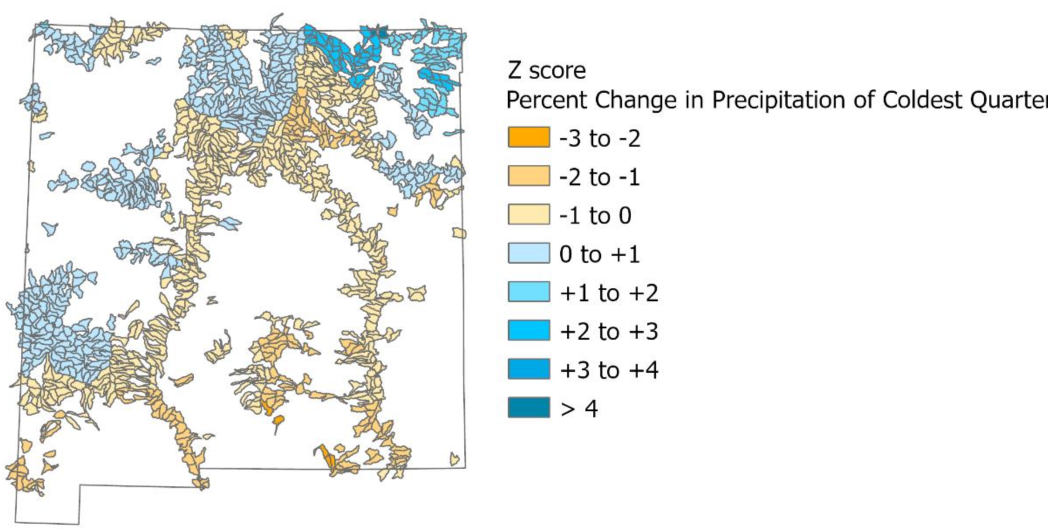
Cold-Water Fish Habitat



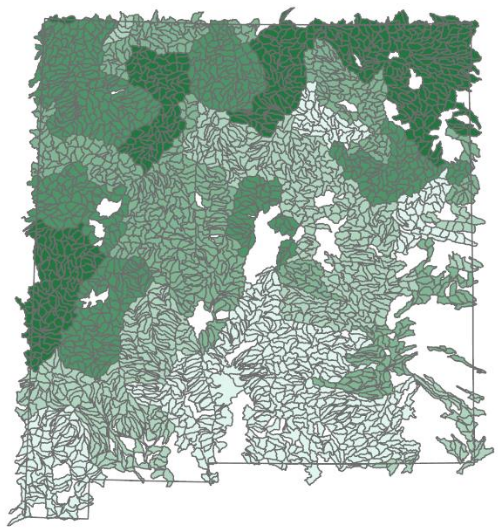


Perennial Streams



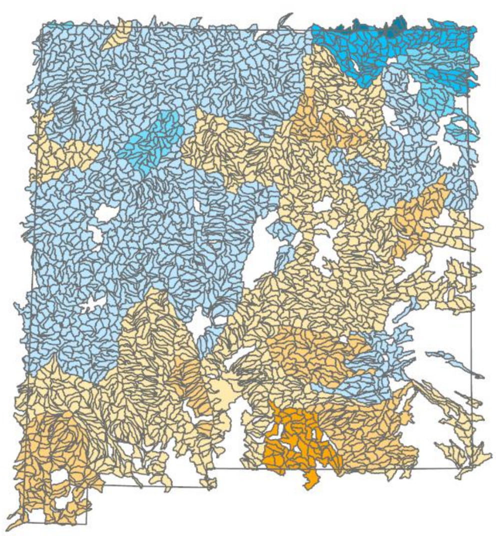


Amphibian and Reptile Habitat



Percent Change in Precipitation of Coldest Quarter

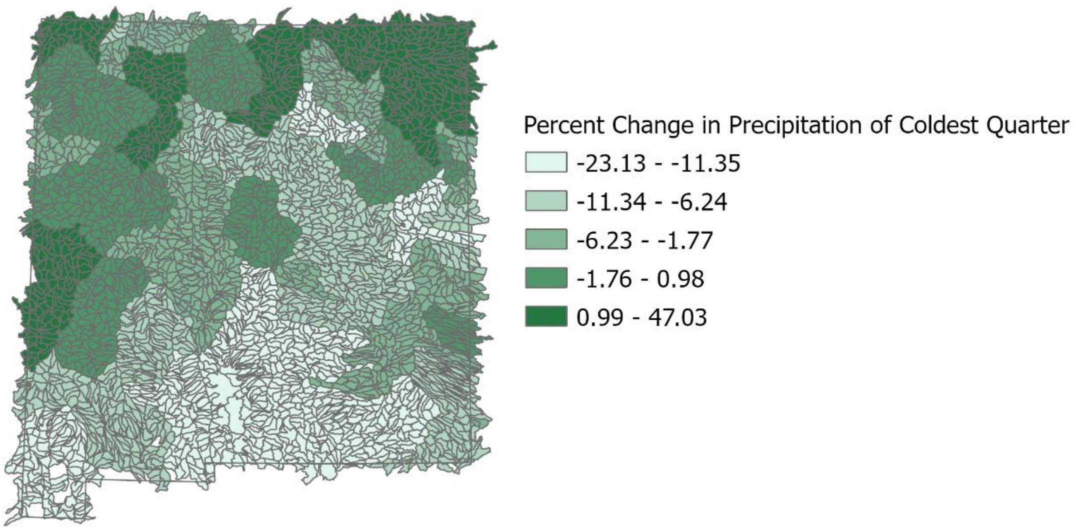
- -23.13 - -11.35
- -11.34 - -6.24
- -6.23 - -1.66
- -1.65 - 1.49
- 1.50 - 47.03

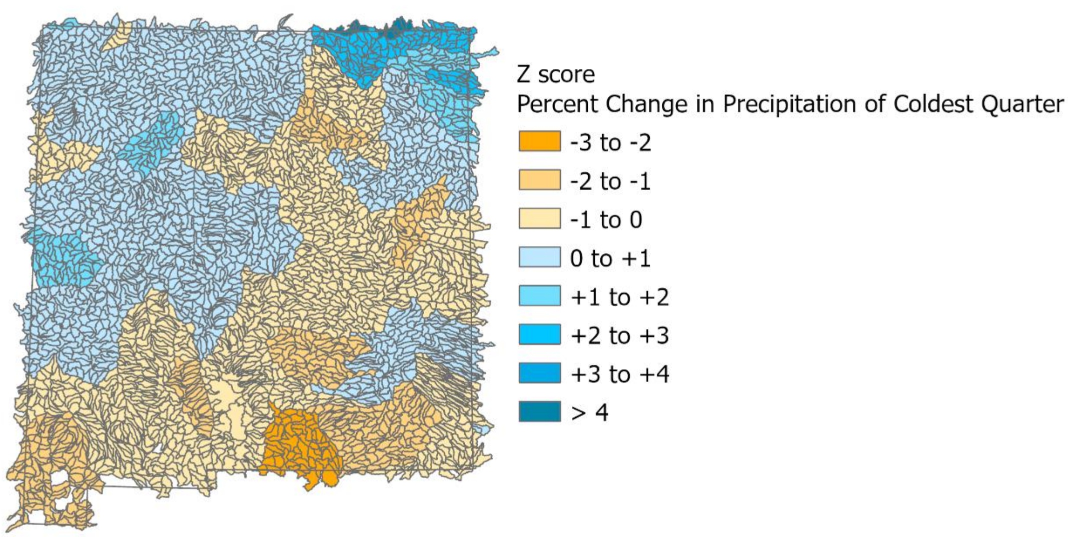


Z score
Percent Change in Precipitation of Coldest Quarter

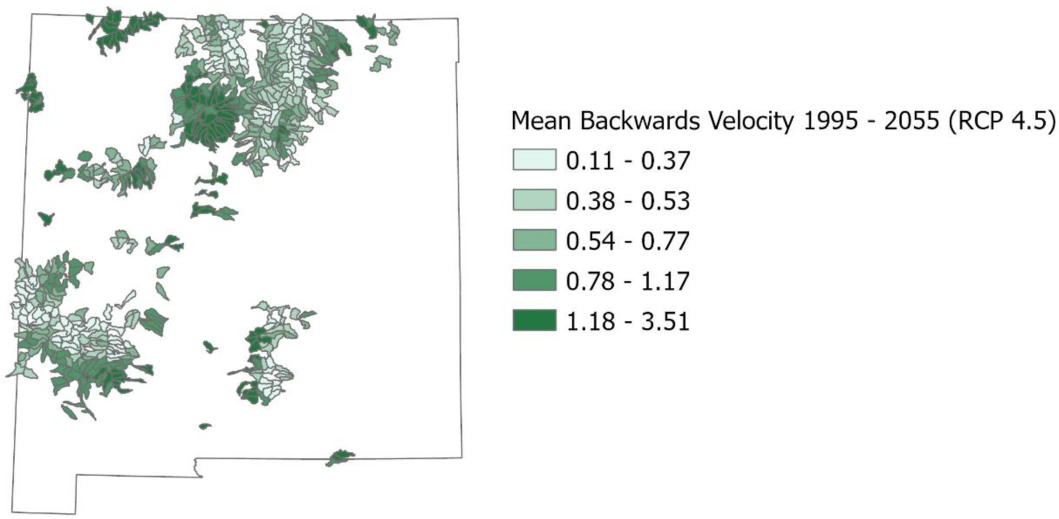
- -3 to -2
- -2 to -1
- -1 to 0
- 0 to +1
- +1 to +2
- +2 to +3
- +3 to +4
- > 4

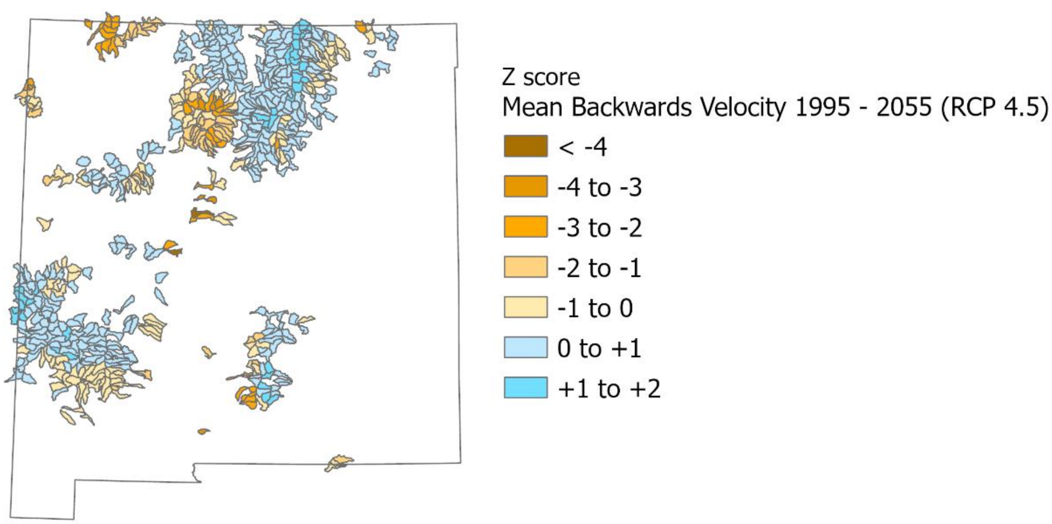
Springs


Percent Change in Precipitation of Coldest Quarter
-23.13 - -11.35
-11.34 - -6.24
-6.23 - -1.77
-1.76 - 0.98
0.99 - 47.03

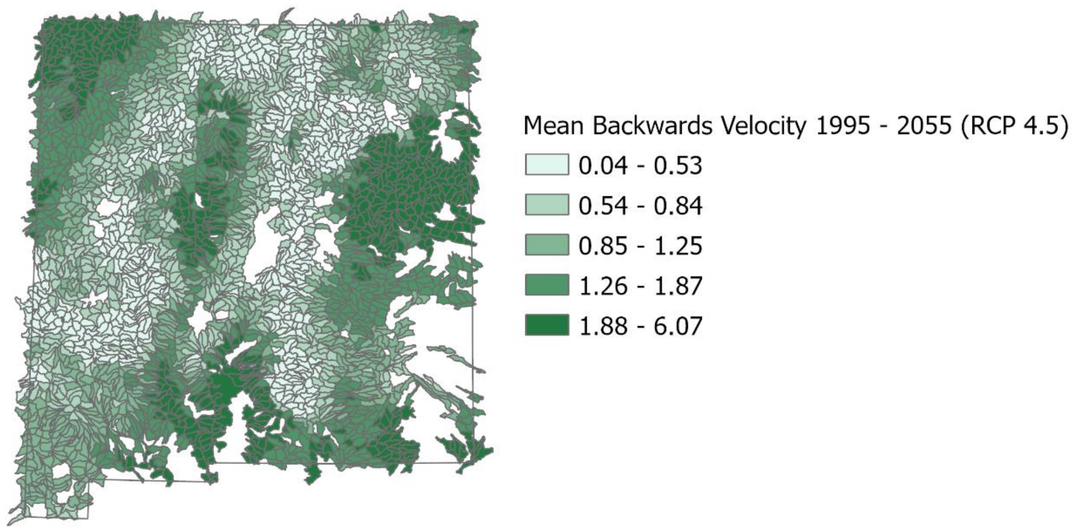

Z score
Percent Change in Precipitation of Coldest Quarter
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
> 4

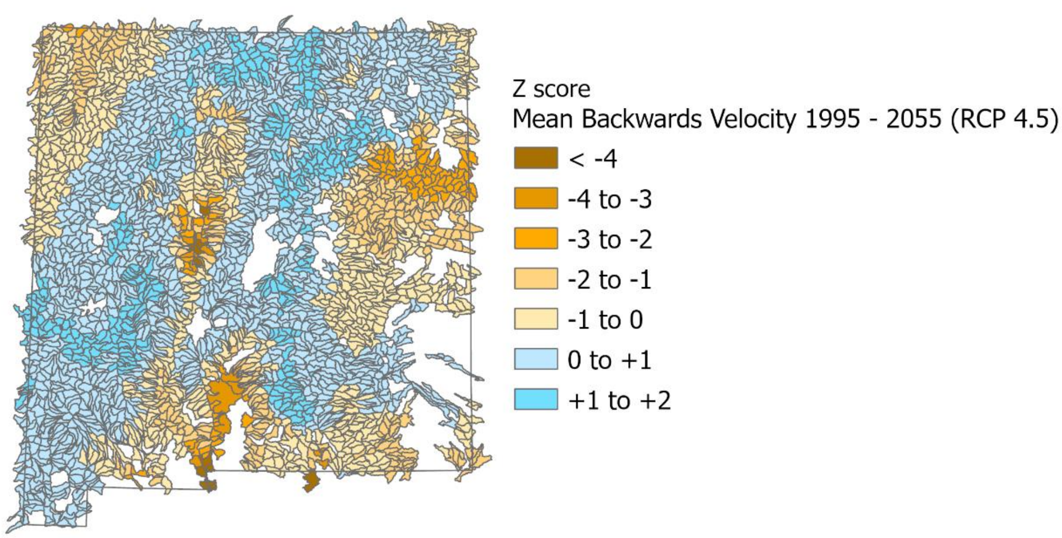
Cold-Water Fish Habitat



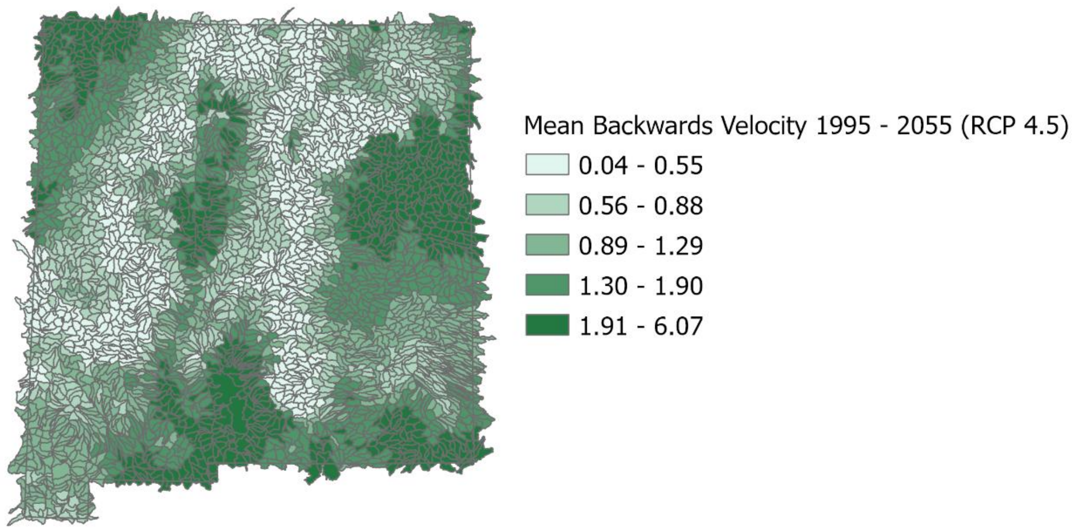


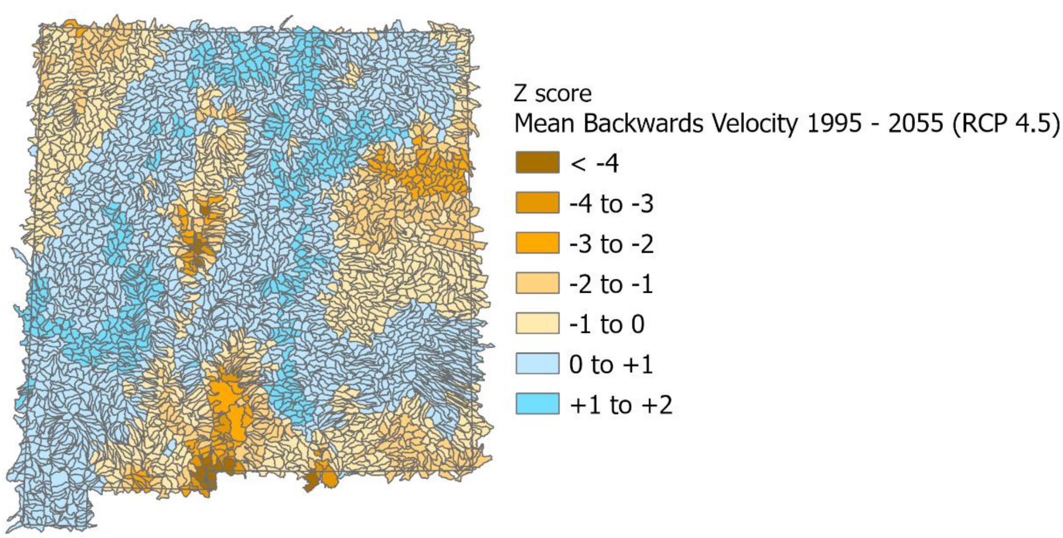
Amphibian and Reptile Habitat



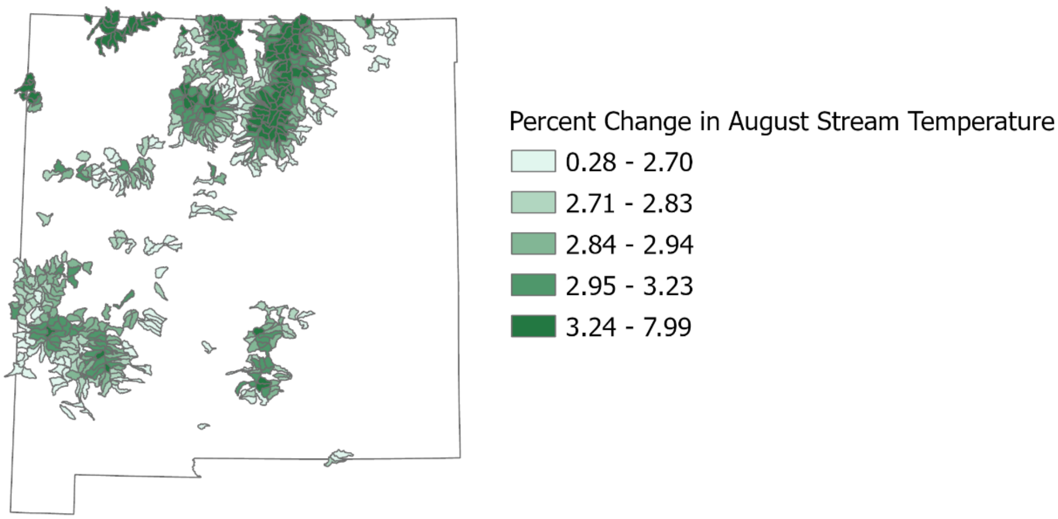


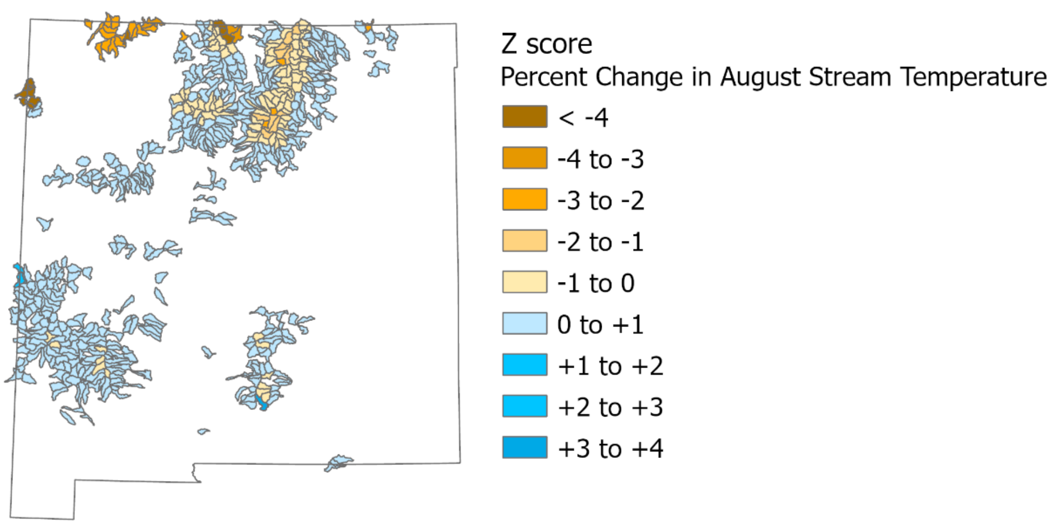
Ephemeral Catchments



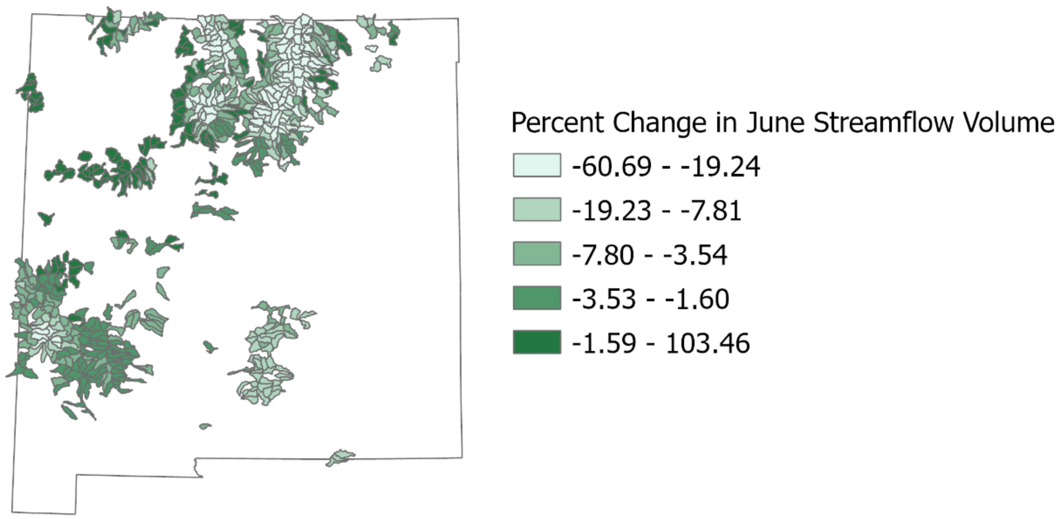


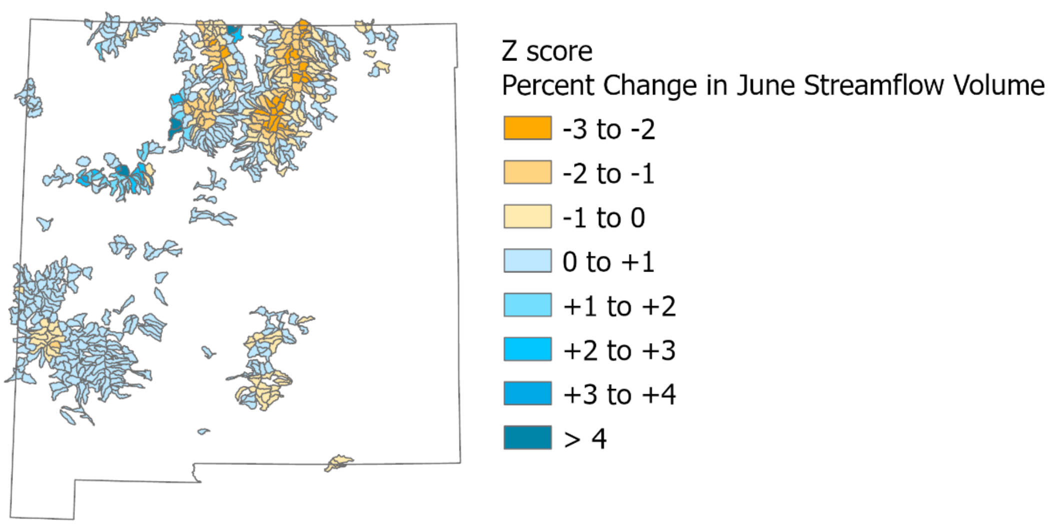
Cold-Water Fish Habitat



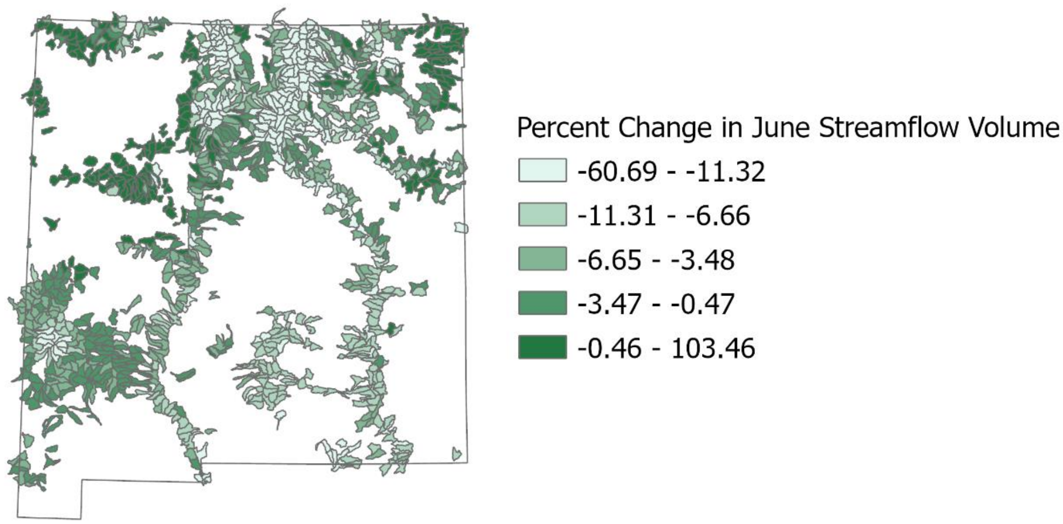


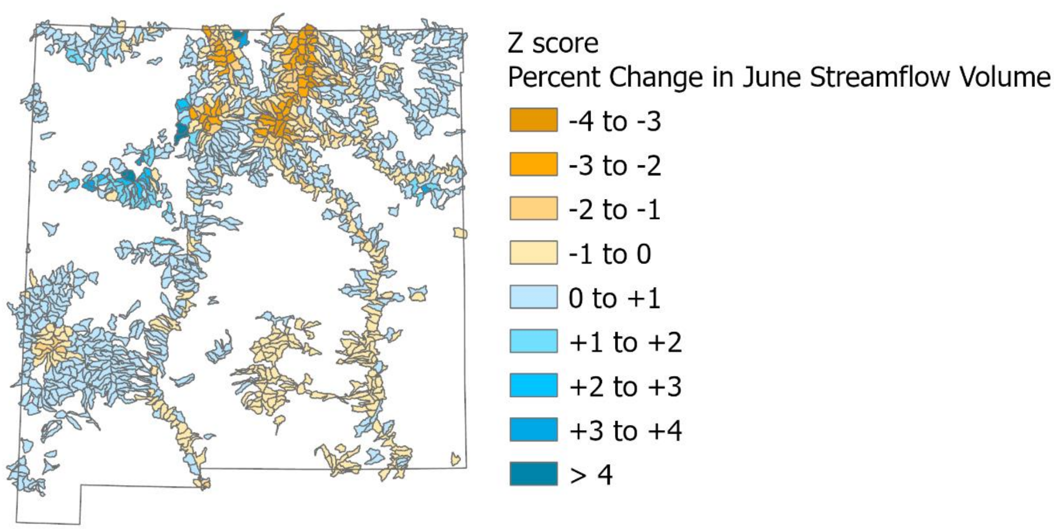
Cold-Water Fish Habitat



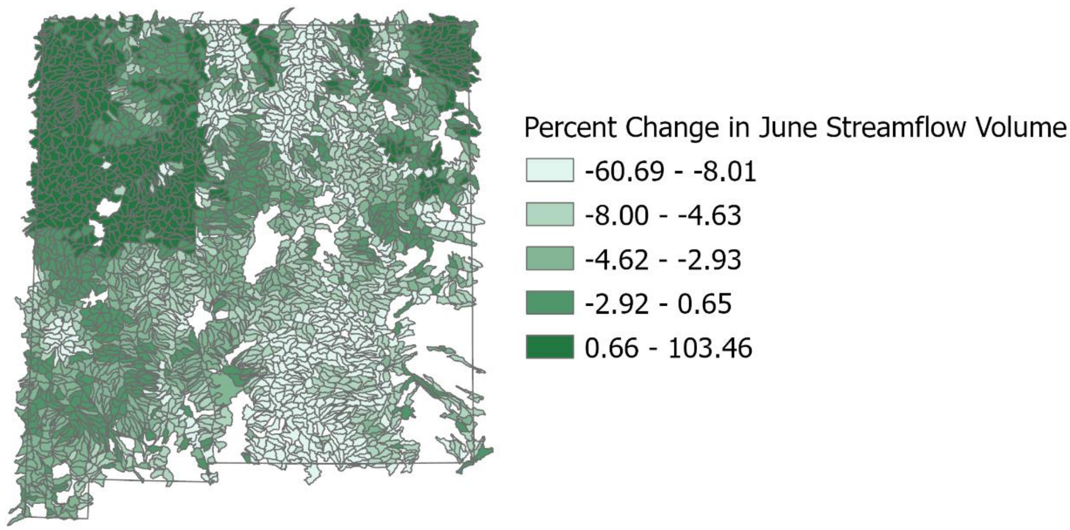


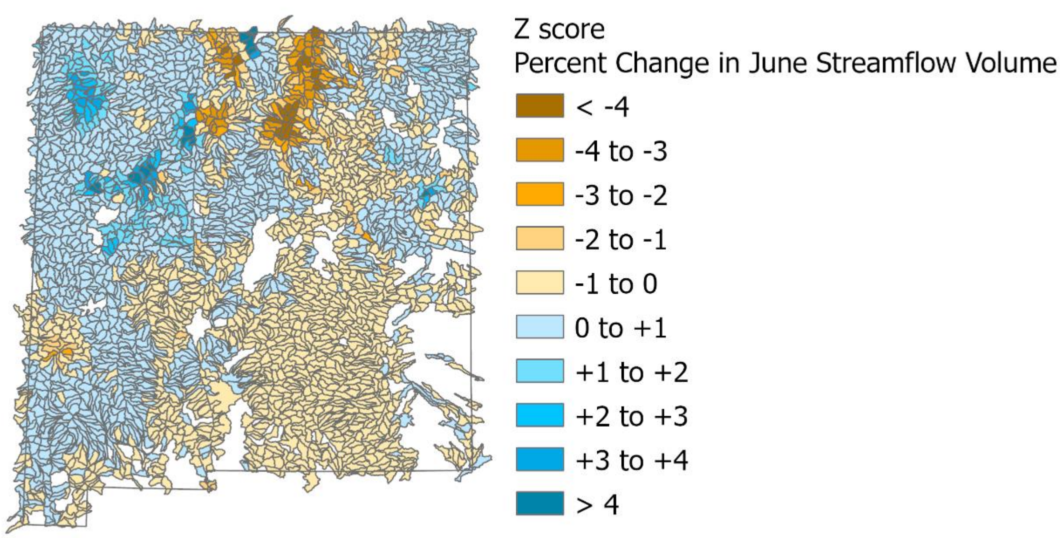
Perennial Streams



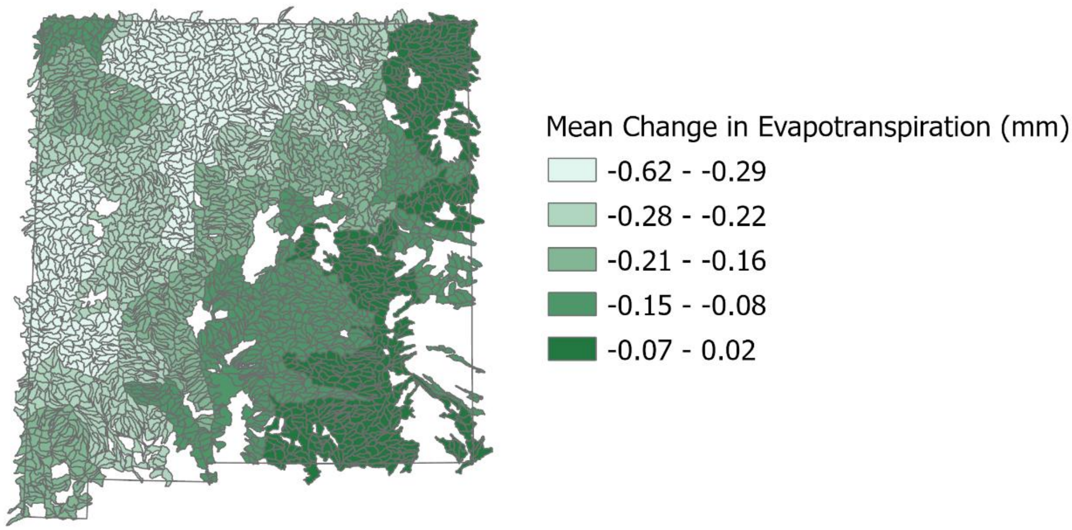


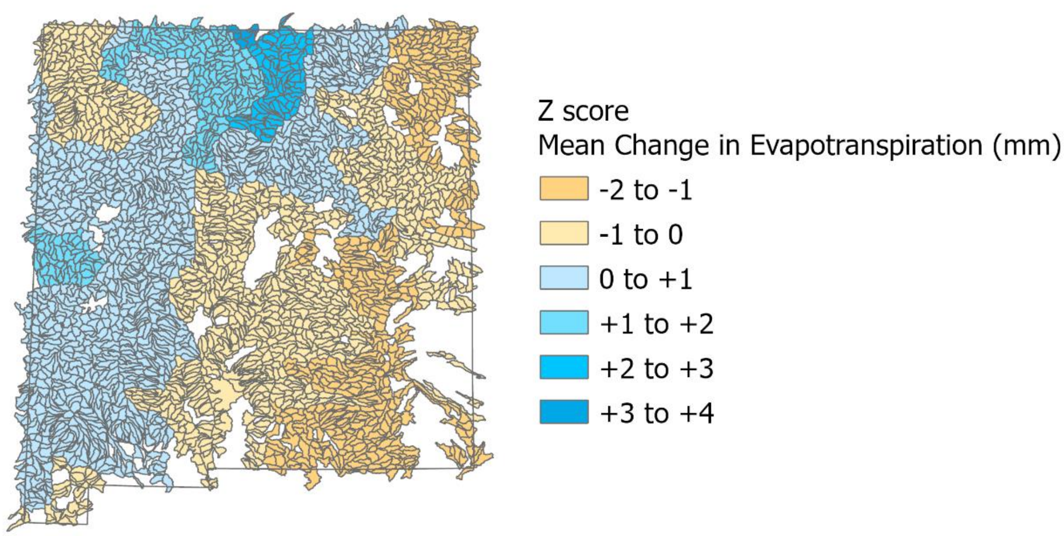
Amphibian and Reptile Habitat



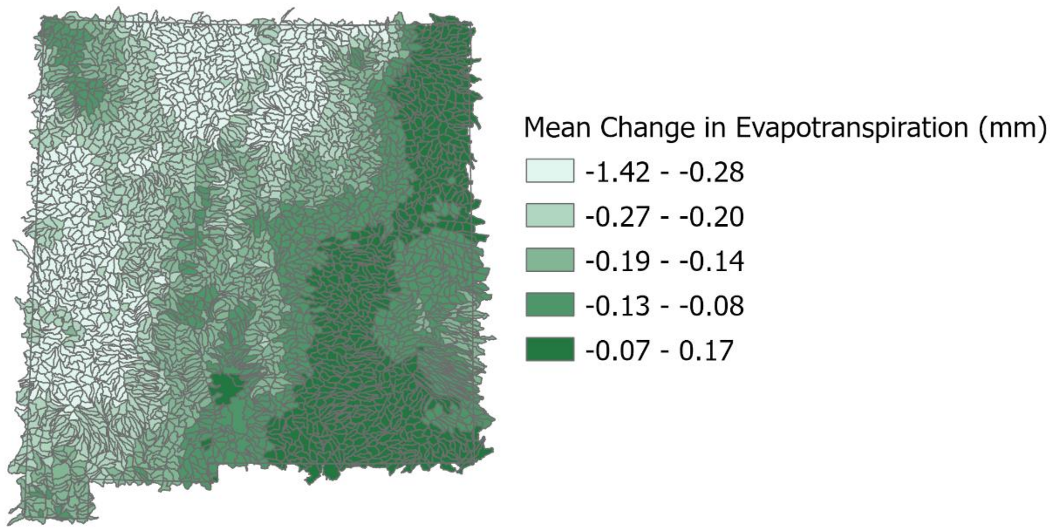


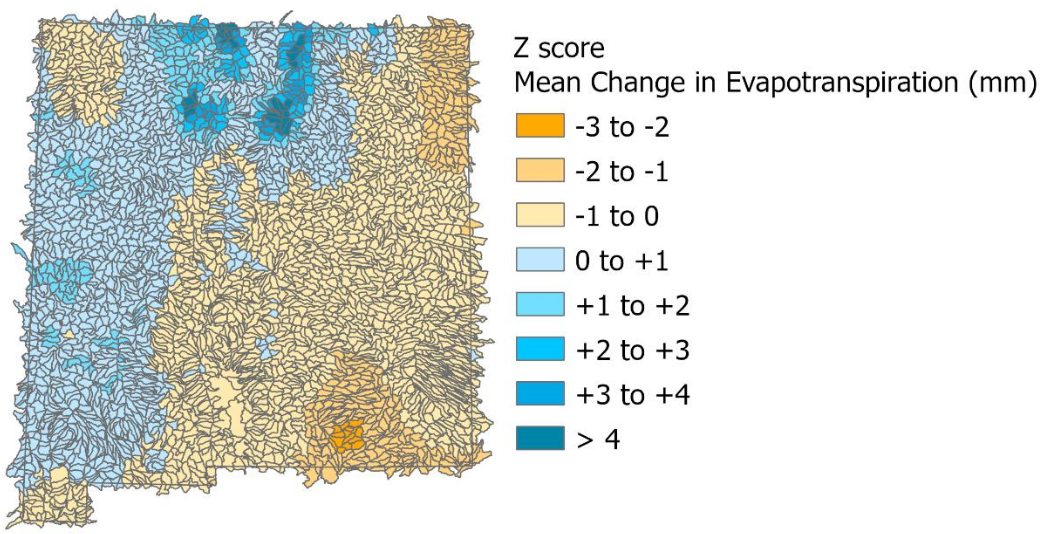
Amphibian and Reptile Habitat



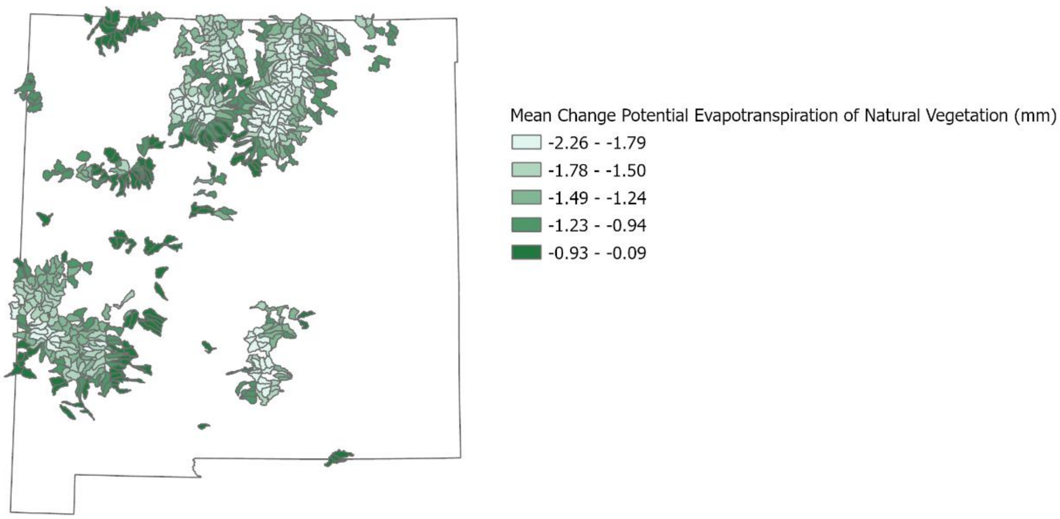


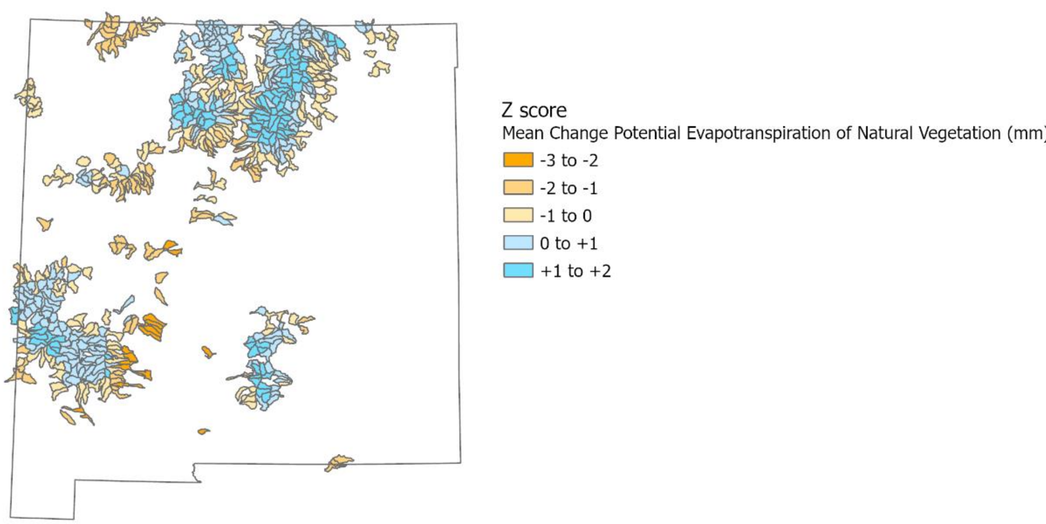
Ephemeral Catchments



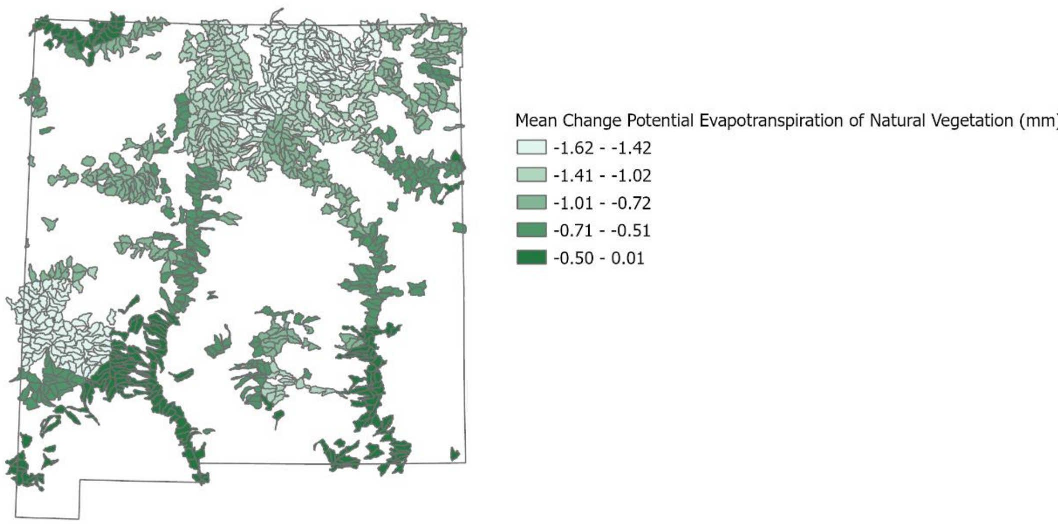


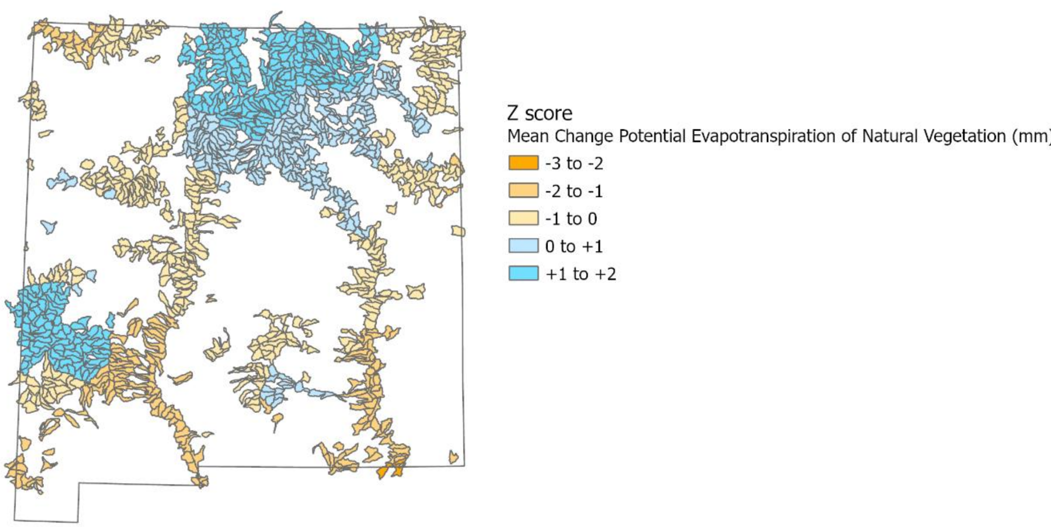
Cold-Water Fish Habitat



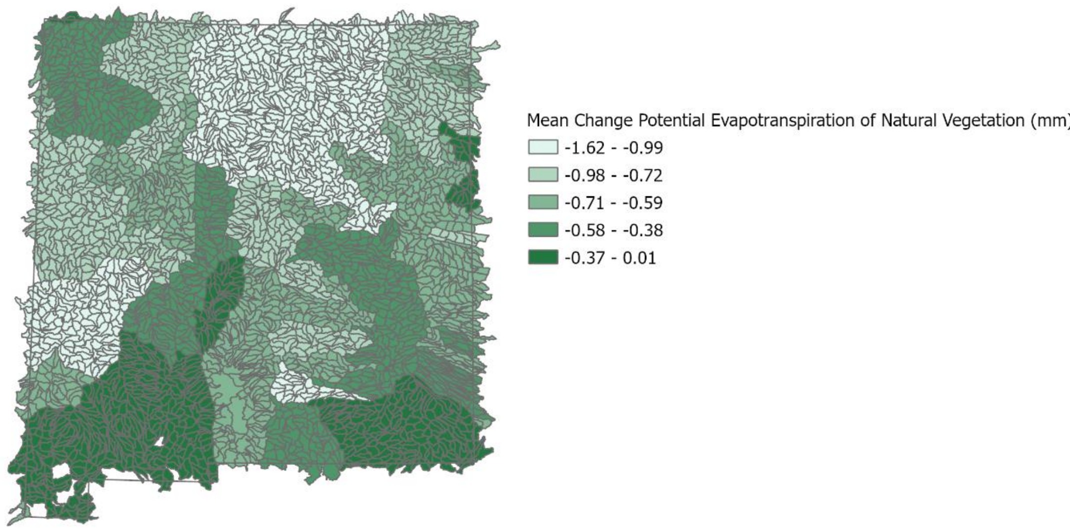


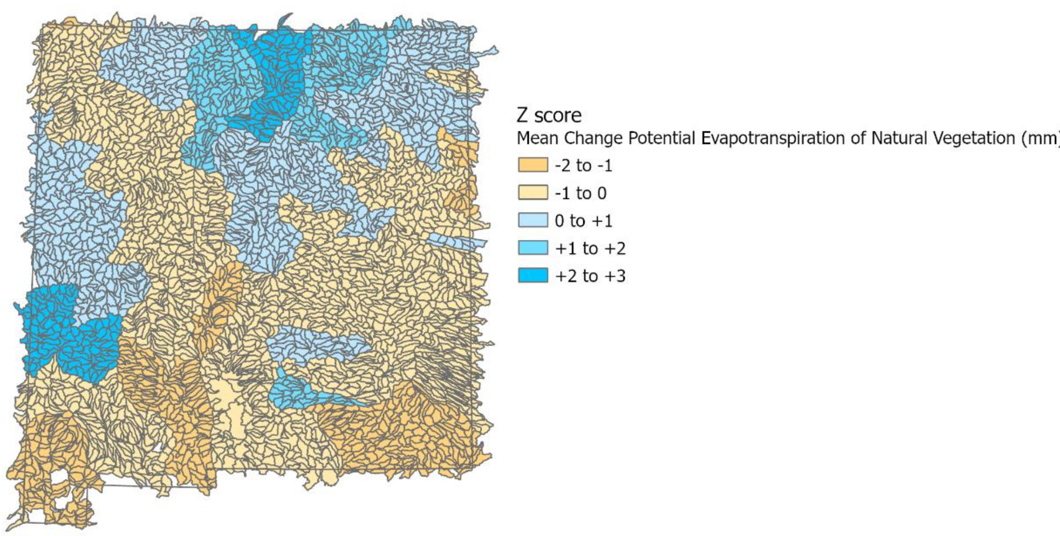
Perennial Streams



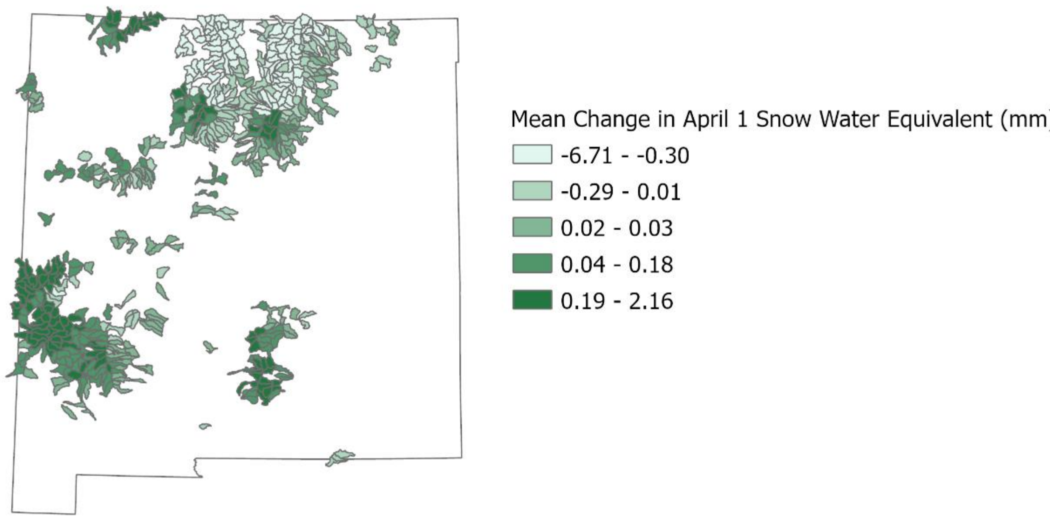


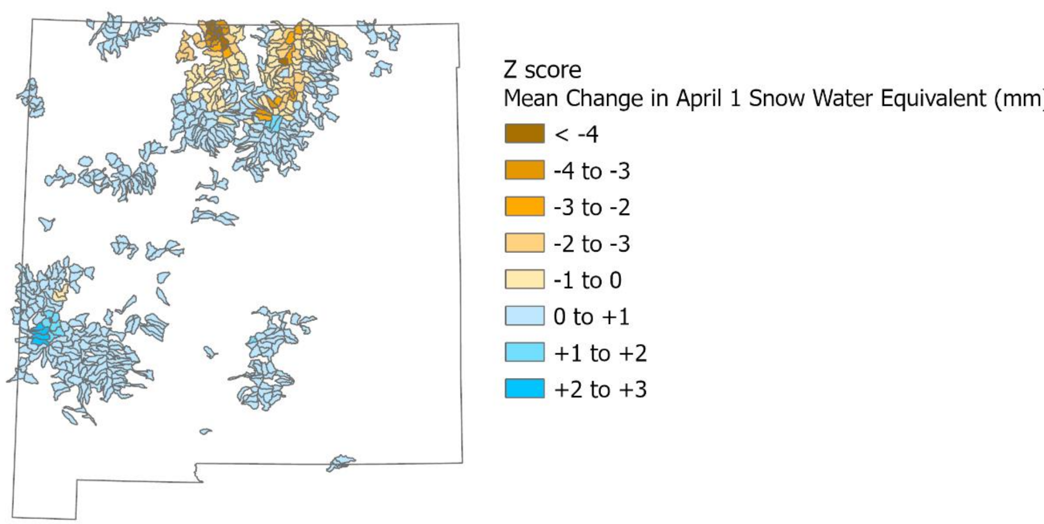
Springs


Mean Change Potential Evapotranspiration of Natural Vegetation (mm)
-1.62 - -0.99
-0.98 - -0.72
-0.71 - -0.59
-0.58 - -0.38
-0.37 - 0.01

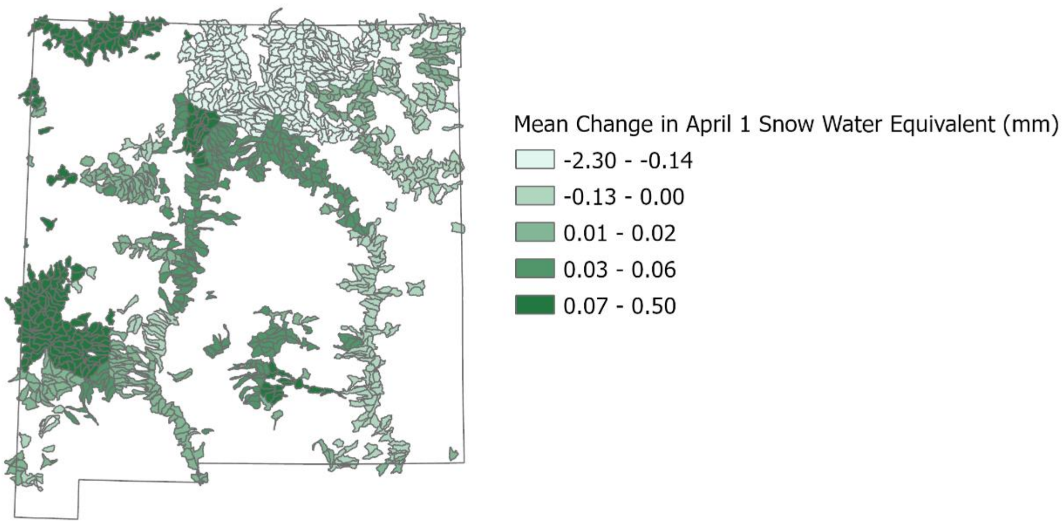

Z score
Mean Change Potential Evapotranspiration of Natural Vegetation (mm)
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3

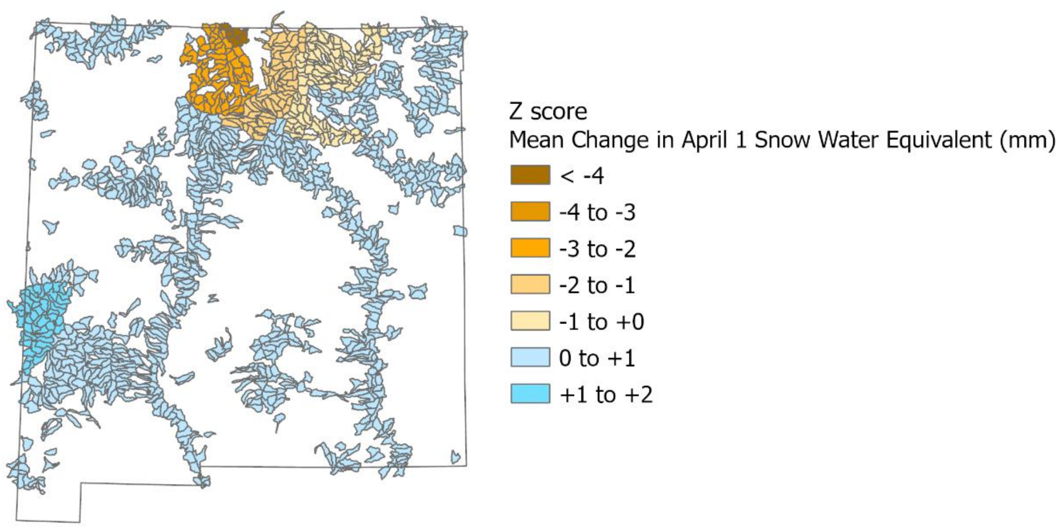
Cold-Water Fish Habitat



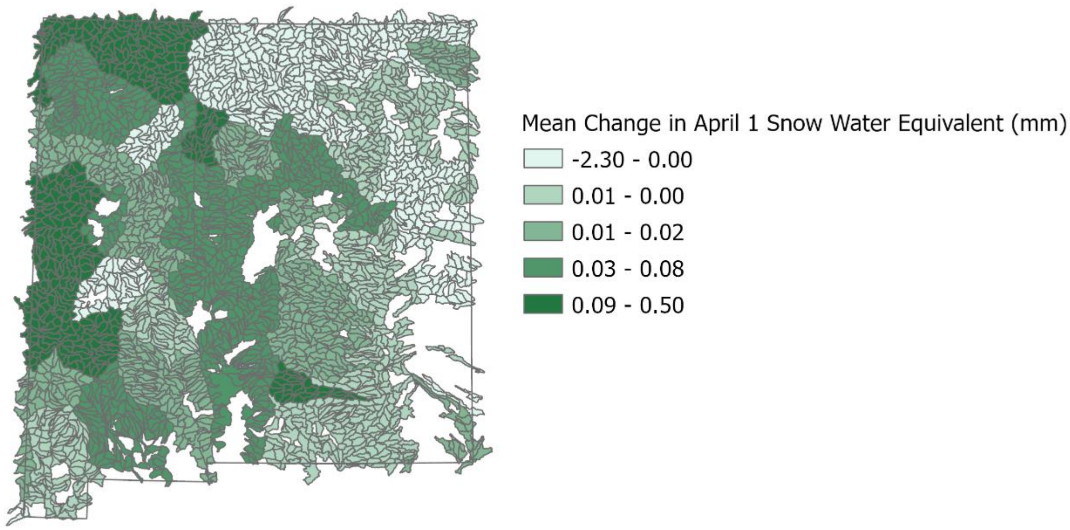


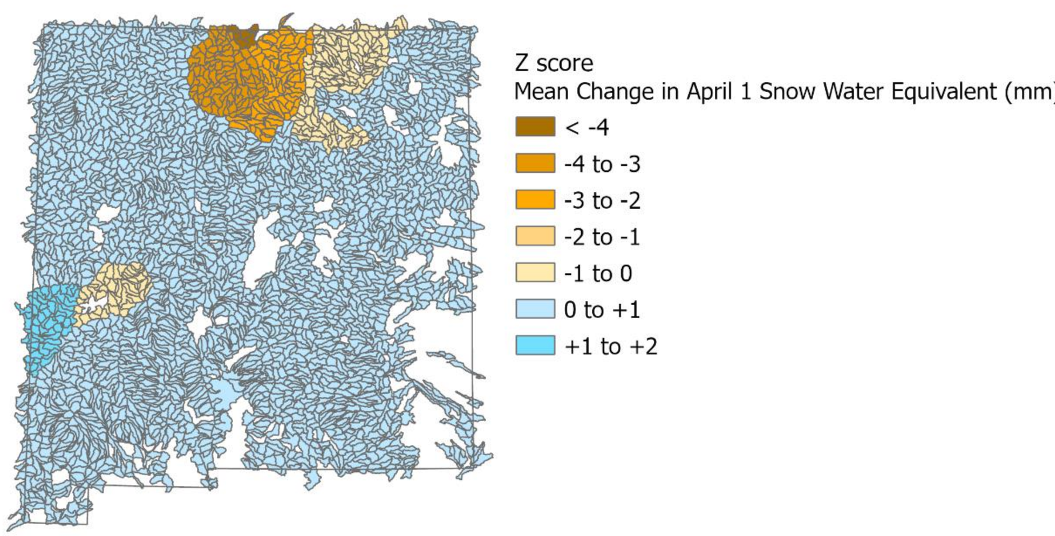
Perennial Streams



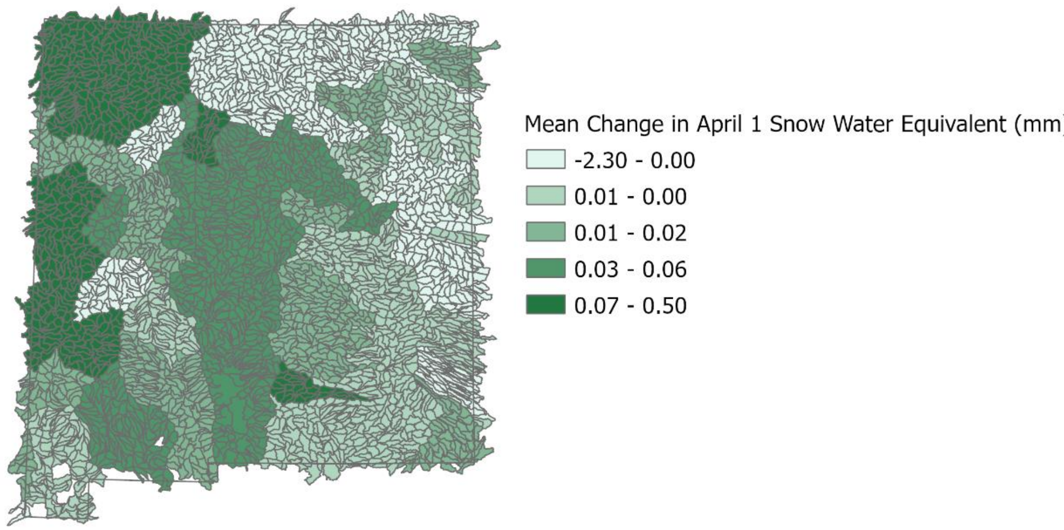


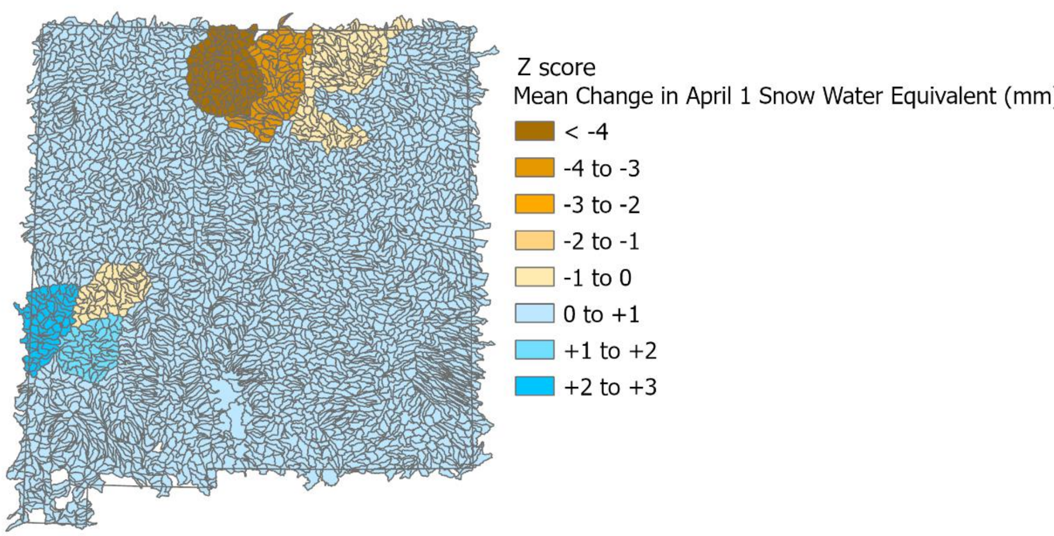
Amphibian and Reptile Habitat



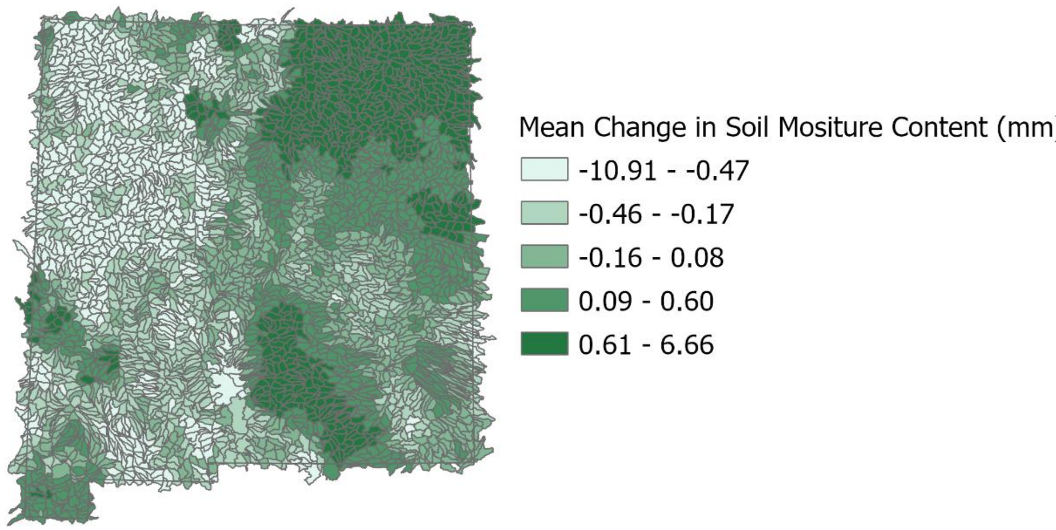


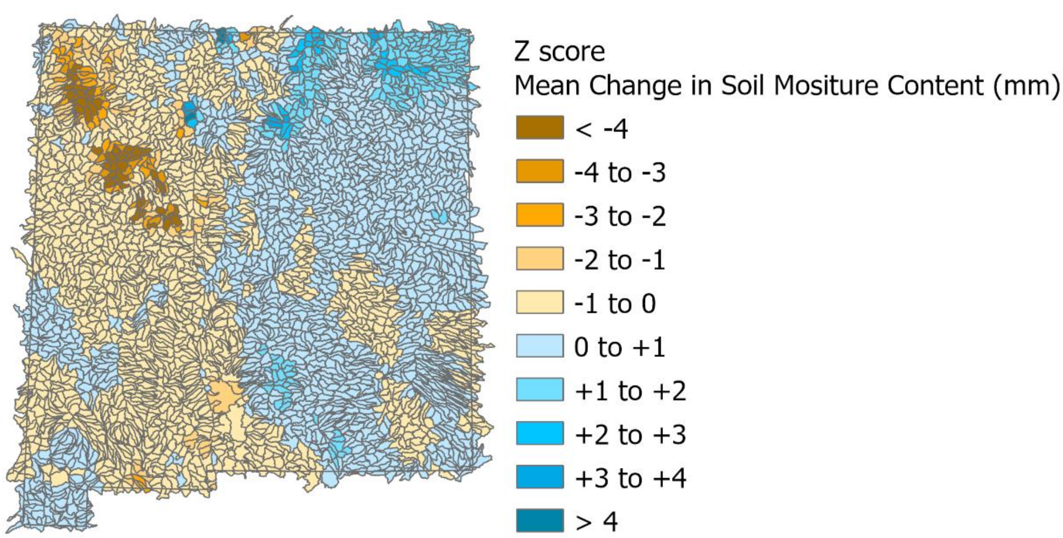
Springs


Mean Change in April 1 Snow Water Equivalent (mm)
-2.30 - 0.00
0.01 - 0.00
0.01 - 0.02
0.03 - 0.06
0.07 - 0.50


Z score
Mean Change in April 1 Snow Water Equivalent (mm)
< -4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3

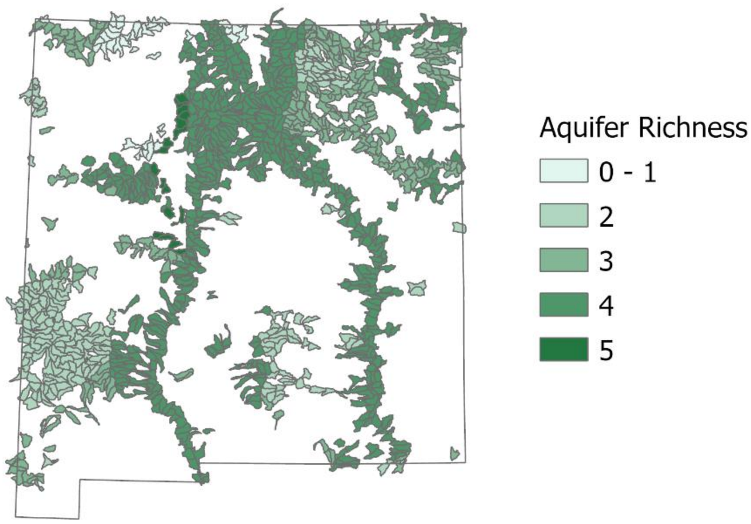
Ephemeral Catchments

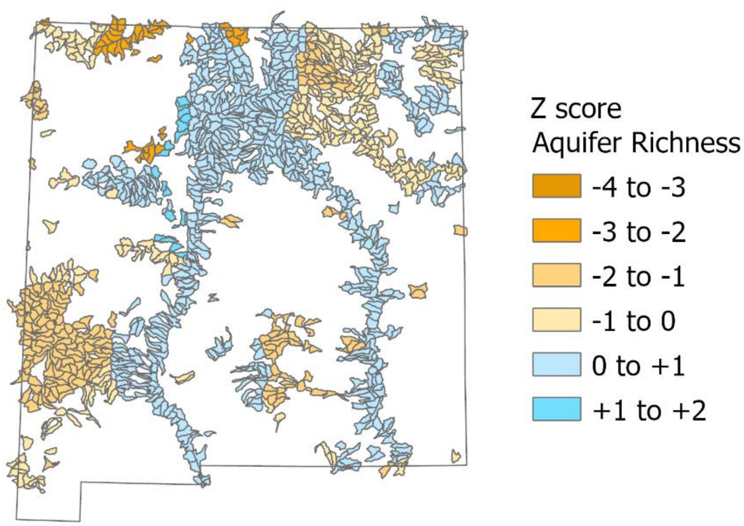




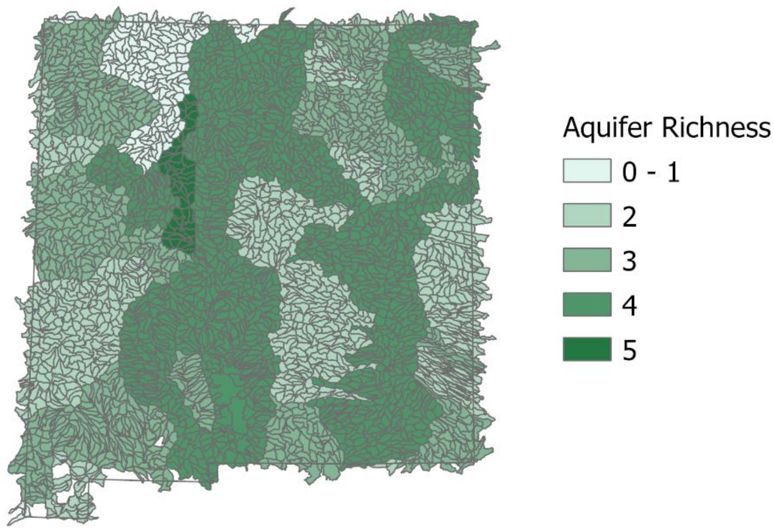
Hydrorefugia Variables

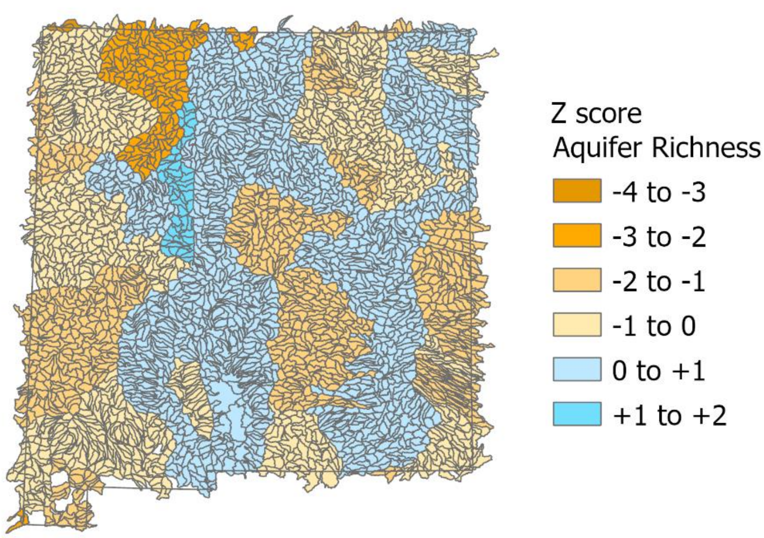
Perennial Streams



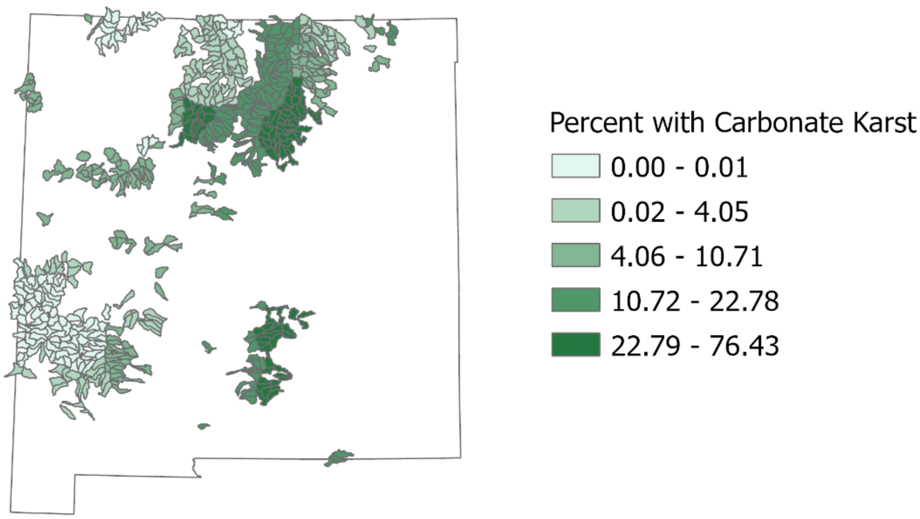


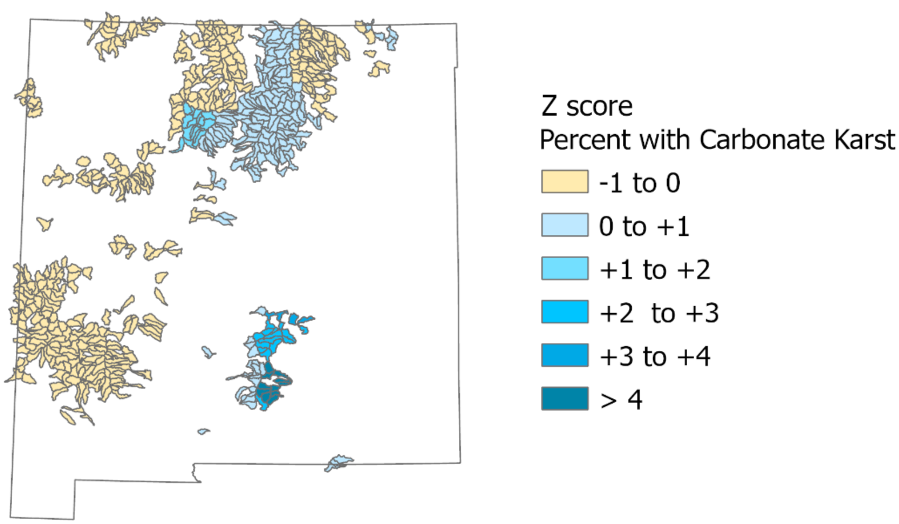
Springs


Aquifer Richness
0 - 1
2
3
4
5

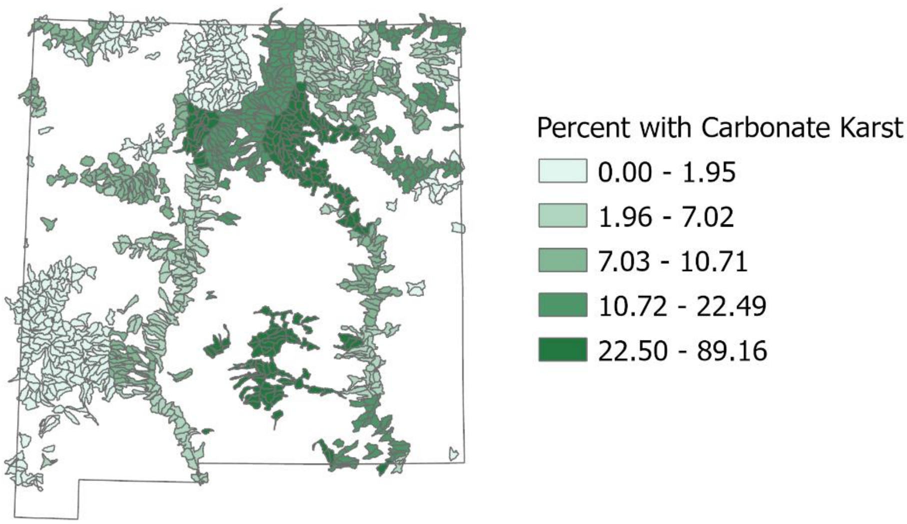

Z score
Aquifer Richness
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2

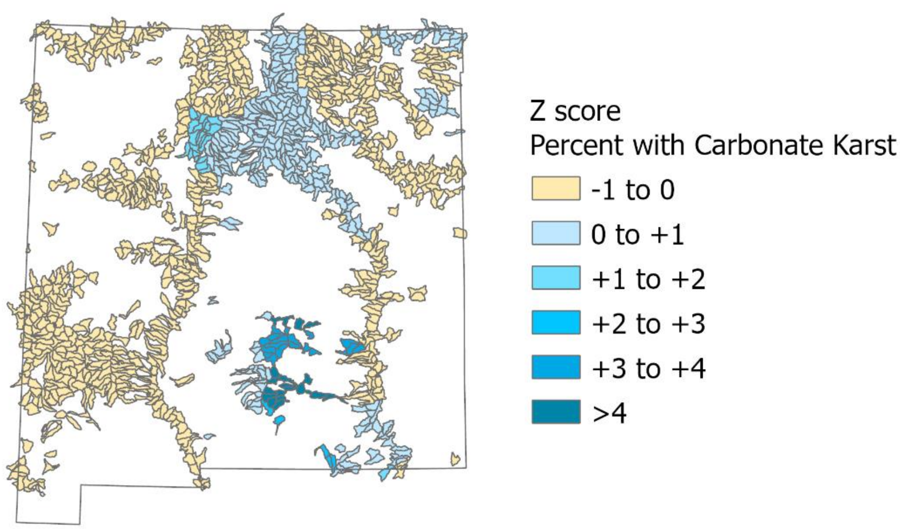
Cold-Water Fish Habitat



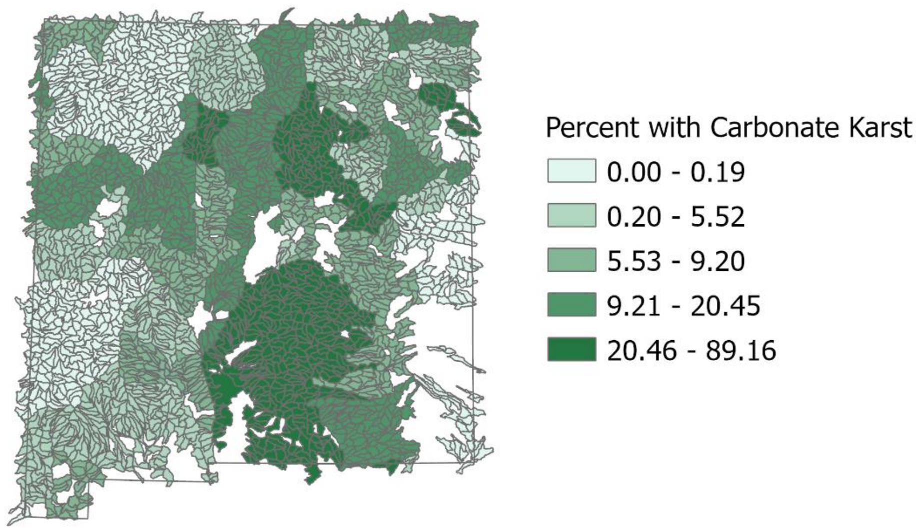


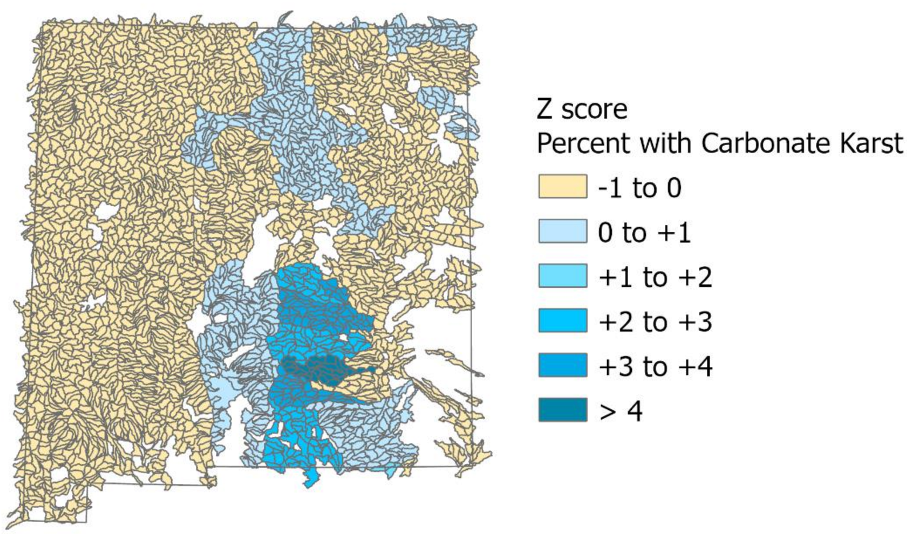
Perennial Streams



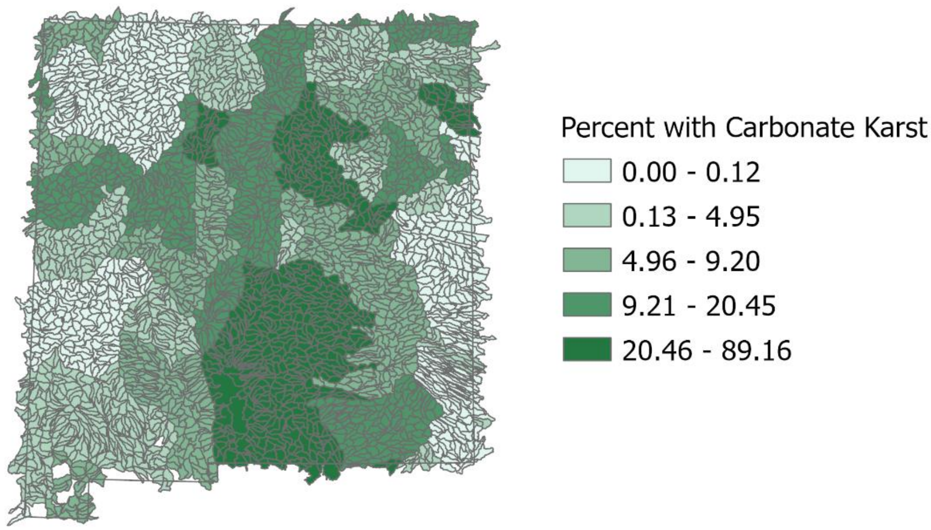


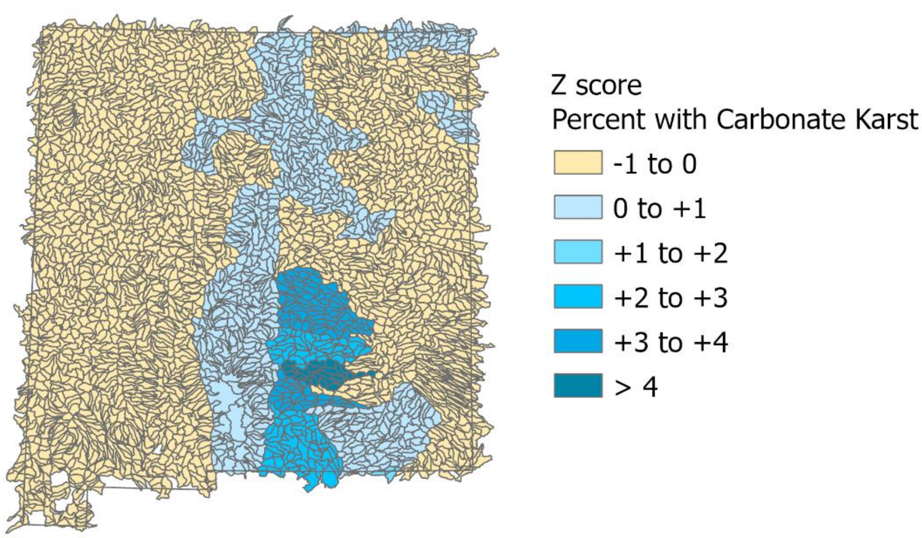
Amphibian and Reptile Habitat



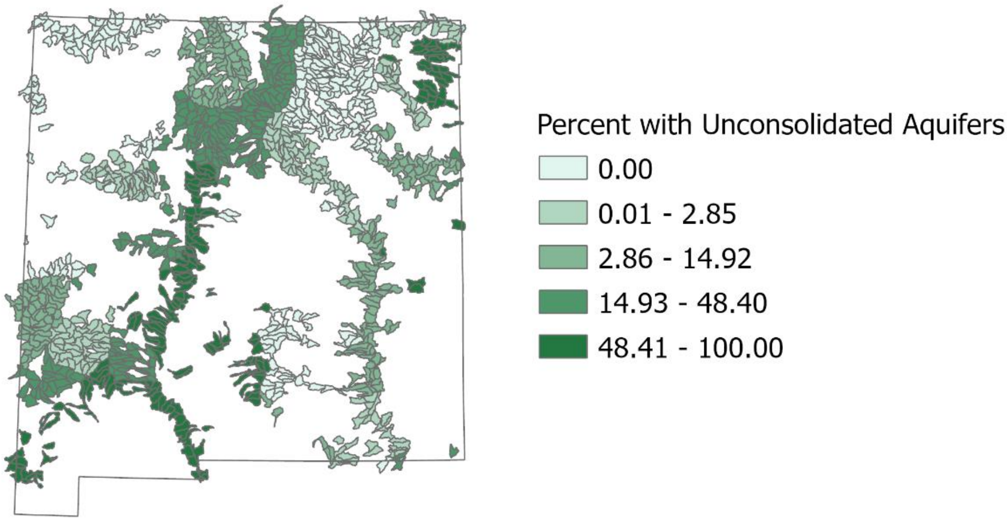


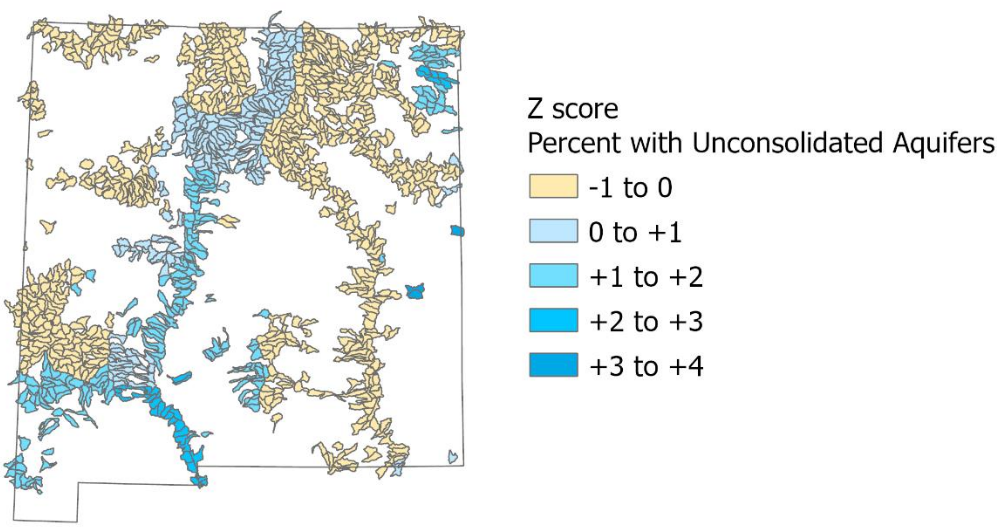
Springs


Percent with Carbonate Karst
0.00 - 0.12
0.13 - 4.95
4.96 - 9.20
9.21 - 20.45
20.46 - 89.16

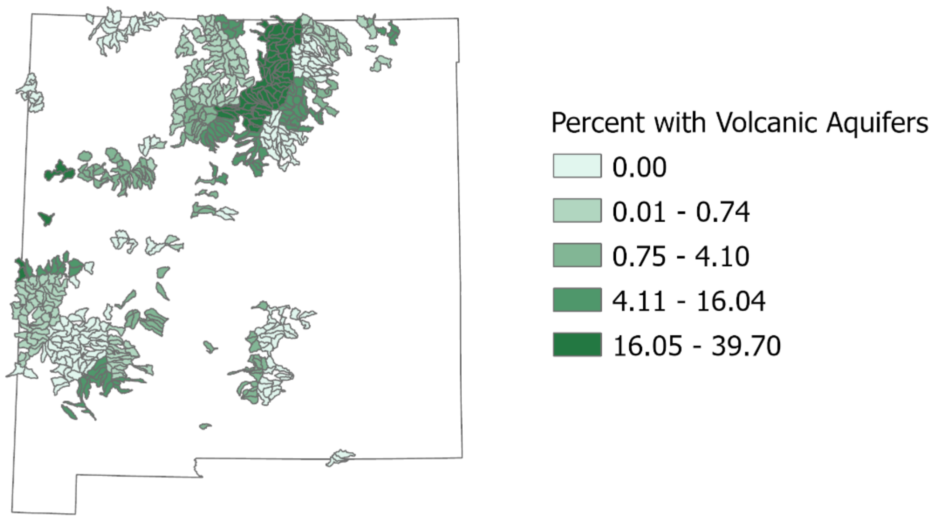

Z score
Percent with Carbonate Karst
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
> 4

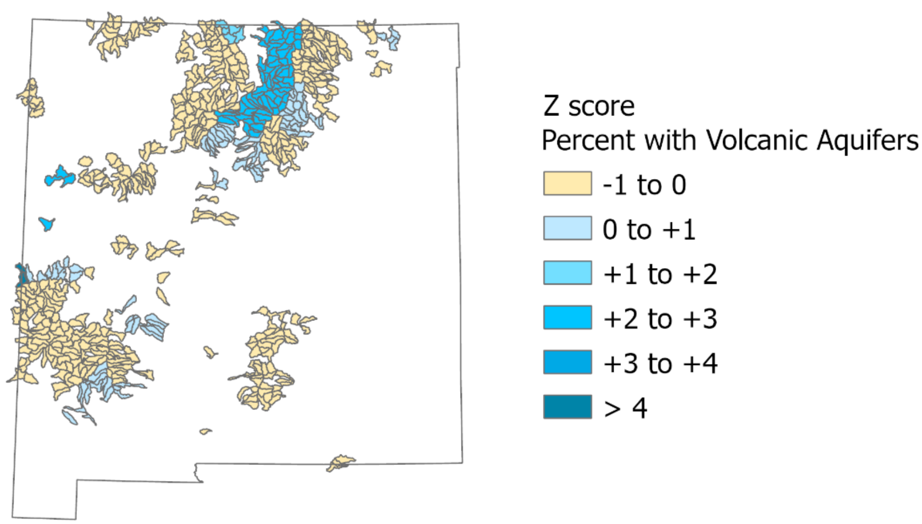
Perennial Streams



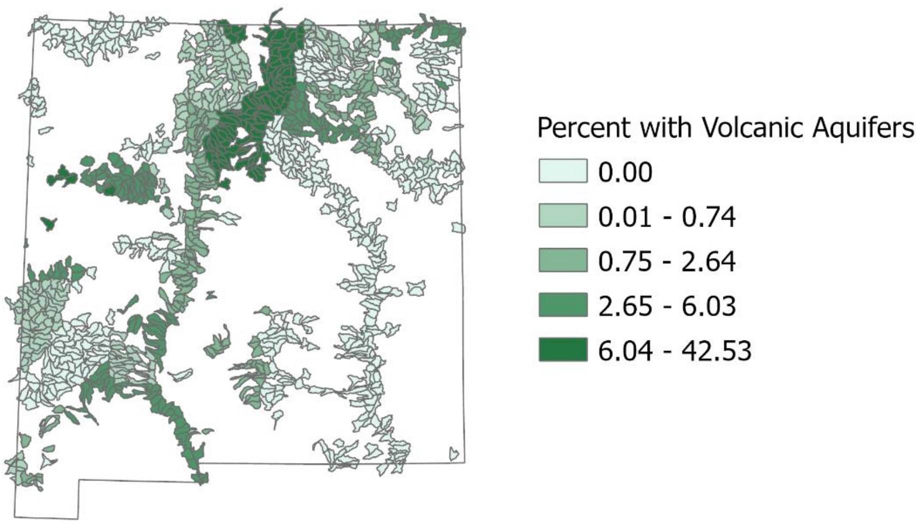


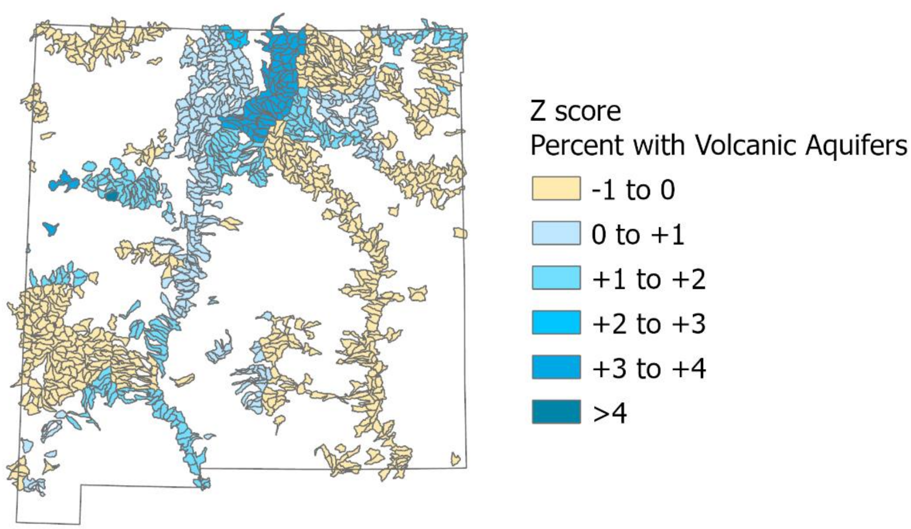
Cold-Water Fish Habitat



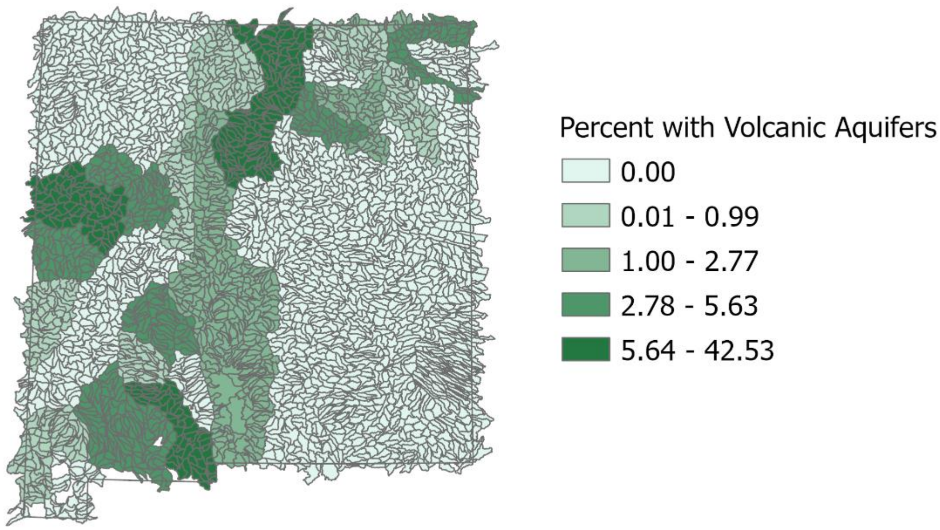


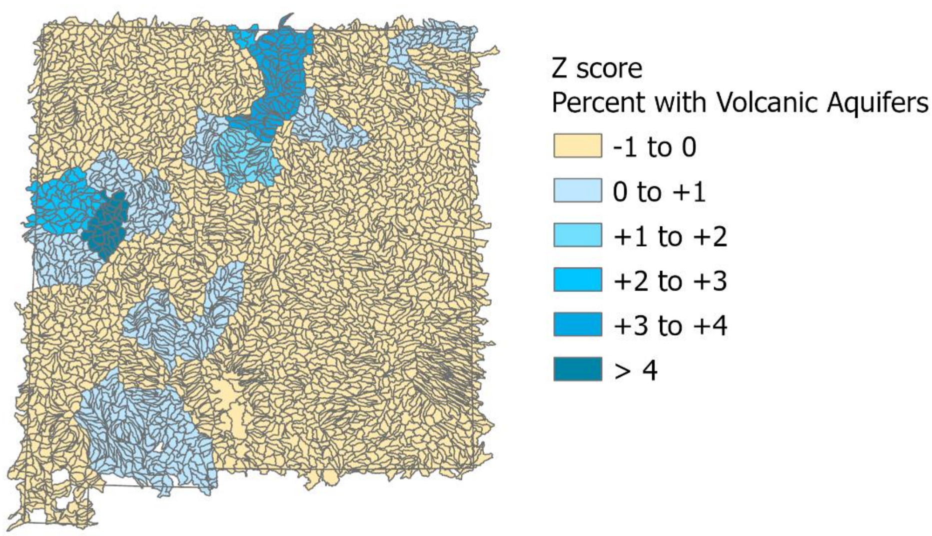
Perennial Streams



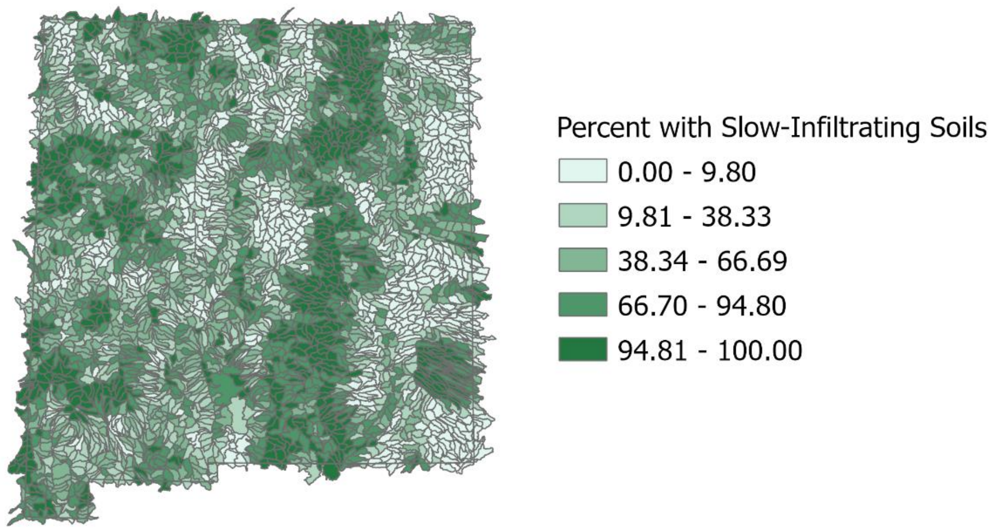


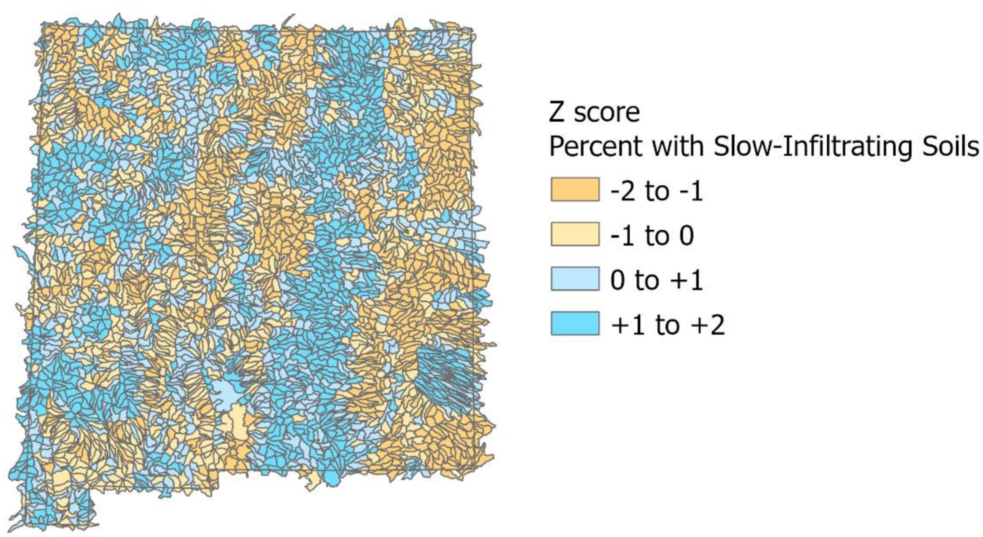
Springs


Percent with Volcanic Aquifers
0.00
0.01 - 0.99
1.00 - 2.77
2.78 - 5.63
5.64 - 42.53

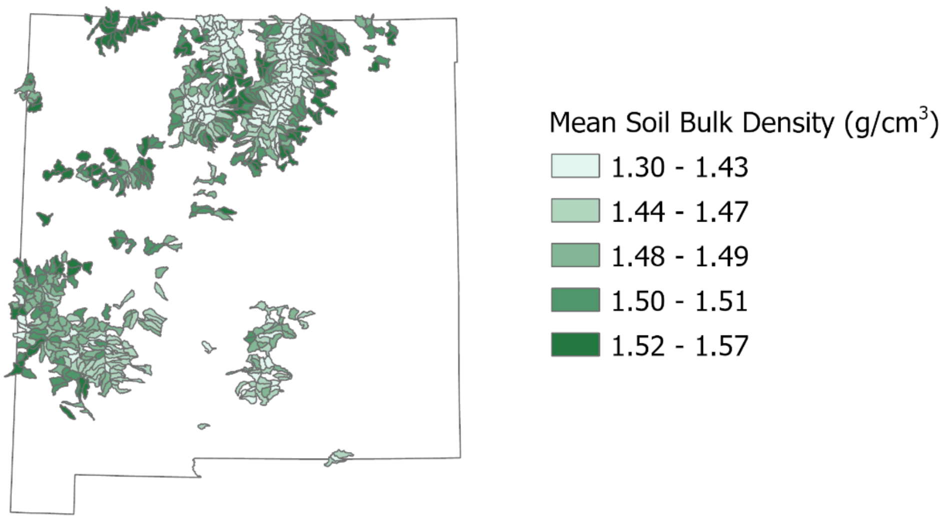

Z score
Percent with Volcanic Aquifers
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
> 4

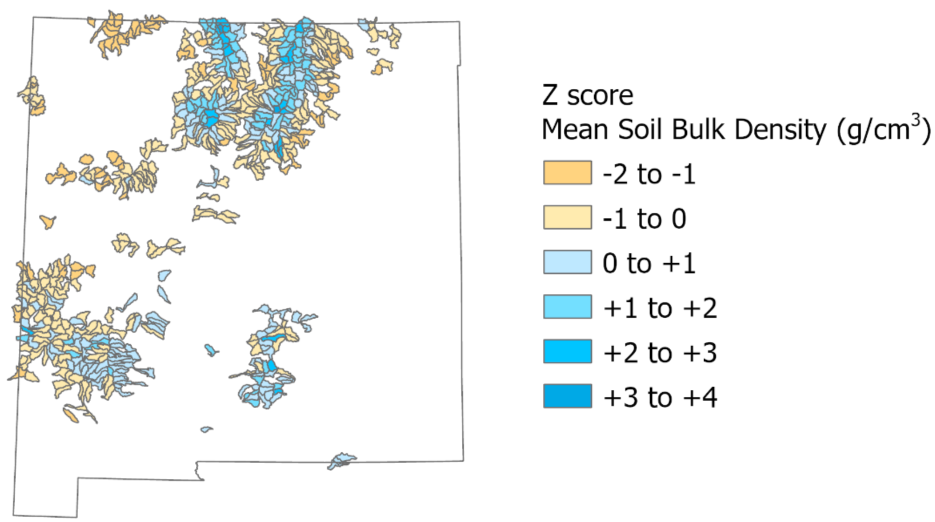
Ephemeral Catchments



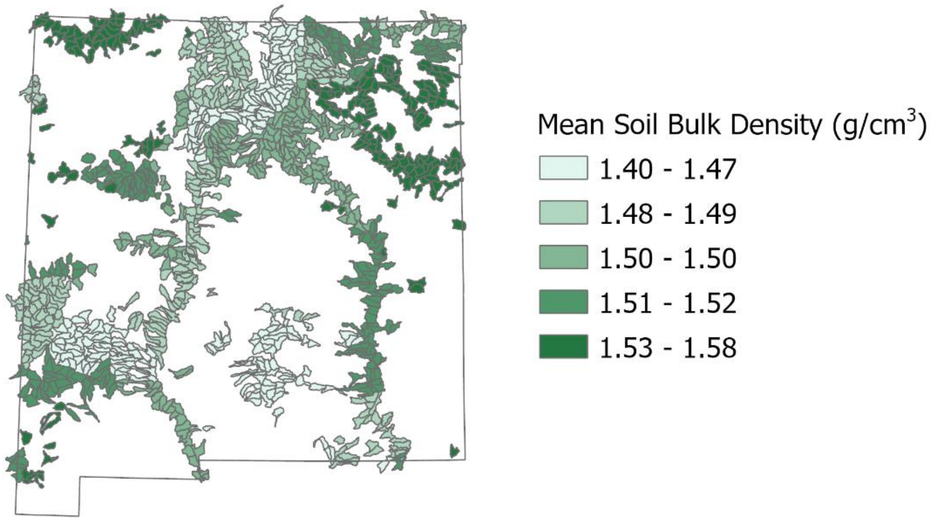


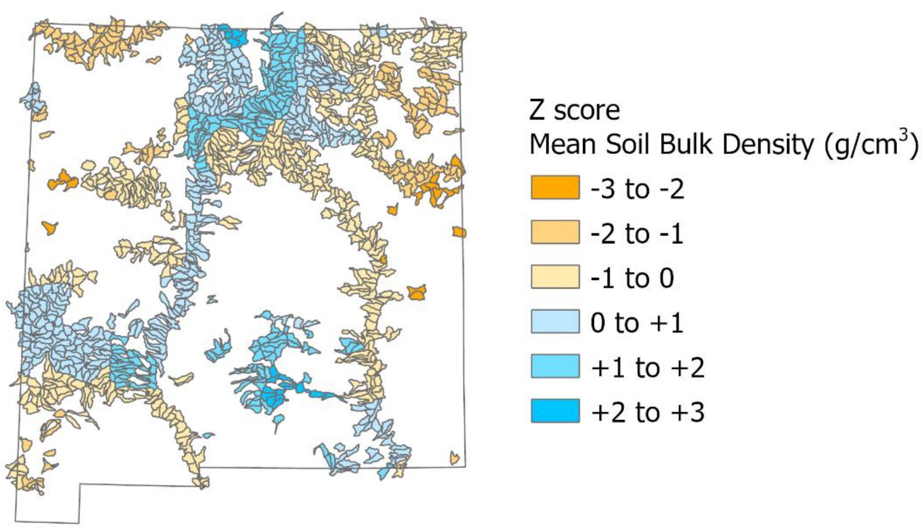
Cold-Water Fish Habitat



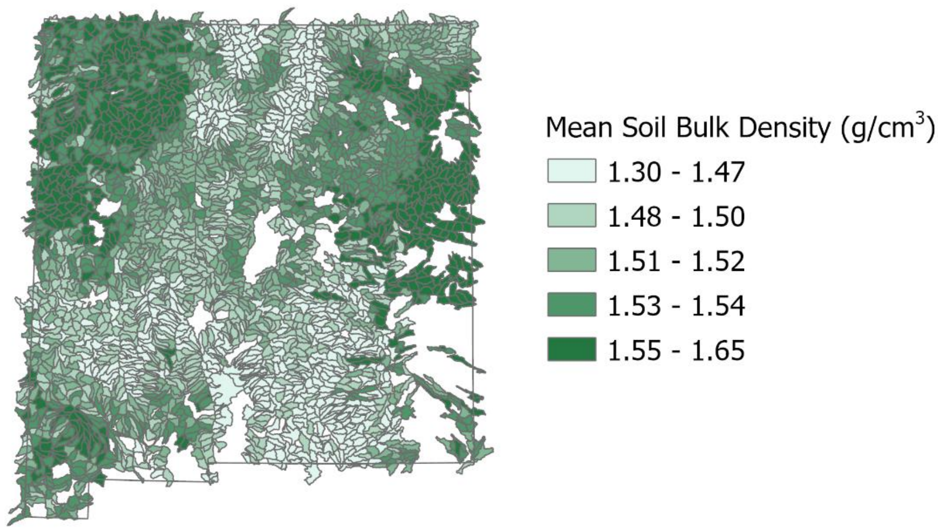


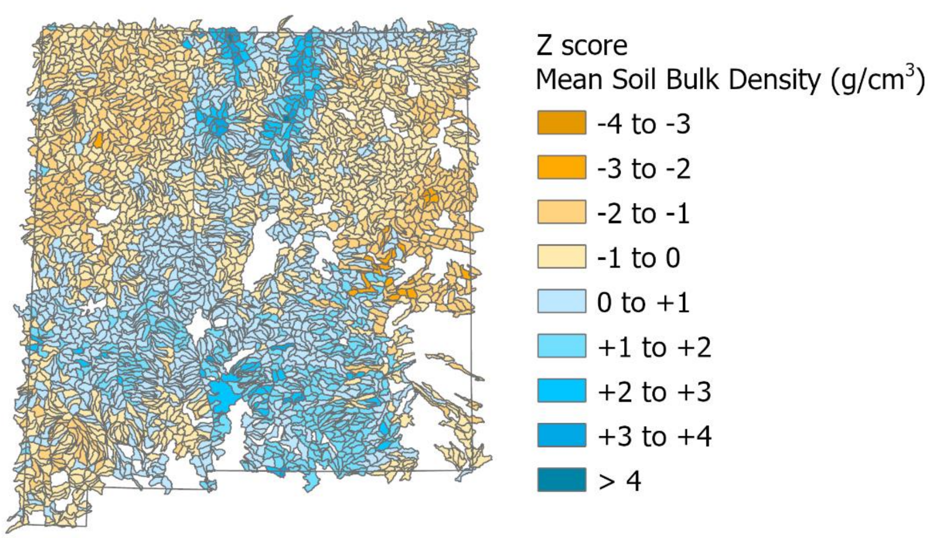
Perennial Streams



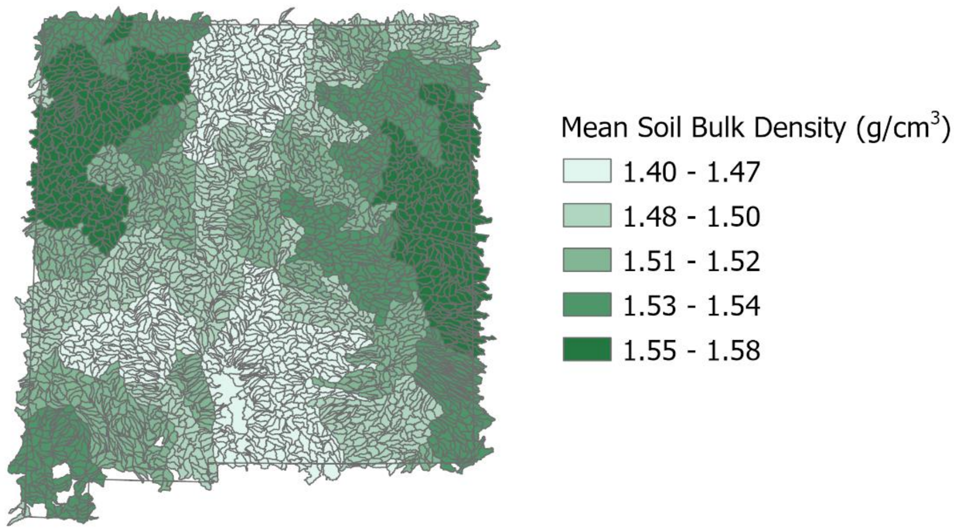


Amphibian and Reptile Habitat

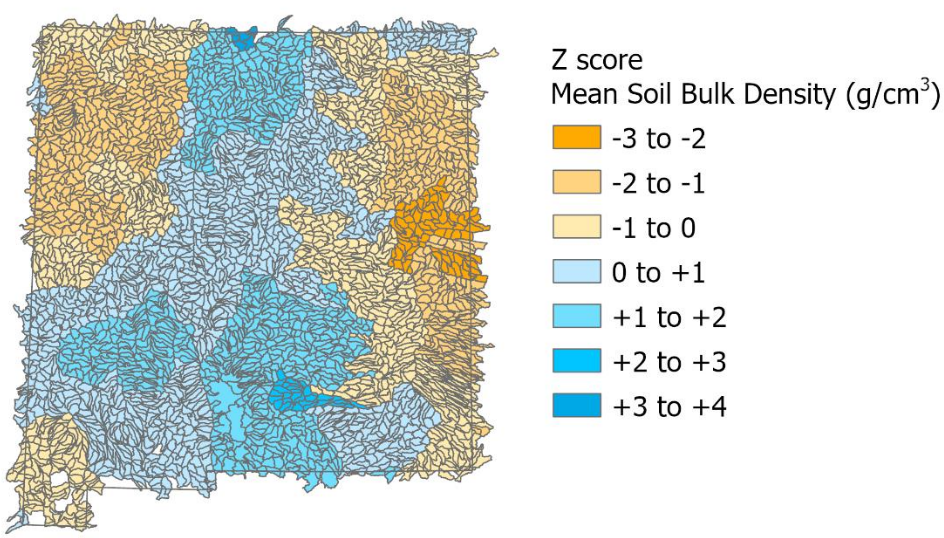




Springs

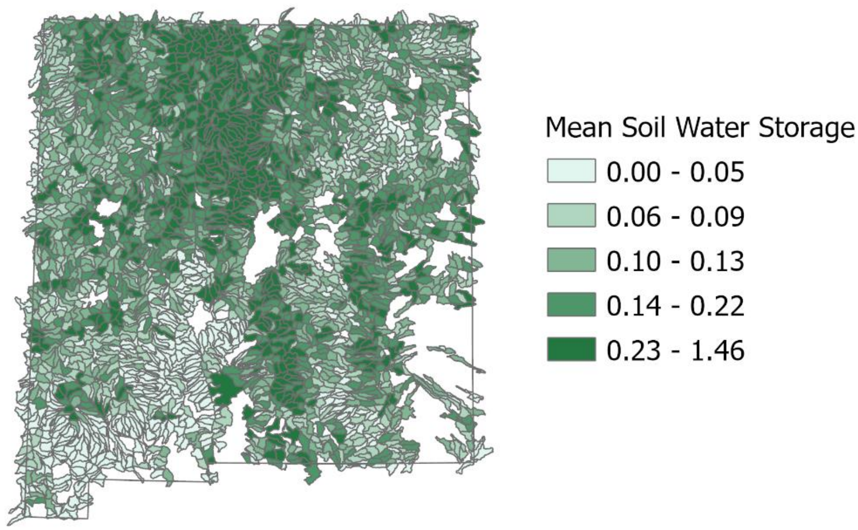


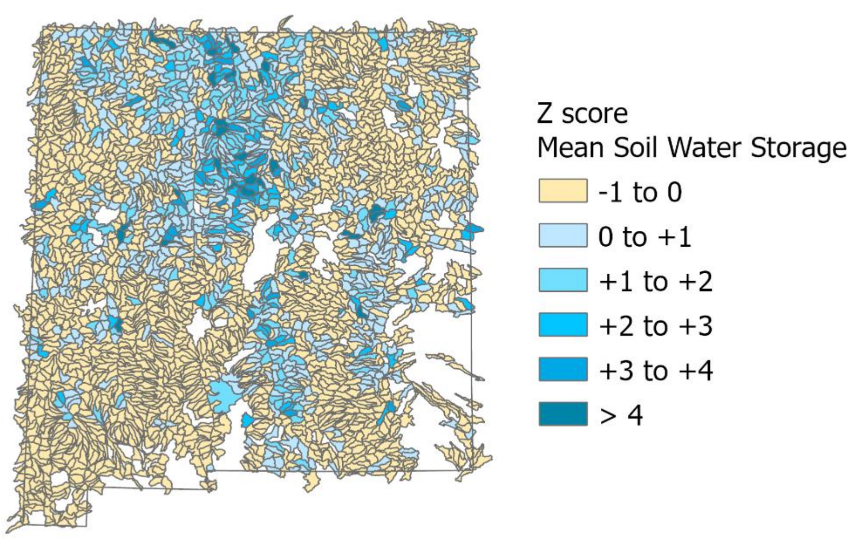
Mean Soil Bulk Density (g/cm3)
1.40 - 1.47
1.48 - 1.50
1.51 - 1.52
1.53 - 1.54
1.55 - 1.58



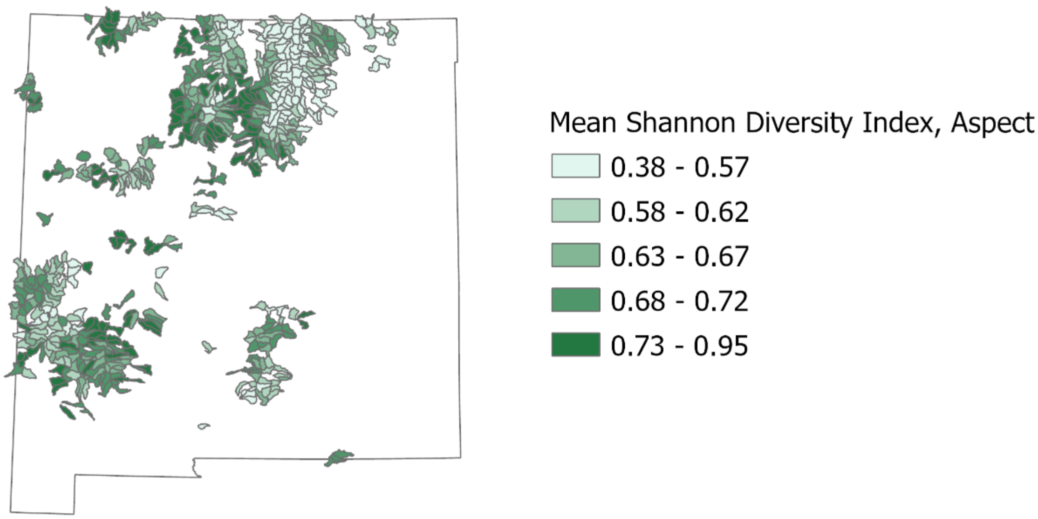
Z score
Mean Soil Bulk Density (g/cm3)
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4

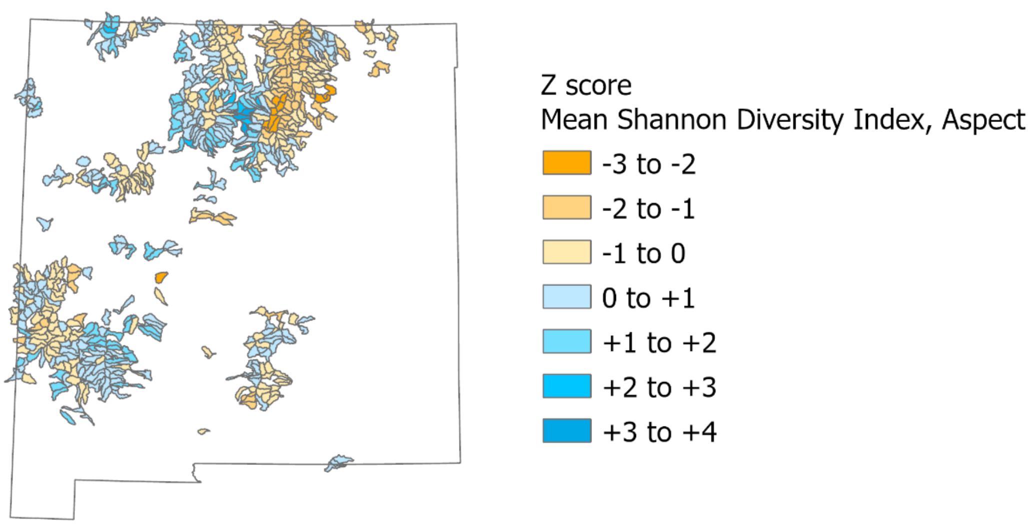
Amphibian and Reptile Habitat



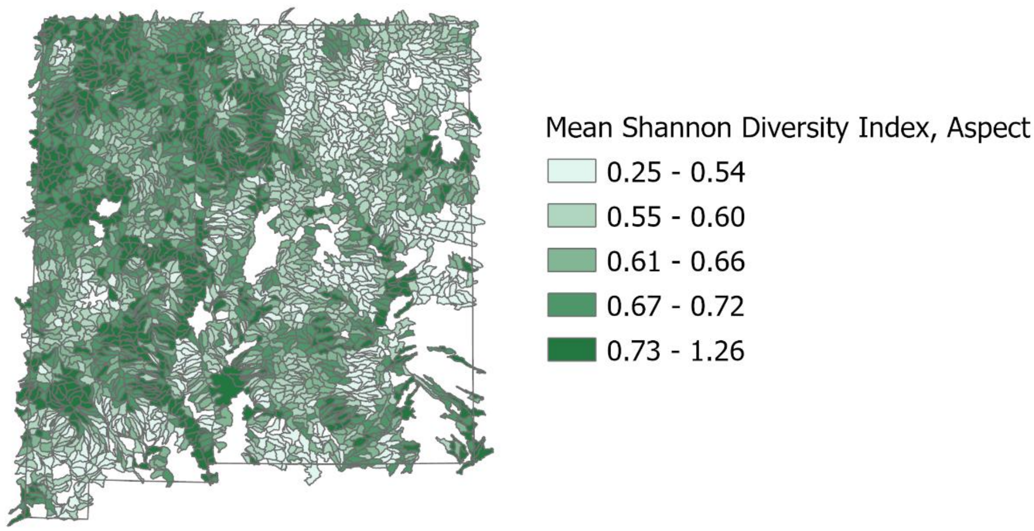


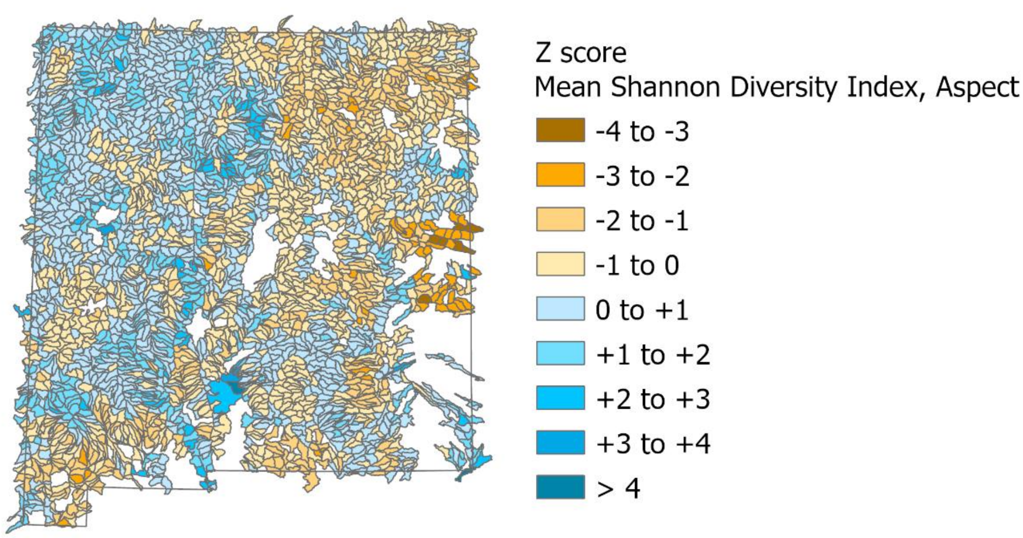
Cold-Water Fish Habitat



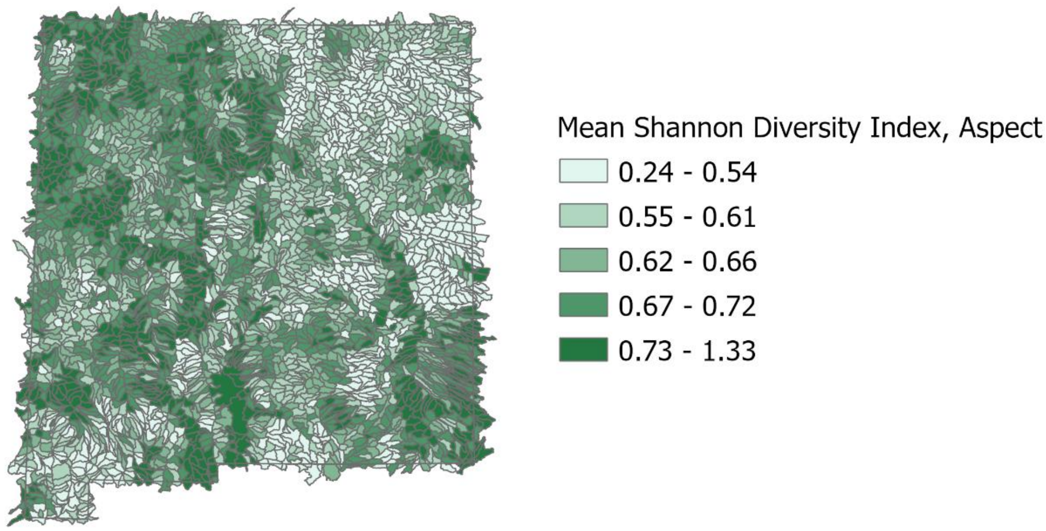


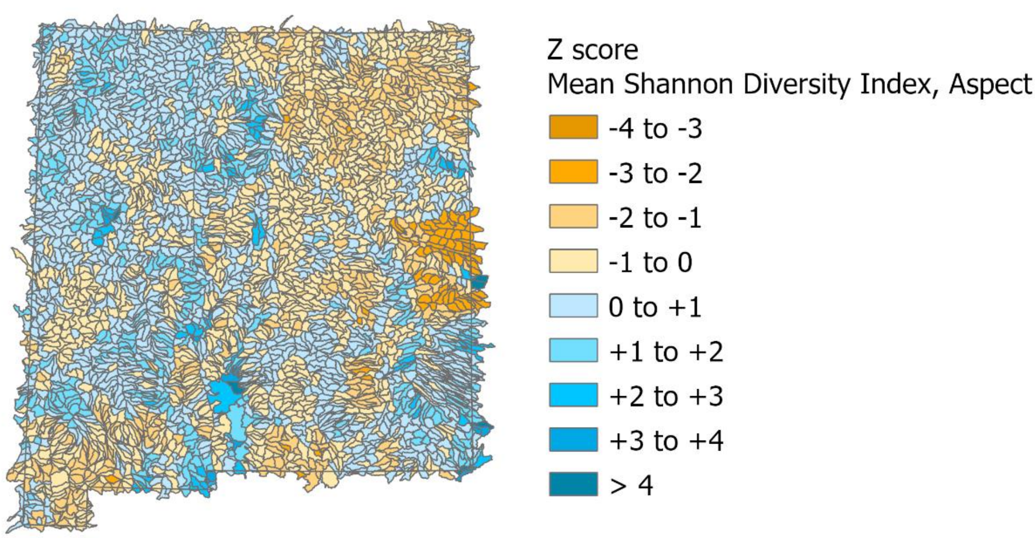
Amphibian and Reptile Habitat



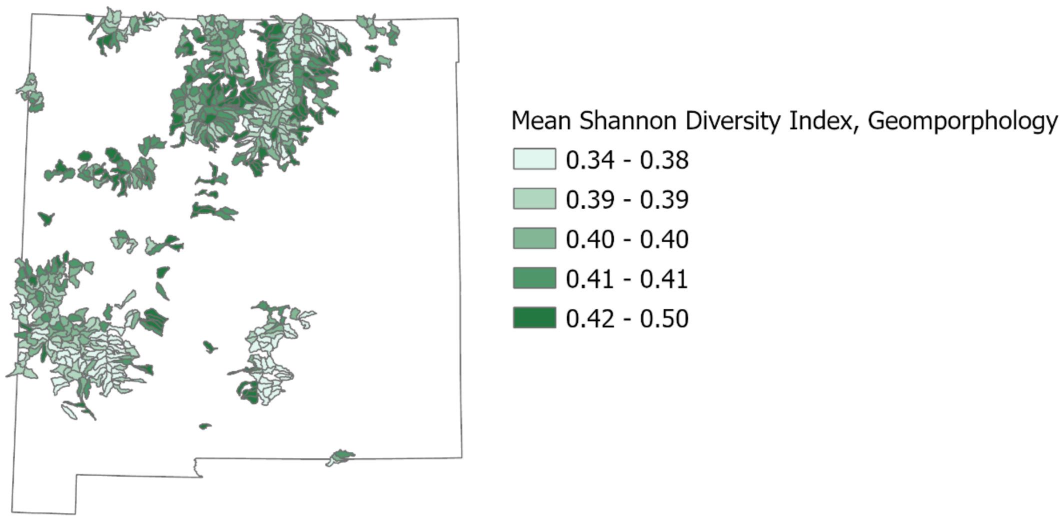


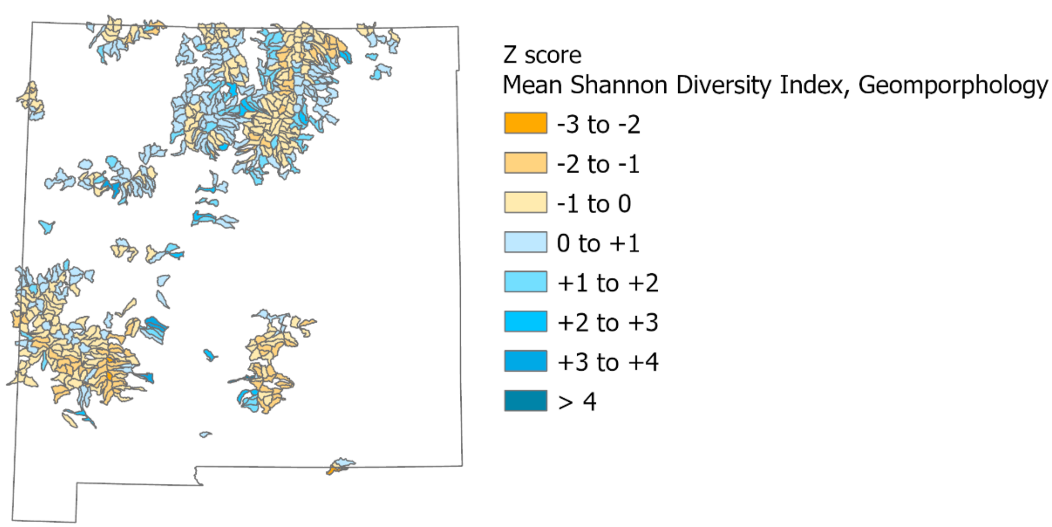
Ephemeral Catchments



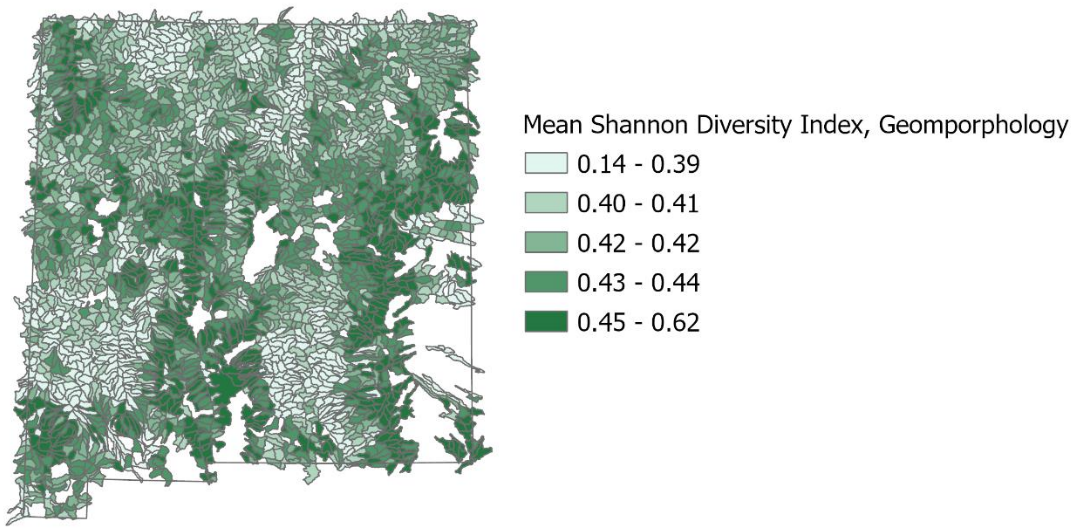


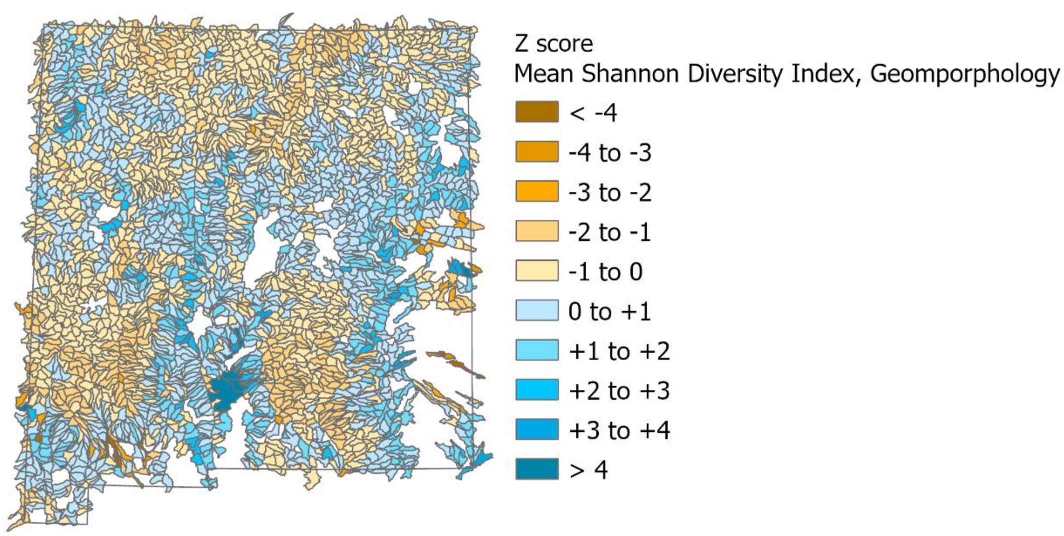
Cold-Water Fish Habitat



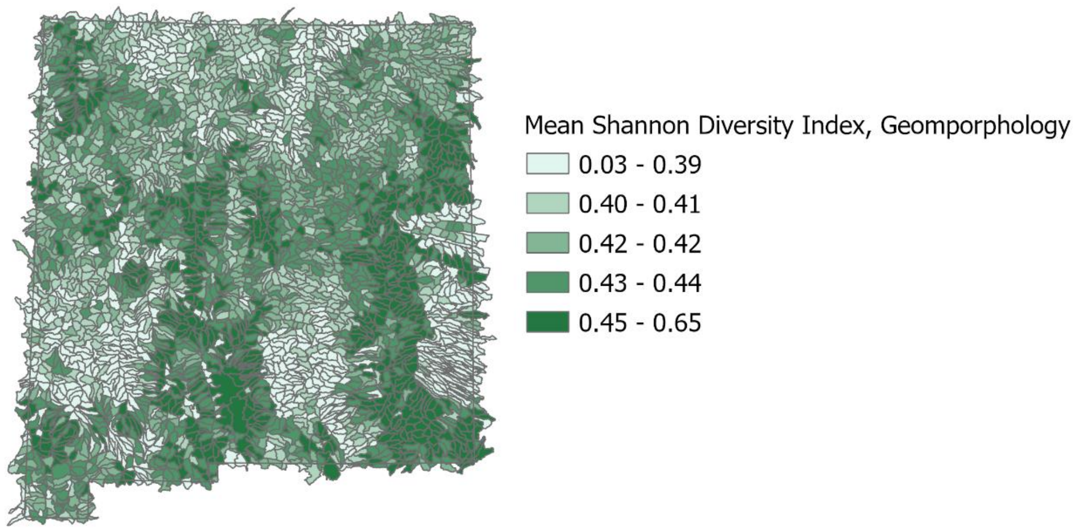


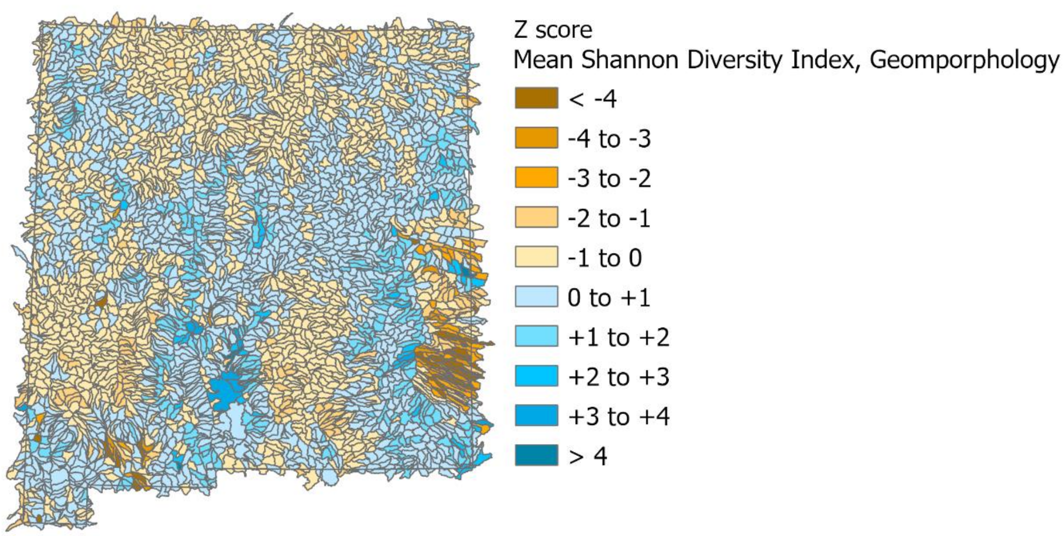
Amphibian and Reptile Habitat



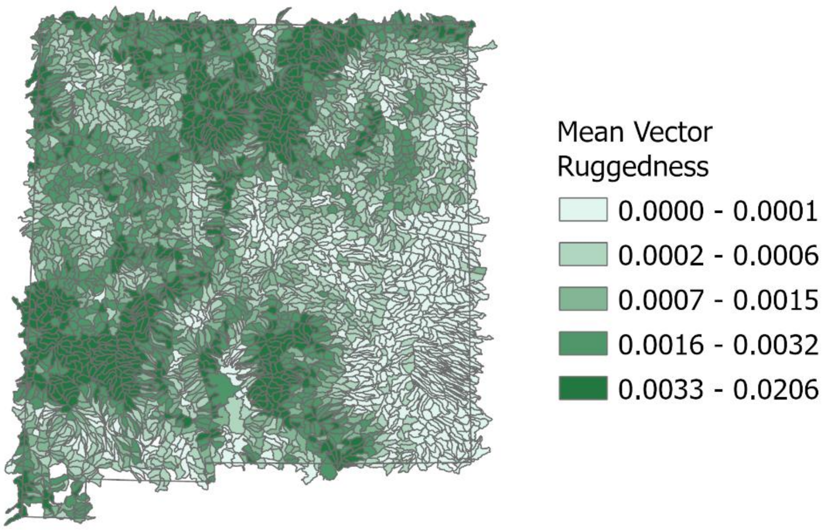


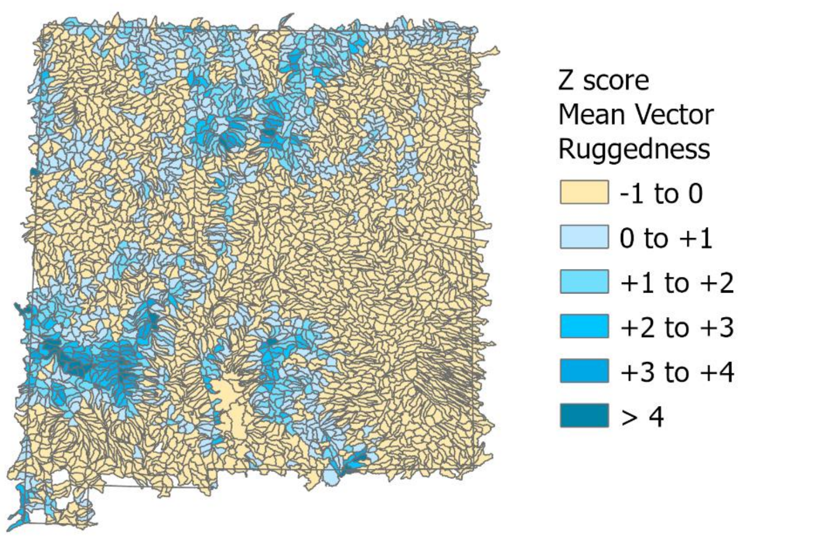
Ephemeral Catchments



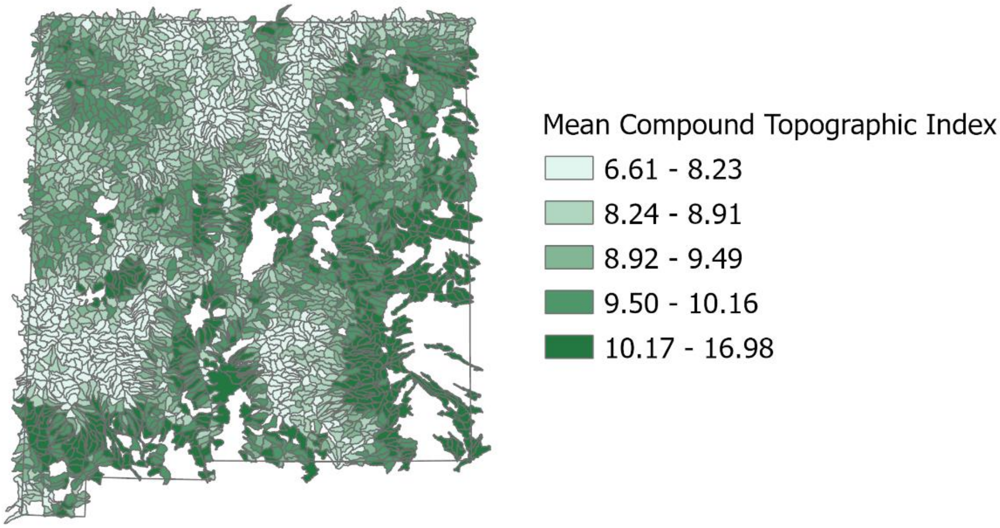


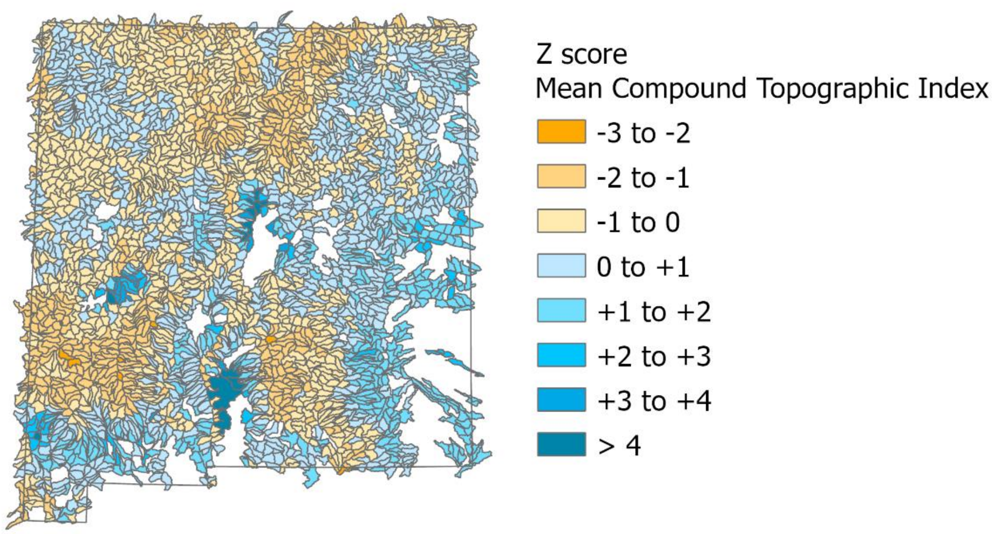
Springs


Mean Vector
Ruggedness
0.0000 - 0.0001
0.0002 - 0.0006
0.0007 - 0.0015
0.0016 - 0.0032
0.0033 - 0.0206

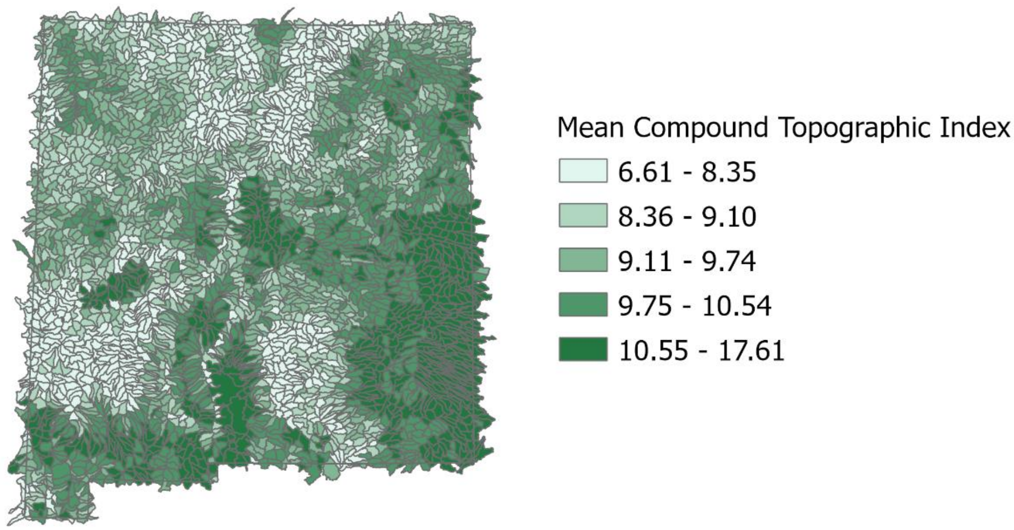

Z score
Mean Vector
Ruggedness
-1 to 0
0 to +1
+1 to +2
+2 to +3
+3 to +4
> 4

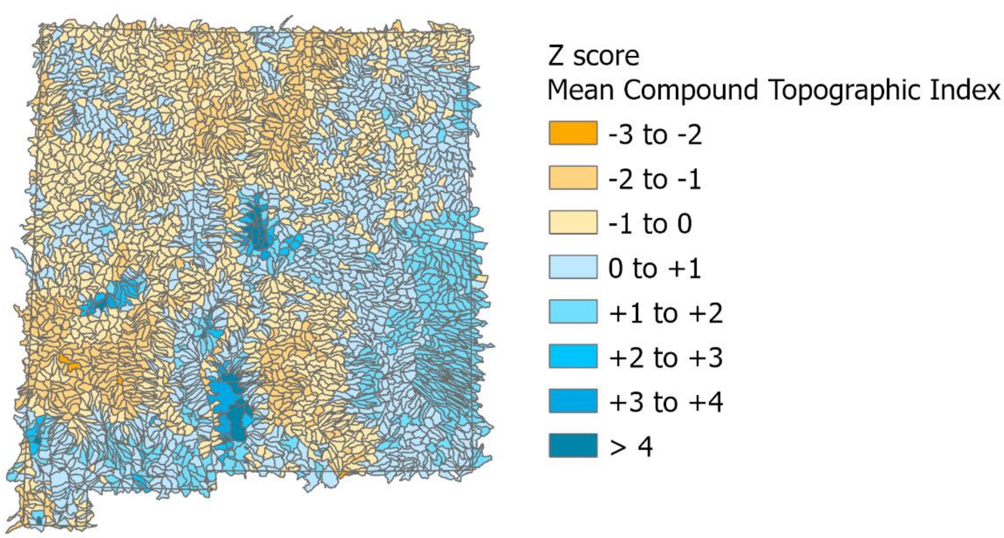
Amphibian and Reptile Habitat



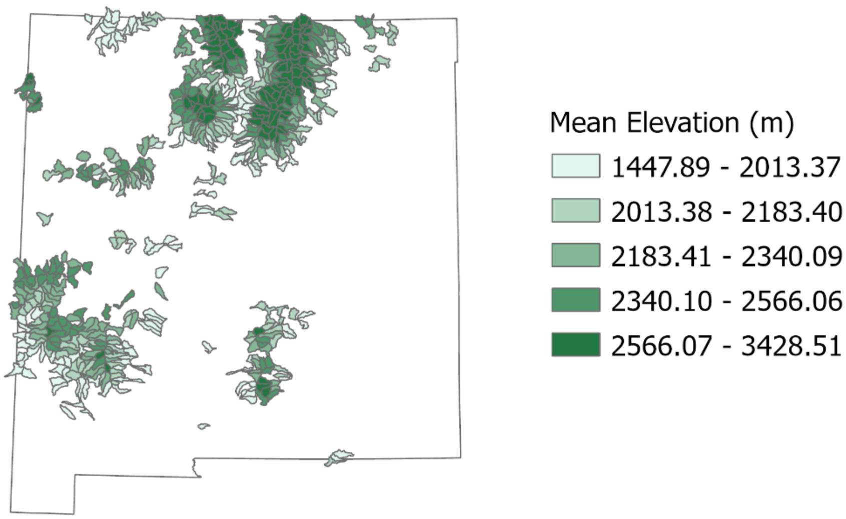


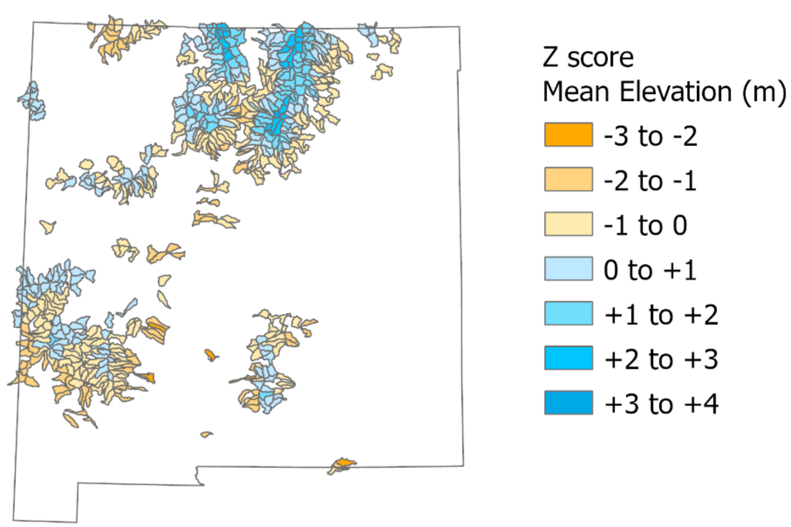
Ephemeral Catchments



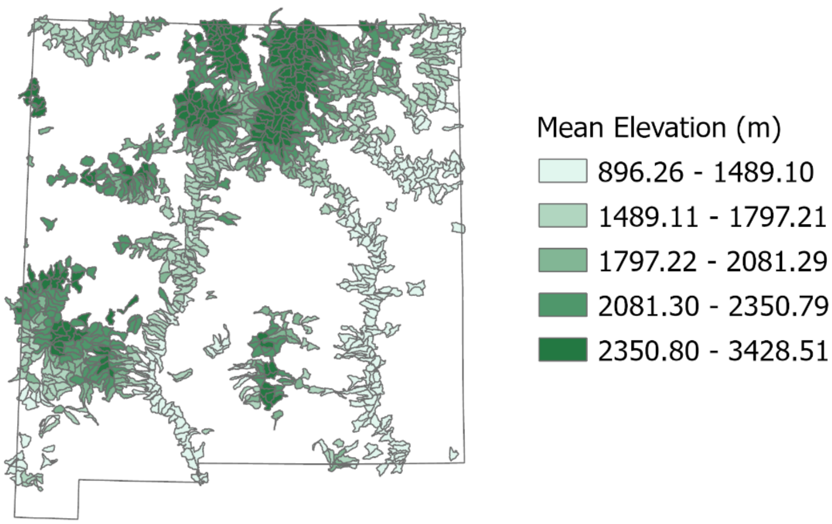


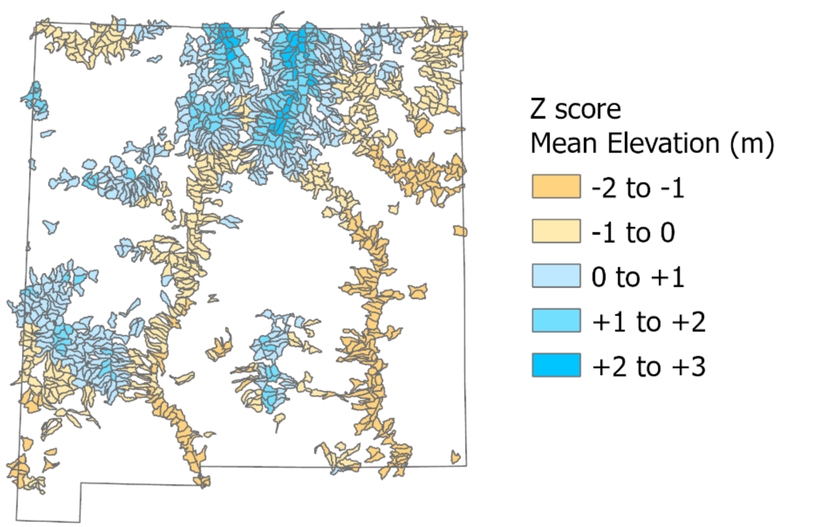
Cold-Water Fish Habitat



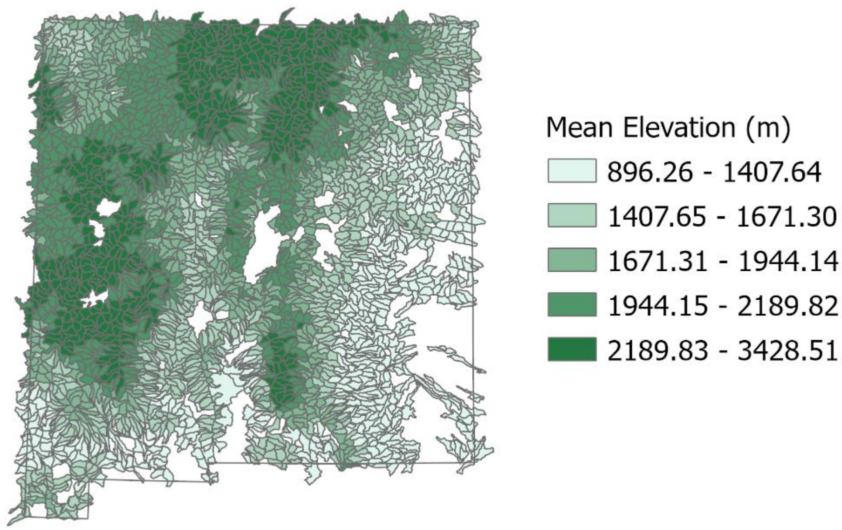


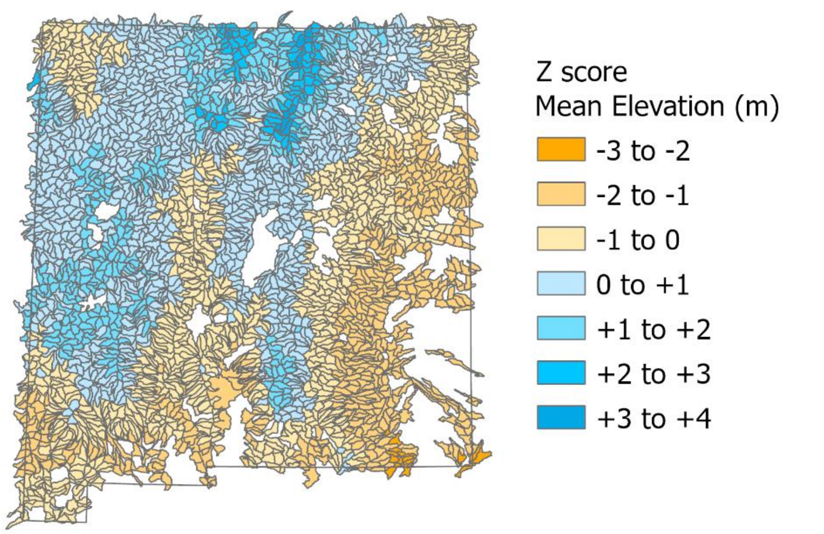
Perennial Streams



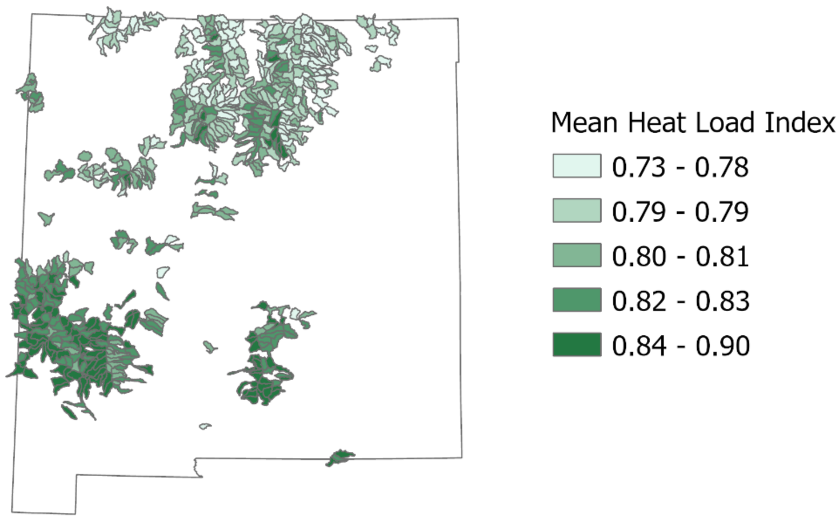


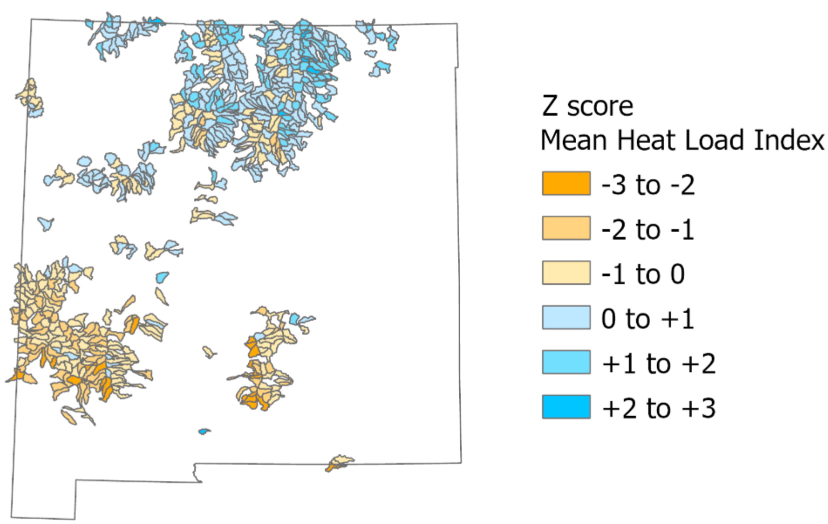
Amphibian and Reptile Habitat



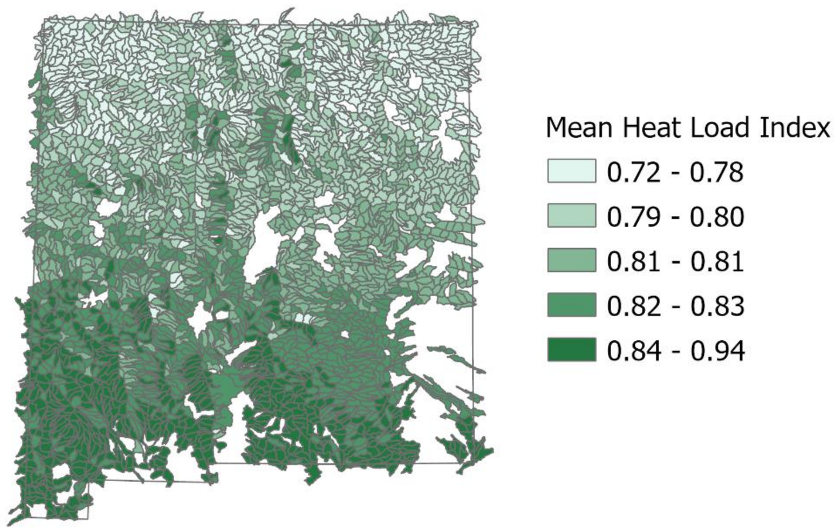


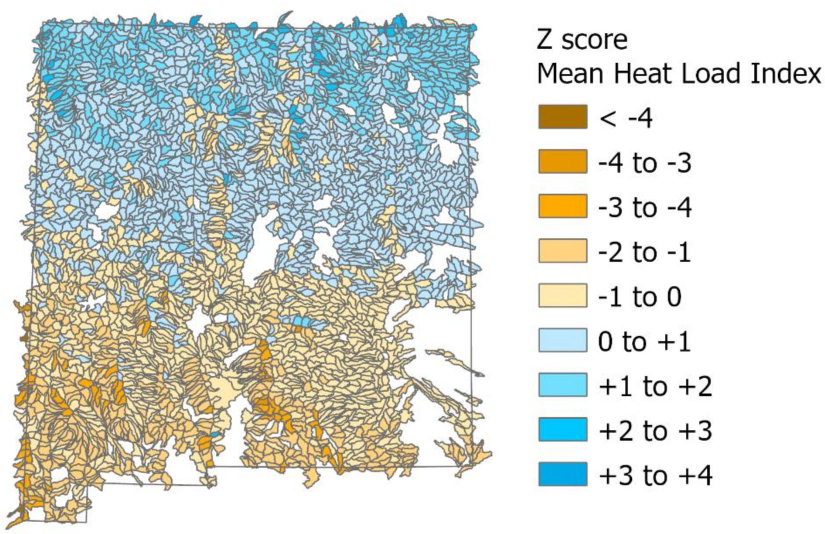
Cold-Water Fish Habitat



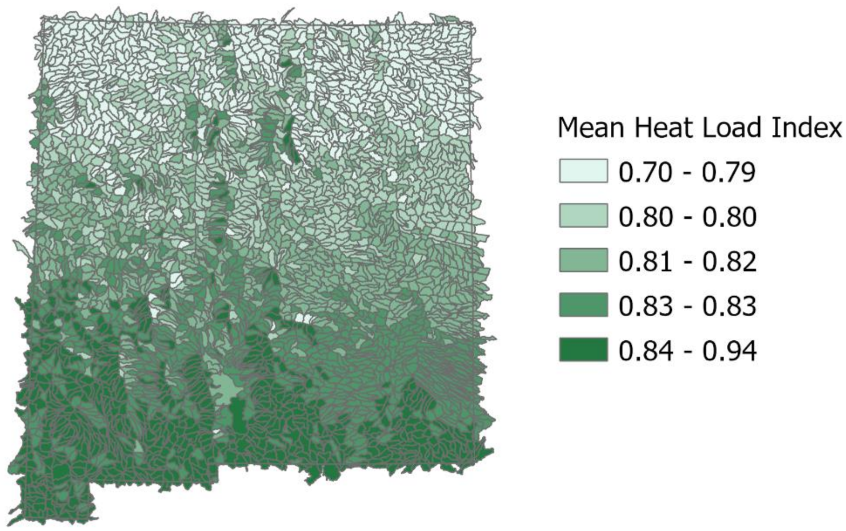


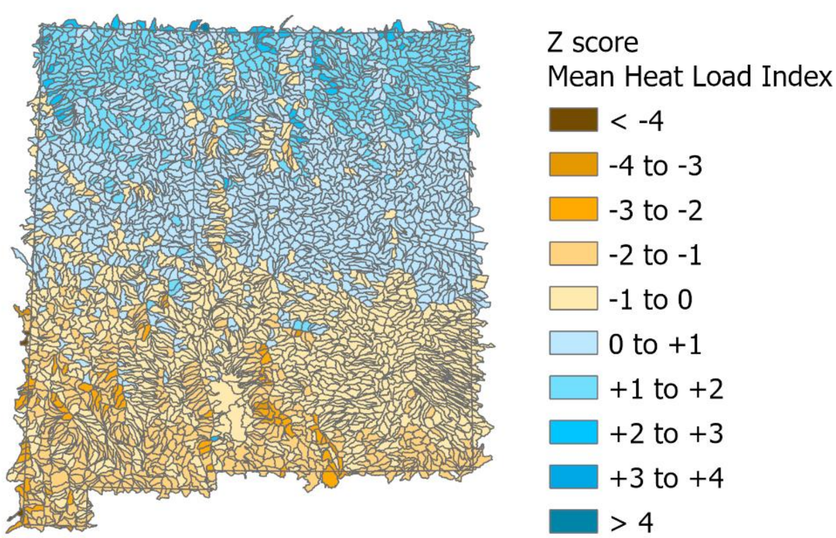
Amphibian and Reptile Habitat



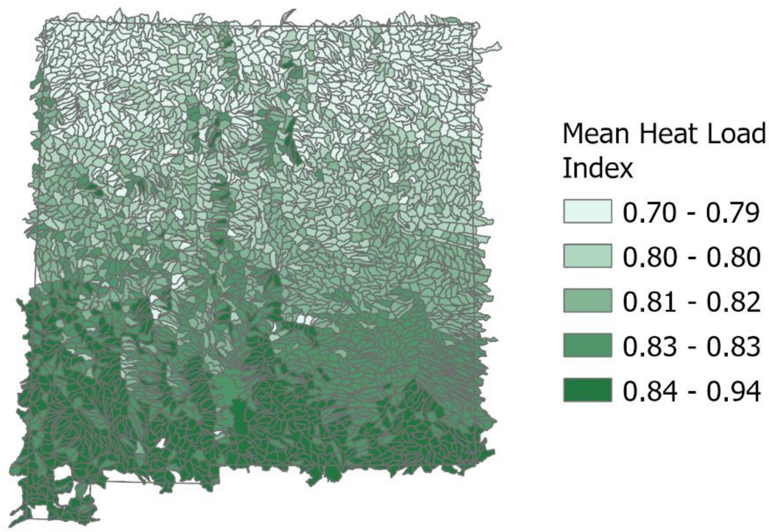


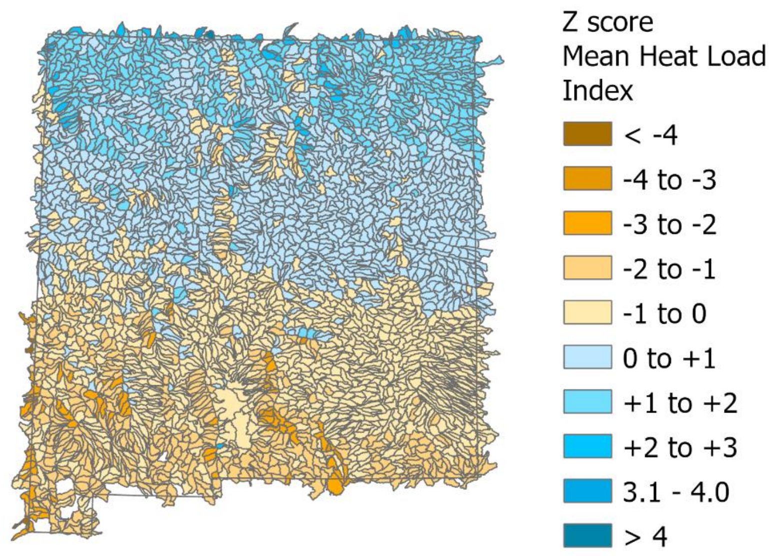
Ephemeral Catchments



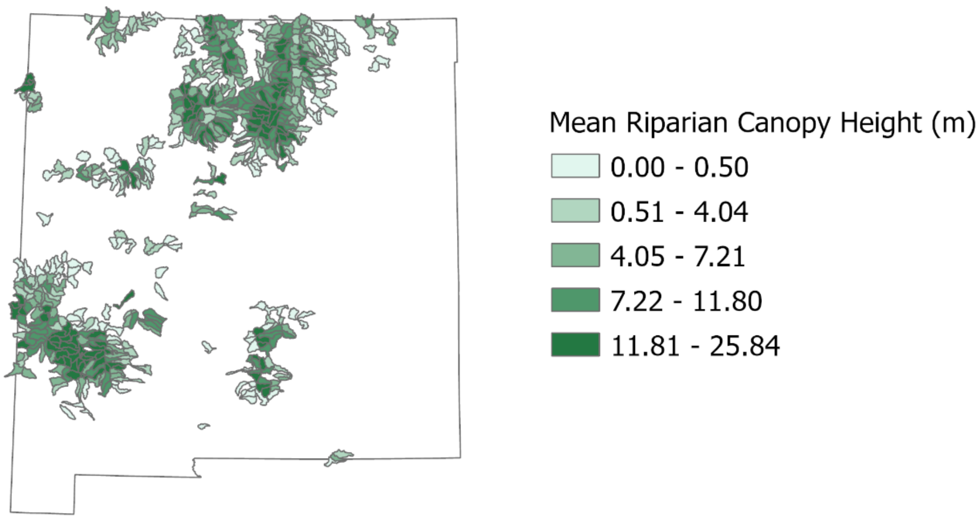


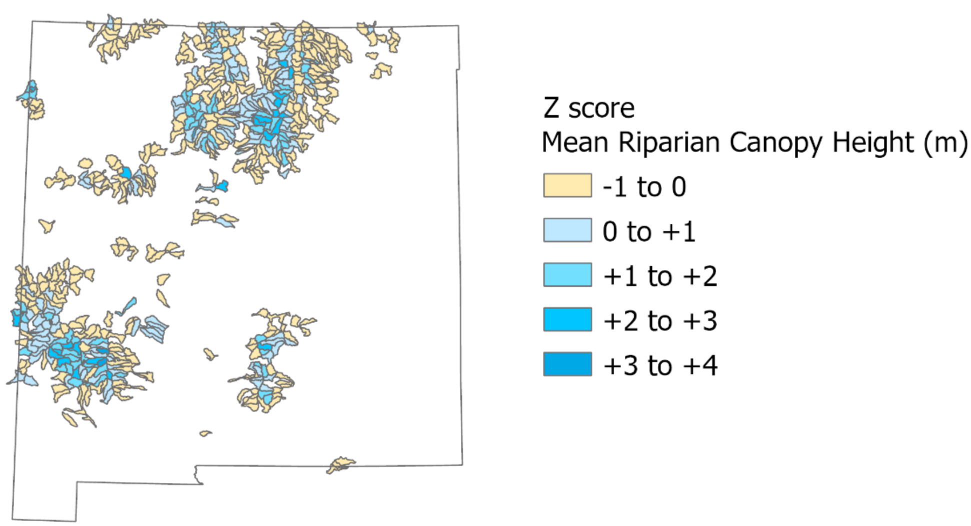
Springs


Mean Heat Load
Index
0.70 - 0.79
0.80 - 0.80
0.81 - 0.82
0.83 - 0.83
0.84 - 0.94

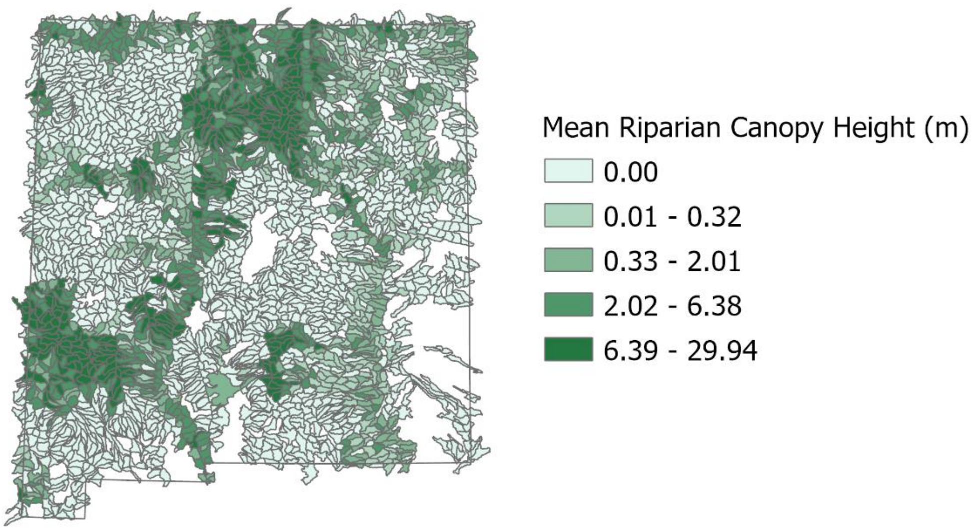

Z score
Mean Heat Load
Index
< -4
-4 to -3
-3 to -2
-2 to -1
-1 to 0
0 to +1
+1 to +2
+2 to +3
3.1 - 4.0
> 4

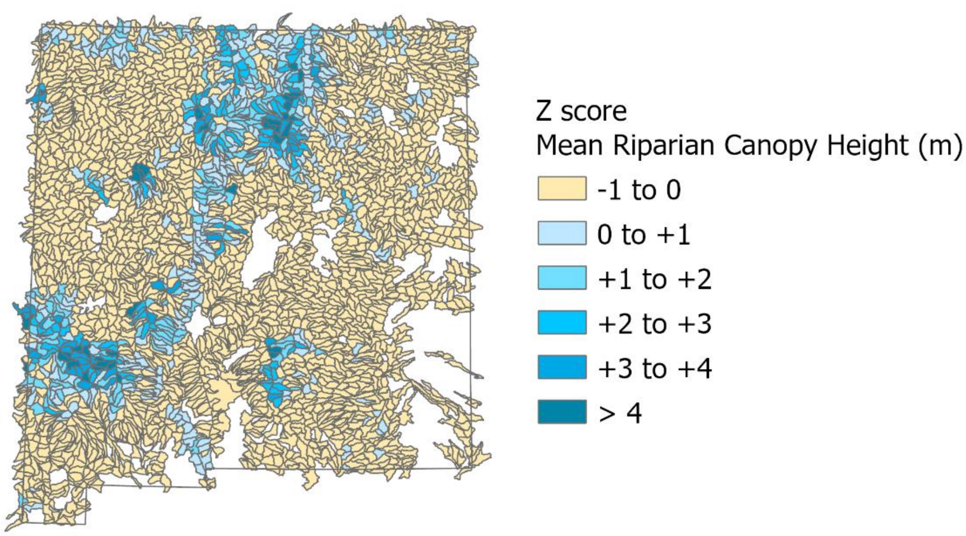
Cold-Water Fish Habitat



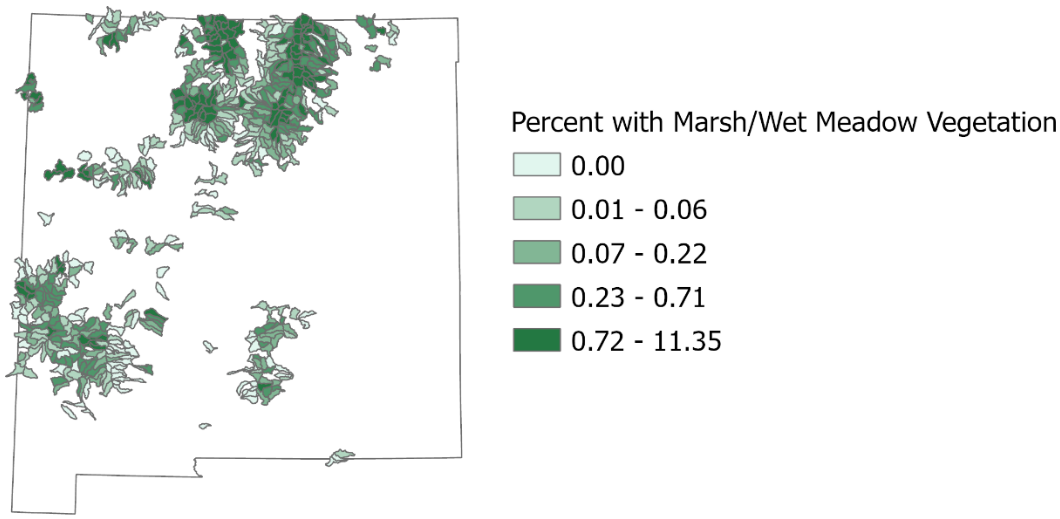


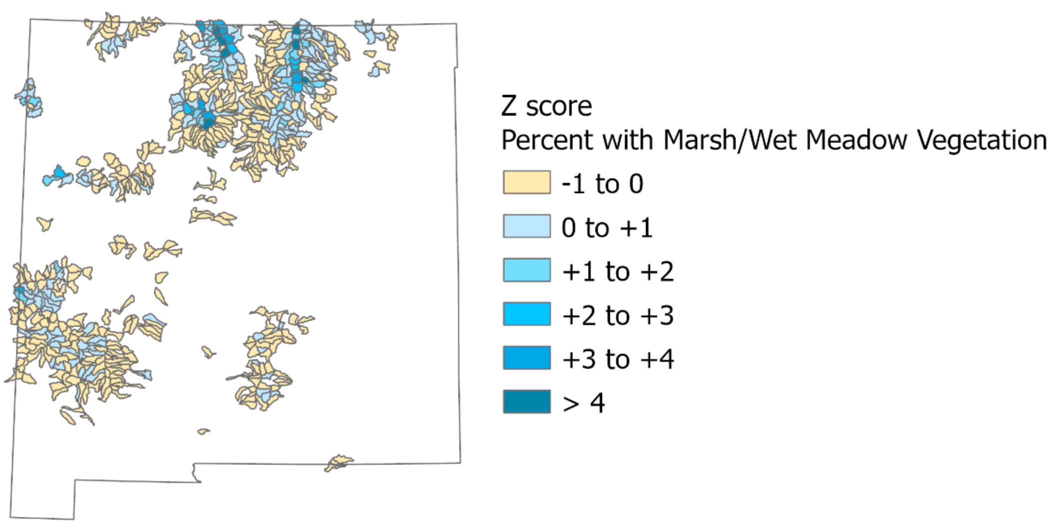
Amphibian and Reptile Habitat



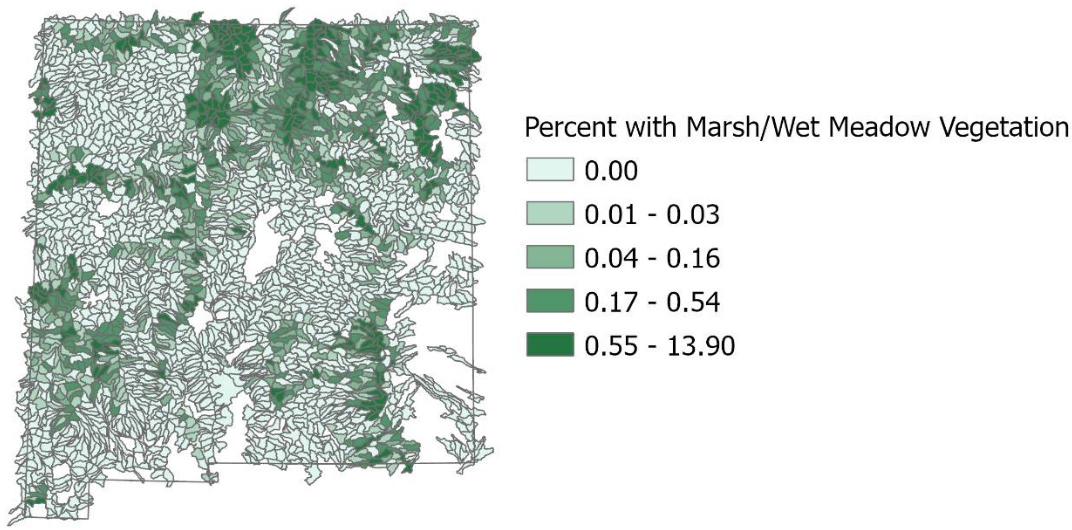


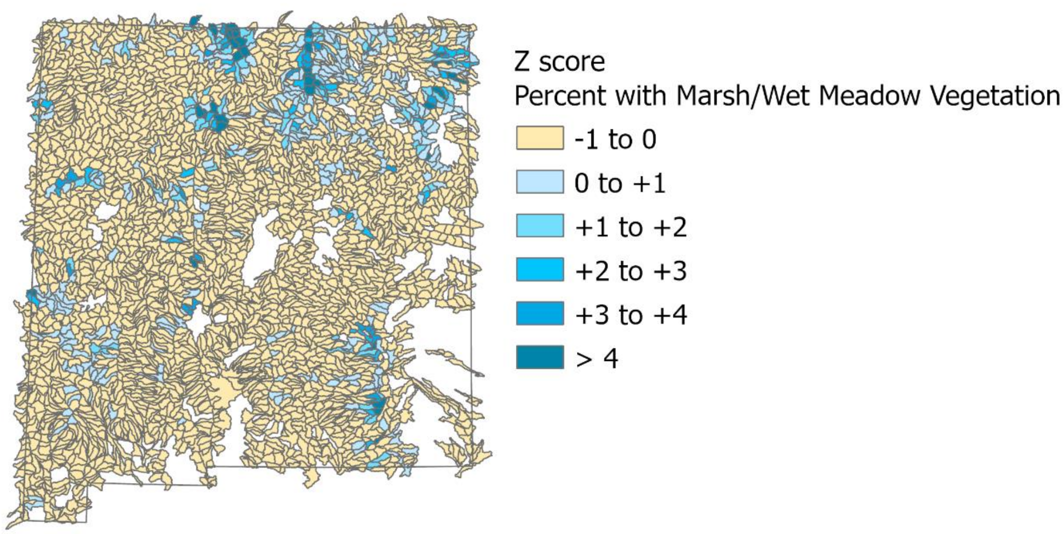
Cold-Water Fish Habitat



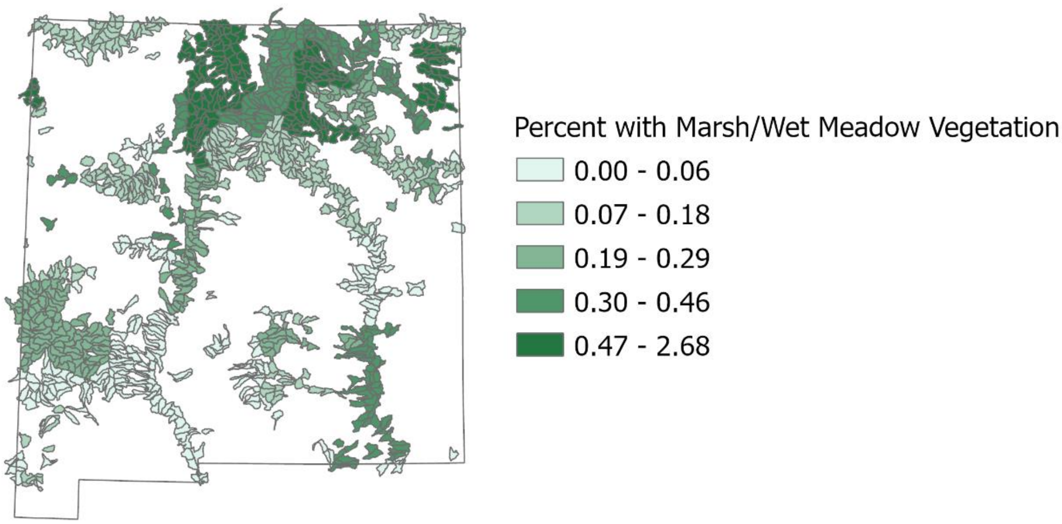


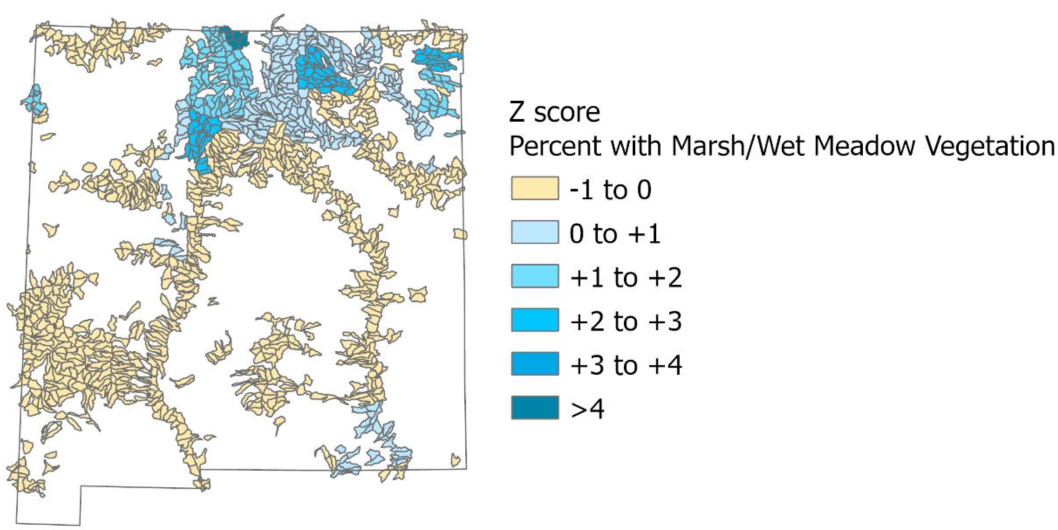
Amphibian and Reptile Habitat



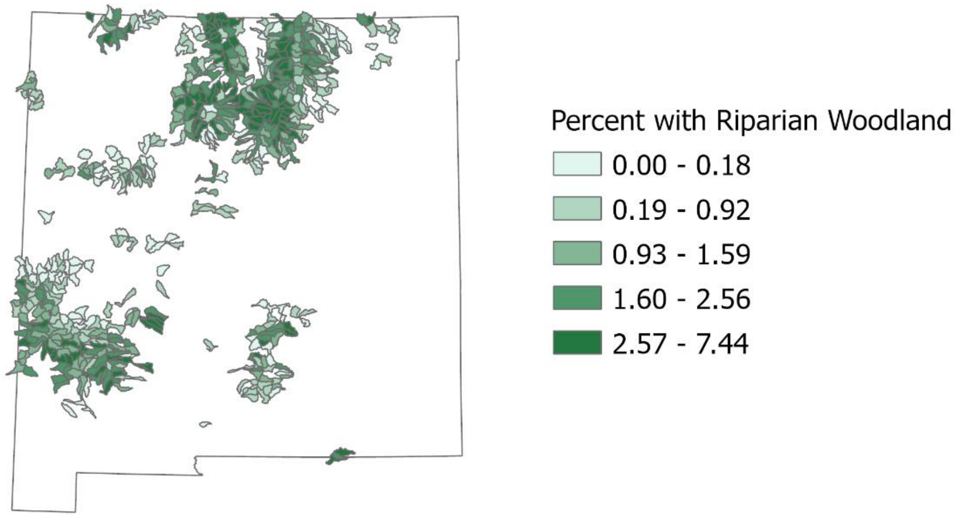


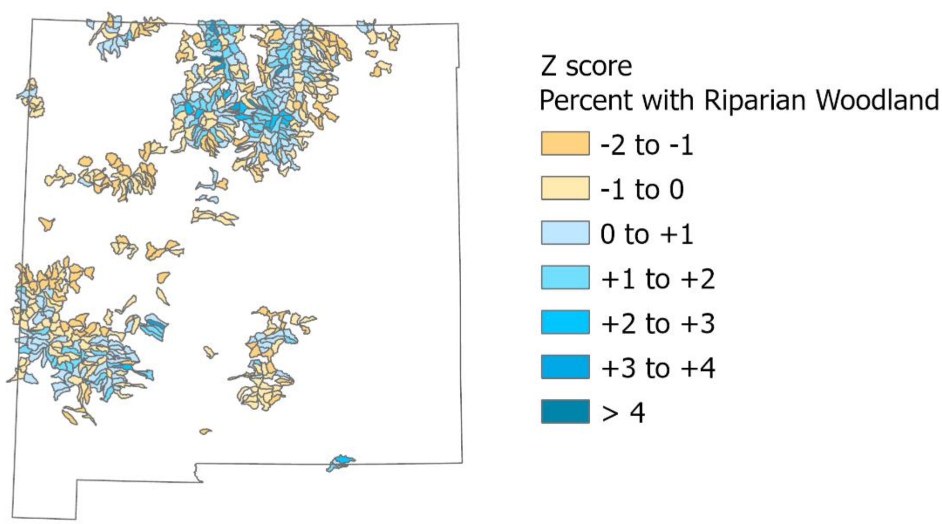
Perennial Streams



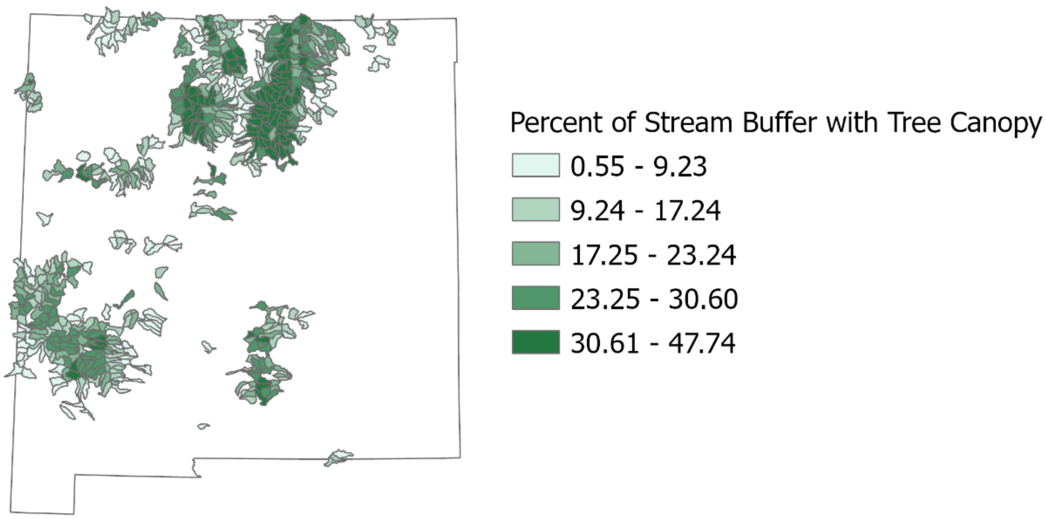


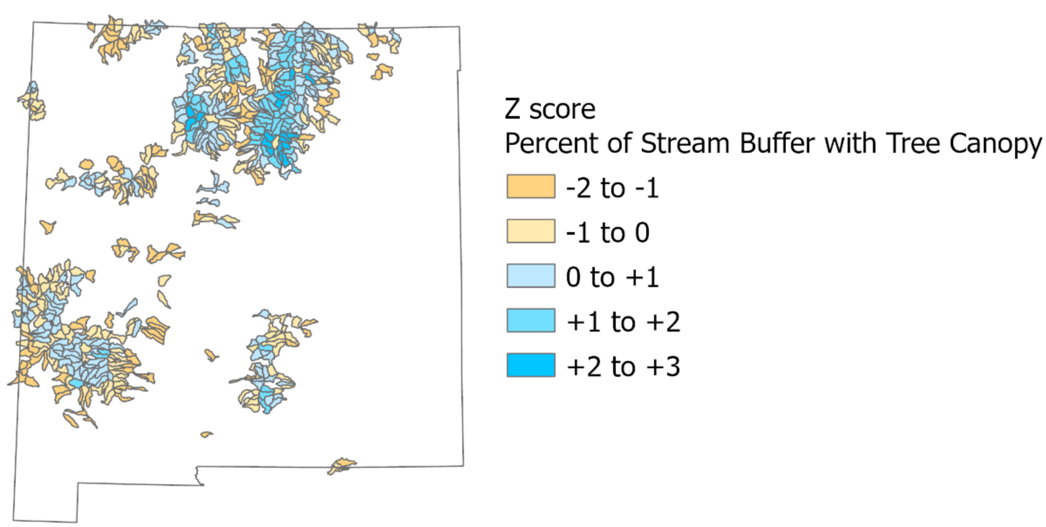
Cold-Water Fish Habitat





Cold-Water Fish Habitat





Amphibian and Reptile Habitat