FUTURE PROJECTIONS OF GROUNDWATER RECHARGE IN NEW MEXICO USING THE CMIP6 DATASET

By

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Project Report

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ABSTRACT

FUTURE PROJECTIONS OF GROUNDWATER RECHARGE IN NEW MEXICO USING THE CMIP6 DATASET

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Groundwater is the primary source of freshwater in New Mexico, supporting agriculture, municipal supply, industry, and ecosystems, yet its sustainability is increasingly challenged by semi arid climatic conditions, recurrent droughts, and projected climate variability. Recharge, the process by which precipitation and snowmelt infiltrate soils and percolate into aquifers, is a critical but spatially heterogeneous component of the hydrologic cycle, influenced by precipitation intensity, slope, soil texture, geology, vegetation, and drainage characteristics. This study applies an integrated Geographic Information Systems (GIS) and Analytical Hierarchy Process (AHP) framework to delineate groundwater recharge potential zones across New Mexico under both baseline and future climate scenarios. Eight thematic layers including slope, precipitation, soil group, geology, land cover, drainage density, lineament density, and geomorphology were reclassified into suitability categories based on hydrogeological principles and weighted using AHP to generate a composite recharge potential map. To incorporate future climate variability, daily precipitation projections from the NASA NEX GDDP CMIP6 dataset were aggregated into annual totals for three representative periods: near future (2030), mid century (2070), and end century (2100) under the SSP2 4.5 scenario. Results indicate that moderate to moderately good recharge zones dominate the northeastern, north-central, and southwestern parts of the state, where permeable soils, favorable geology, and structural lineaments coincide with moderate rainfall. In contrast, very low and low recharge potential is prevalent in the southern and southeastern areas characterized by steep slopes, clay rich soils, and high drainage density. Future projections suggest spatial shifts in recharge zones, with localized declines in precipitation reducing recharge potential in eastern basins while areas of the Rio Grande Valley and northern highlands may maintain moderate to high suitability. The outcomes provide a spatially explicit, forward looking tool for groundwater management, land use planning, and climate adaptation strategies, supporting long term water sustainability in a highly water stressed region.

Keywords: Groundwater recharge, GIS, AHP, CMIP6, climate change, New Mexico, recharge potential mapping, SSP2 4.5

1 Introduction

Groundwater is the primary source of freshwater in New Mexico, sustaining agriculture, domestic supply, industry, and ecosystems across both rural and urban areas. In many regions, it is the only practicable source of water because surface water is scarce, highly variable, and often fully appropriated. According to the New Mexico Environment Department (NMED), approximately 78% of residents rely on groundwater for drinking water, and nearly half of the state's total annual withdrawals are derived from aquifers. This dependence is further magnified by the state's desert climate, where average annual precipitation is only about 250 mm and more than 95% of surface water from rainfall or snowmelt is lost to evapotranspiration. As population growth and economic development increase demand, concerns about groundwater sustainability have intensified, particularly under conditions of recurrent drought and climate variability (New Mexico Environment Department, 2025).

Groundwater recharge is the process by which precipitation and snowmelt infiltrate soils and percolate into aquifers and is one of the most critical yet spatially variable components of the hydrological cycle. Recharge depends on a combination of climatic, geomorphological, geological, and land-surface factors such as rainfall intensity, slope, soil texture, vegetation cover, and drainage characteristics (Arulbalaji et al., 2019). Previous studies in New Mexico have contributed significantly to understanding recharge dynamics. For example, the Statewide Water Assessment project applied the Evapotranspiration and Recharge Model (ETRM) to generate recharge estimates across the state, while later refinements employed a high-balance soil–water model for more detailed estimation (Ketchum et al., 2016). More recently, Li et al. (2021) evaluated long-term changes in regional recharge using a water balance approach, providing valuable insight into historical trends.

Despite these advances, most prior research has concentrated on historical or baseline recharge conditions, with limited attention to future climate variability. This represents a critical knowledge gap because New Mexico's semi-arid environment and reliance on recharge from precipitation and snowmelt make it highly vulnerable to projected reductions in rainfall and increases in evapotranspiration under climate change. Without forward-looking assessments, policymakers and water managers lack the spatially explicit tools necessary to plan for long-term groundwater sustainability.

This study addresses that gap by integrating geospatial analysis and multi-criteria decision-making with climate projections to evaluate groundwater recharge potential under both present and future conditions. A Geographic Information Systems (GIS) and Analytical Hierarchy Process (AHP) framework was employed to generate and weight eight thematic layers: slope, precipitation, soil group, geology, land cover, drainage density, lineament density, and geomorphology. Each layer was reclassified into suitability categories based on hydrogeological principles, and weights were derived from literature and expert judgment to ensure consistency and transparency. The resulting composite recharge potential map provides a spatially continuous index of recharge favorability across the state.

To account for future climatic variability, precipitation projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were incorporated under Shared Socioeconomic Pathway (SSP) scenarios for 2030, 2070, and 2100. By combining intrinsic landscape controls with projected climatic drivers, the study develops a forward-looking assessment of groundwater recharge potential.

The outcomes of this research are expected to provide good decision-support tools for groundwater management and climate adaptation planning in New Mexico. In particular, the results can guide managed aquifer recharge (MAR) initiatives, inform land-use policies, and help prioritize regions most vulnerable to climate-induced reductions in recharge. By situating the analysis within both hydrological science and state-level water management priorities, this study contributes to ensuring long-term groundwater sustainability in one of the most water-stressed regions of the United States.

2 Importance of the Study

In New Mexico, groundwater is the lifeline for communities, agriculture, and industry, making it the most critical source of freshwater across the state. As noted by Li et al. (2021), “Groundwater is the only practicable source of water in many areas of the state and makes up nearly half of the annual total water withdrawn for all uses.” This heavy reliance underscores the urgent need to identify, protect, and sustain groundwater recharge zones, particularly in a region facing recurrent droughts and increasing water demand.

Recharge processes in arid and semi-arid regions are inherently complex. Erratic precipitation patterns, high evapotranspiration rates, and heterogeneous geological and soil characteristics mean that recharge is often confined to specific landscape features such as alluvial fans, fracture zones, and gently sloping terrains. These areas provide the permeability and storage capacity necessary for effective infiltration. Numerous studies have confirmed that lithological formations, slope gradients, and land use are among the most decisive factors influencing recharge opportunities and groundwater availability (Lentswe and Molwalefhe, 2020).

The application of remote sensing and GIS-based approaches has made it possible to delineate these zones at large scales in a cost-effective manner. This study builds on that foundation by employing a GIS–AHP framework, which has been demonstrated in other regions to improve accuracy and reliability. For example, Dar et al. (2021) successfully applied GIS–AHP in the Kashmir Valley, validating their model with borehole data and achieving an Area Under Curve (AUC) of 79.69%. Their work highlights the practical value of integrating geospatial data with decision-support techniques. Similarly, Baghel et al. (2023) emphasized that groundwater management requires systematic planning, not only to secure drinking water supplies but also to sustain livelihoods and support regional economies.

An additional contribution of this study is the integration of climate change projections into recharge assessment. Using CMIP6 climate scenarios, it becomes possible to evaluate how future precipitation and evapotranspiration patterns will alter recharge potential across New Mexico. Li et al. (2021) demonstrated that shifts in precipitation regimes already produce significant regional variability in recharge. Incorporating these projections into groundwater assessments provides a forward-looking perspective that can guide water managers and policymakers.

By situating recharge mapping within both present and future contexts, this study offers more than a static inventory of recharge zones. It provides a dynamic framework for adaptive water management in New Mexico. The findings are expected to inform priority setting for artificial recharge projects, protection of groundwater-dependent ecosystems, and long-term strategies that strengthen resilience to climate change. In this way, the study addresses both the immediate and future challenges of groundwater sustainability in one of the most water-stressed states in the United States.

3 Literature Review

Numerous studies have demonstrated the effectiveness of GIS and multi-criteria decision-making techniques, particularly the Analytical Hierarchy Process (AHP), in delineating groundwater recharge potential zones across diverse hydrogeological settings.

Arulbalaji et al. (2019) applied an integrated GIS–AHP framework in the Vamanapuram river basin of the Southern Western Ghats, India, using 12 thematic layers including geology, geomorphology, slope, land use/land cover, drainage density, lineament density, soil, rainfall, curvature, roughness, topographic wetness index, and topographic position index. Their results classified the basin into five groundwater potential categories and achieved an overall accuracy of approximately 85%, with moderate recharge zones covering nearly 59% of the study area. The authors emphasized that permeable lithologies, gentle slopes, and high rainfall zones were the most favorable for recharge, while steep slopes and crystalline lithologies restricted infiltration (Arulbalaji et al., 2019).

Hossain et al. (2024) further advanced the application of geospatial–AHP methods in the Barind Tract of Bangladesh, one of the most groundwater-stressed regions in South Asia. Their study integrated geology, soil, slope, rainfall, and land use layers to delineate groundwater recharge potential, assigning weights through AHP and validating results with well-yield data. They concluded that the GIS–AHP approach provides a reliable and sustainable framework for identifying suitable areas for artificial recharge and sustainable groundwater management, especially in regions with agricultural water demand pressures (Hossain et al., 2024).

In southern India, Lavanya and Muthukumar (2024) emphasized the novelty of combining geospatial techniques with AHP to delineate recharge zones. Their study highlighted the importance of pairwise comparison matrices, normalization, and consistency checks for minimizing subjectivity in thematic weight assignment. The methodological strength of their framework provides replicable guidelines for application in other semi-arid regions, including the hydrogeological context of New Mexico.

Das and Pal (2019) extended the methodology by incorporating fuzzy-AHP in the Goghat-II block of West Bengal, India, to address uncertainties in thematic weight assignments. They observed that groundwater recharge was strongly dependent on porosity and permeability, which in turn were governed by geology, geomorphology, lineaments, slope, soil texture, and land use. This demonstrated the importance of incorporating fuzzy logic to account for imprecision in parameter influence.

Outside South Asia, Lentswe and Molwalefhe (2020) applied GIS–AHP to delineate groundwater potential in Botswana. They reported that high recharge sites, covering only 8% of the basin, were strongly associated with sandstone and fractured basaltic outcrops, a finding that resonates with similar geological controls observed in parts of New Mexico.

In the U.S. context, Miller et al. (2021) evaluated the Bear Canyon Recharge Project in Albuquerque, New Mexico. Their study highlighted the necessity of integrating hydrological feasibility with institutional and regulatory frameworks in the implementation of recharge projects, demonstrating that scientific mapping of recharge potential must be paired with governance and management considerations for effective water resource planning.

Collectively, these studies affirm the utility of combining GIS, AHP, and climate datasets in groundwater research. They also demonstrate the adaptability of the approach across diverse climatic and geological settings. By synthesizing intrinsic physical parameters with extrinsic climatic variables, the GIS–AHP methodology provides a robust and transferable framework for delineating groundwater recharge potential, justifying its application in New Mexico's structurally complex and water-stressed environment.

4 Materials and Methods

This study applies a GIS-based Analytical Hierarchy Process (AHP) framework to delineate groundwater recharge potential zones in New Mexico. Multiple thematic layers representing topographic, hydrological, geological, and climatic factors were developed, standardized, and integrated through a weighted overlay procedure. All analyses were carried out using Geographic Resources Analysis Support System (GRASS) in the NAD83 / Conus Albers projection (EPSG:5070) (GRASS Development Team, 2024). The following subsections describe the preparation of each thematic layer in detail.

4.1 Drainage Density

The extraction of drainage density was performed for the entire state of New Mexico, which encompasses an area of approximately 315,000 km^2. Drainage density (DD) is one of the most widely used morphometric indices in hydrological and geomorphological studies. The concept was first introduced by Horton (1932, 1945), who defined it as the total length of streams within a given drainage area, expressed in km/km^2. Mathematically, it is represented as:

$$DD = \frac{L}{A}$$

where L is the total length of streams (km) and A is the drainage area (km^2). Hydrologically, drainage density reflects the balance between surface runoff and infiltration. Areas with sparse drainage networks (low DD) are typically associated with permeable substrates, gentle slopes, and high infiltration capacity, which collectively promote groundwater recharge. Conversely, high drainage density indicates well-developed channel networks that promote rapid runoff, leaving less opportunity for water to percolate into the subsurface. As noted by Zhang et al. (2021), drainage density is a macroscale measure of hydrological development, reflecting how climate, slope, lithology, vegetation, and soil properties shape surface and subsurface water pathways. Similarly, Yang et al. (2025) emphasized that high drainage density promotes rapid hydrological responses, whereas low density is characteristic of arid and semi-arid settings with greater recharge opportunities.

To compute drainage density, a 10 m resolution Digital Elevation Model (DEM) was used as the primary input. Flow direction and flow accumulation rasters were then generated. Flow direction assigns each DEM cell a downslope path toward its steepest neighbor, while flow accumulation quantifies the number of upstream cells contributing flow into a given cell. Together, these layers provided the hydrological foundation for stream network extraction.

Stream networks were delineated by applying a threshold to the flow accumulation raster. Only cells with upstream contributing areas greater than the threshold were classified as streams, while all others were excluded. In this study, a threshold of 30,000 cells was selected, corresponding to a contributing area of approximately 3 km^2 for the 10 m DEM. According to Zhang et al. (2021), the flow accumulation threshold (FAT) directly influences river network density: thresholds that are too low produce spurious channels, while overly high thresholds omit genuine stream segments. To balance these considerations, the threshold in this study was calibrated iteratively to ensure that the extracted stream network captured the primary hydrological channels while minimizing pseudo rivers.

The extracted stream network was vectorized to represent drainage lines. Stream lengths were calculated in kilometers for each grid cell, and the total stream length was normalized by the corresponding drainage area derived from the DEM. This procedure yielded a continuous drainage density raster for New

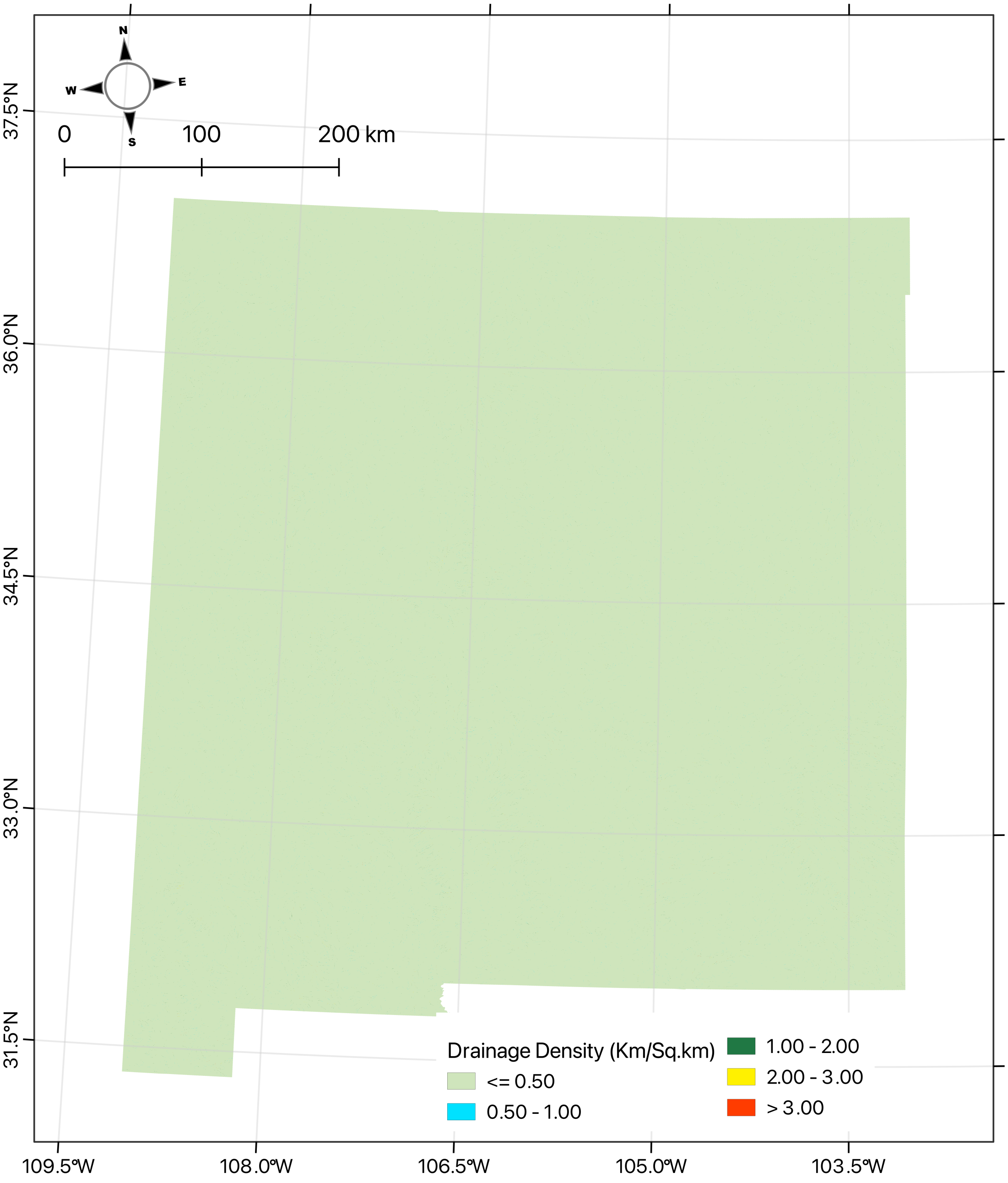

Figure 1: Spatial distribution of drainage density across New Mexico, expressed in km/km^2. Lower values correspond to higher groundwater recharge potential.

Mexico, providing a spatially distributed measure of runoff potential relative to infiltration opportunity.

For use in the Analytical Hierarchy Process (AHP) framework, the drainage density raster was reclassified into five recharge suitability categories: very high (≤ 0.5 km/km^2), high (0.5–1.0 km/km^2), moderate (1.0–2.0 km/km^2), low (2.0–3.0 km/km^2), and very low (> 3.0 km/km^2). This classification reflects the inverse relationship between drainage density and recharge: areas of low drainage density correspond to favorable recharge conditions due to reduced surface runoff and enhanced infiltration, while areas of high drainage density correspond to unfavorable conditions dominated by rapid runoff.

Figure 1 illustrates the drainage density distribution for New Mexico. The map shows that most of the state exhibits low to very low drainage density, which is favorable for recharge, whereas localized regions with higher drainage density indicate hydrologically less favorable zones. The drainage density layer thus provided an essential geomorphic indicator of groundwater recharge potential across New Mexico. By integrating this parameter with other thematic layers such as slope, geology, soils, lineament density, and precipitation, the model effectively captured the influence of surface hydrology on spatial recharge patterns.

4.2 Lineament Density

Lineament density is a key structural parameter for delineating groundwater recharge potential zones. Lineaments, which represent linear features such as faults, fractures, and joints, enhance secondary porosity and permeability of bedrock, thereby facilitating infiltration and subsurface water movement. Numerous studies have demonstrated that groundwater potential is positively correlated with lineament density, with higher densities associated with greater recharge potential (Arulbalaji et al., 2019; Dar et al., 2021). For example, Manyoe and Hutagalung (2022) showed that areas with high lineament density in the Libungo geothermal area were associated with good permeability and increased infiltration capacity. Similarly, Saepuloh et al. (2018) found that zones with high lineament length density coincided with geothermal fluid paths and recharge sites in West Java, confirming the importance of fractures and lineaments in enhancing fluid circulation. Conversely, areas of low lineament density tend to be structurally less favorable for infiltration due to the absence of such preferential flow paths.

Lineaments are often aligned with tectonic discontinuities, which are expressed at the surface as terrain breaks or abrupt slope changes. Slope analysis is therefore frequently incorporated in lineament mapping. Steep slopes, particularly those greater than 30°, may correspond to escarpments or scarps formed along fault and fracture zones, which are commonly associated with enhanced groundwater storage and recharge conditions. As emphasized in earlier groundwater potential studies, “the intensity of groundwater potential decreases with increasing distance from lineaments,” underscoring the hydrological importance of these features.

For this study, lineament density was computed using a grid-based approach to provide a spatially standardized measure of structural influence across New Mexico. First, a 10 m resolution DEM was processed to derive slope and aspect maps, which aided in the identification of structural breaks. Lineaments were then digitized from high-resolution satellite imagery and terrain derivatives. A fishnet grid of 10 km × 10 km (100 km^2) was superimposed across the study area, and the total length of lineaments intersecting each grid cell was calculated in kilometers. Lineament density (LD) was expressed as:

$$LD = \frac{L}{A}$$

where L is the cumulative length of lineaments (km) within a grid cell and A is the grid area (100 km^2). The resulting values, expressed in km/km^2, were subsequently rasterized to produce a continuous surface of lineament density.

The raster was then reclassified into five groundwater recharge suitability classes: very low (< 0.8 km/km^2), low (0.8–1.5 km/km^2), moderate (1.5–2.3 km/km^2), high (2.3–3.1 km/km^2), and very high (> 3.1 km/km^2). Areas with higher lineament density were assigned greater suitability values, reflecting their increased structural permeability and enhanced potential for recharge.

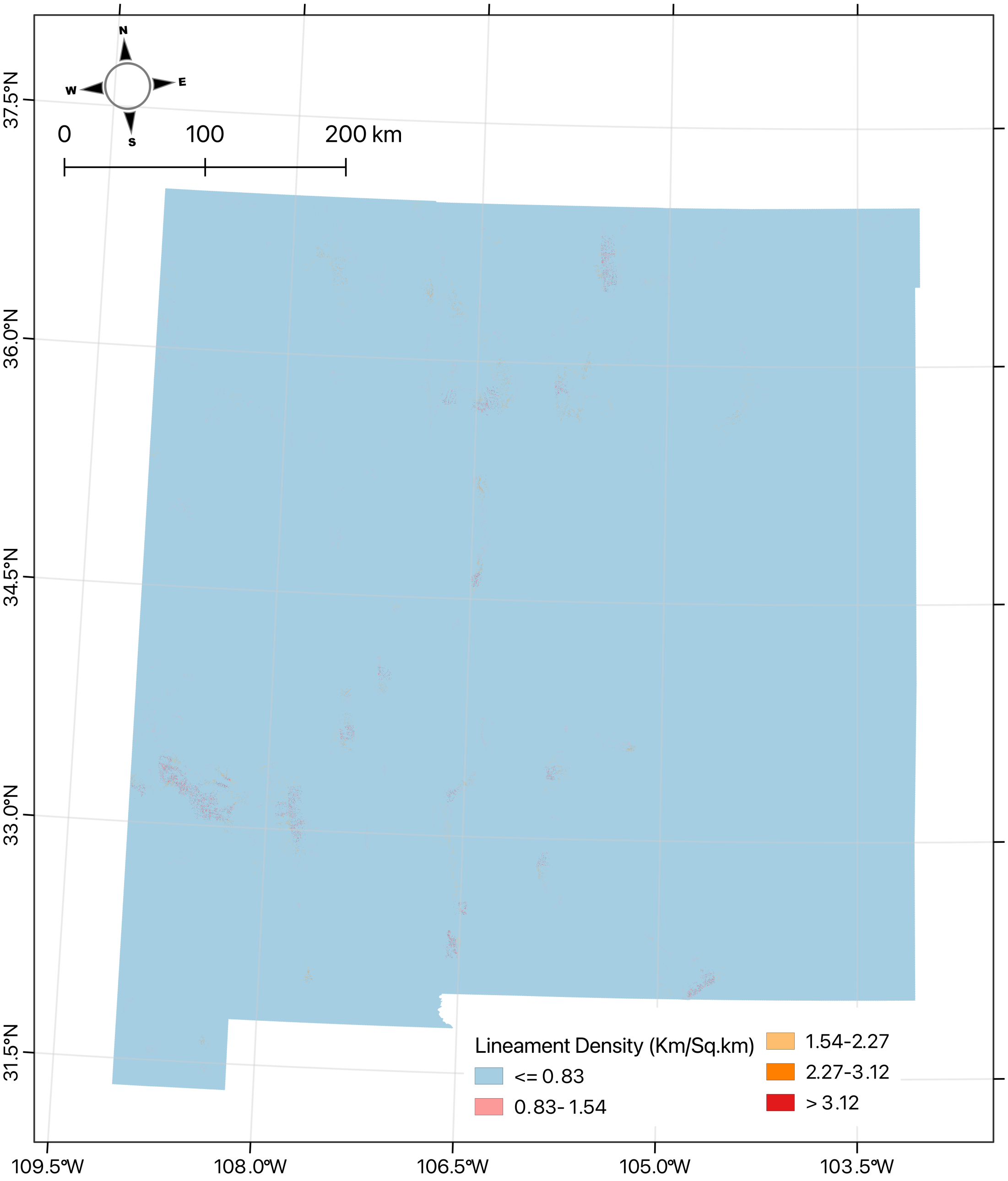

Figure 2: Spatial distribution of lineament density across New Mexico.

The spatial distribution of lineament density across New Mexico is shown in Figure 2. The map highlights that most of the state exhibits relatively low lineament density values (≤ 0.83 km/km^2), particularly in the southern and eastern regions, while localized pockets of higher density occur in the north-central and southwestern portions of the state. These higher-density areas correspond to structurally complex regions where faulting and fracturing are more pronounced, thereby enhancing secondary porosity and permeability. Such zones are considered more favorable for groundwater recharge because the presence of abundant lineaments provides preferential pathways for infiltration. In contrast, regions of low lineament density are structurally less favorable, limiting the potential for vertical and lateral groundwater movement.

The lineament density layer thus provided a critical structural control in the GIS–AHP framework. Its integration with hydrological, geomorphological, and climatic variables ensured that both surface and subsurface controls on recharge were explicitly accounted for in the groundwater potential mapping.

4.3 Slope

Slope is a fundamental topographic parameter that exerts strong control over surface hydrology and groundwater recharge. Gentle slopes favor infiltration by increasing the residence time of water on the land surface, while steep slopes accelerate runoff and reduce the opportunity for percolation (Das and Pal, 2019;

Li et al., 2021). Mahmoud (2014) further demonstrated that areas with excellent to good suitability for groundwater recharge are typically characterized by gentle slopes ranging from 4% to 8%, emphasizing that slope is one of the most decisive factors in recharge mapping. As a result, slope is widely used in groundwater potential studies to distinguish between areas conducive to infiltration and those dominated by runoff and erosion processes.

In this study, slope was derived from the 10 m resolution DEM using the GRASS (GRASS Development Team, 2024). The slope raster was reclassified into five recharge suitability classes following thresholds reported in previous studies: very high ($\leq 3°$), high (3–8°), moderate (8–15°), low (15–25°), and very low ($> 25°$). This classification reflects the principle that flatter terrains are more favorable for infiltration, while steeper terrains correspond to rapid runoff conditions.

The slope distribution across New Mexico is shown in Figure 3. The eastern and southeastern parts of the state are dominated by gentle slopes ($\leq 8°$), which are highly favorable for groundwater recharge. In contrast, the north-central and southwestern regions are characterized by slopes exceeding 15° and in some areas greater than 25°. These steeper terrains are hydrologically important for generating runoff and sustaining river systems, but they provide limited direct recharge due to reduced infiltration capacity.

The slope layer therefore played a critical role in the GIS–AHP framework,

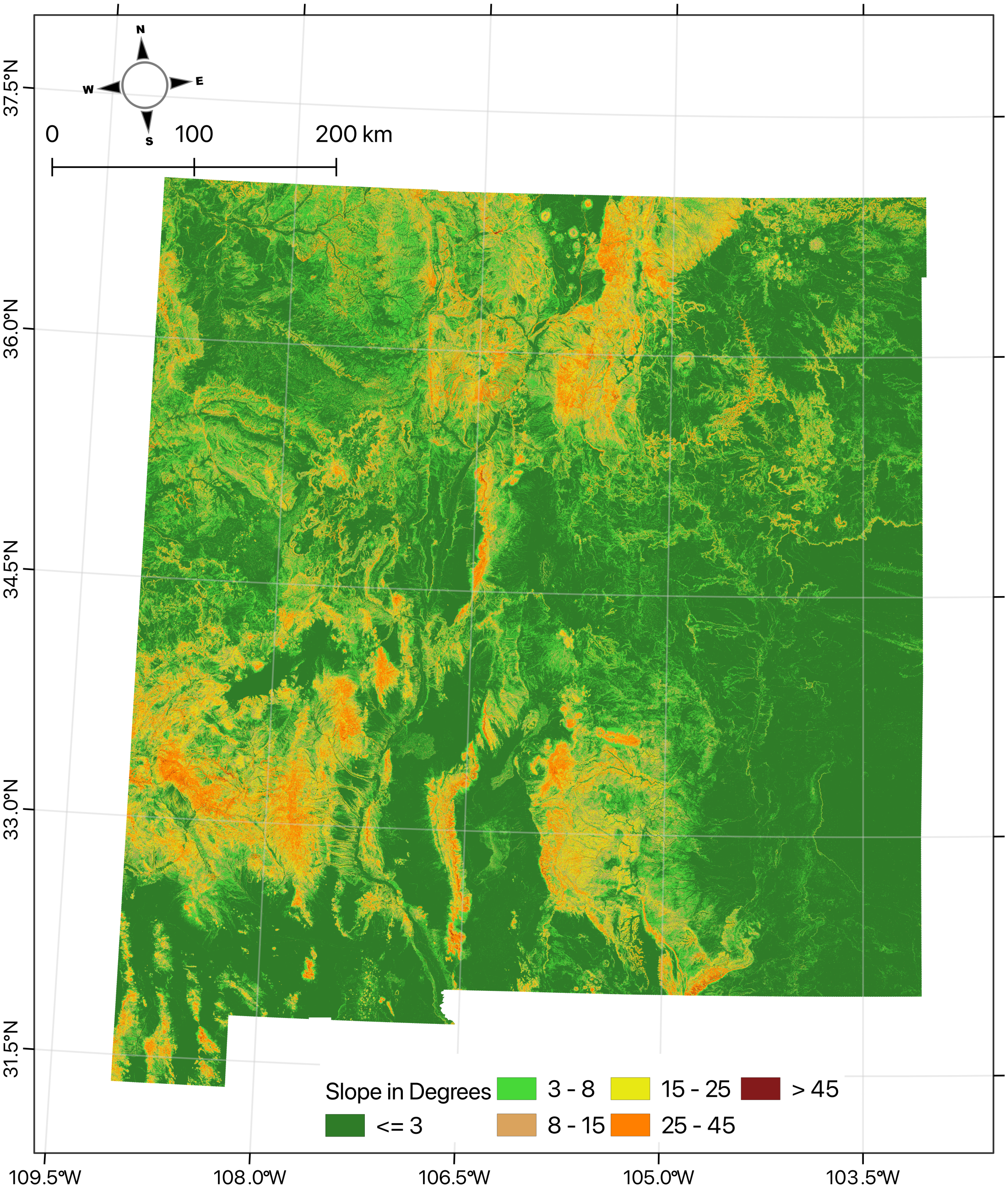

Figure 3: Slope distribution of New Mexico derived from a 10 m resolution DEM. Flatter regions in the east exhibit higher recharge potential, while steep mountain ranges in the north-central and southwest correspond to lower recharge potential.

ensuring that topographic influences on infiltration and runoff were explicitly incorporated into the assessment of groundwater recharge potential.

4.4 Geology

Geology is a fundamental factor influencing groundwater recharge because the lithological and structural characteristics of rocks determine their porosity, permeability, and infiltration capacity. Unconsolidated sediments and sedimentary formations typically exhibit higher primary porosity and permeability, thereby facilitating infiltration and recharge. In contrast, igneous and metamorphic rocks are generally less permeable due to their crystalline nature; however, secondary porosity resulting from fractures, joints, and weathering can locally enhance groundwater movement (Das and Pal, 2019). For instance, Mogaji et al. (2019) observed that quartzites, schists, and weathered basement rocks in Nigeria supported higher recharge potential because of their enhanced secondary porosity, whereas massive crystalline rocks were associated with low recharge potential. Similarly, Olabode (2019) reported that although crystalline basement aquifers are typically poor groundwater reservoirs due to limited primary porosity, weathering and fracturing processes can significantly improve their recharge potential. Thus, lithology plays a central role in delineating recharge potential zones.

For this study, the geology map of New Mexico was obtained from the United States Geological Survey (USGS) state geologic data compilation, available through the National Geologic Map Database (U.S. Geological Survey, 2025). The dataset was generalized into four major lithological categories relevant to groundwater recharge assessment: unconsolidated, sedimentary, igneous, and metamorphic. Water bodies were included as a separate class. The original vector data were processed and reclassified in a GIS environment to standardize lithological groups for suitability analysis.

The geology layer was then ranked according to recharge potential based on lithological properties. Unconsolidated deposits were assigned the highest suitability due to their high infiltration capacity, followed by sedimentary formations that provide moderate porosity and permeability. Igneous and metamorphic rocks were assigned lower suitability values, reflecting their generally impermeable nature except where fractures are present. The classification scheme is summarized as follows: very high (unconsolidated), high (sedimentary), moderate (weathered or fractured igneous/metamorphic), low (massive igneous), and very low (unfractured metamorphic).

As shown in Figure 4, the geology of New Mexico is dominated by sedimentary rocks, particularly in the eastern and central parts of the state, which provide moderate to high recharge potential. Igneous and metamorphic rocks are more prevalent in the north-central and southwestern mountainous regions, where recharge potential is relatively low except in fractured or weathered zones. Unconsolidated deposits, although spatially limited, represent areas of very high recharge

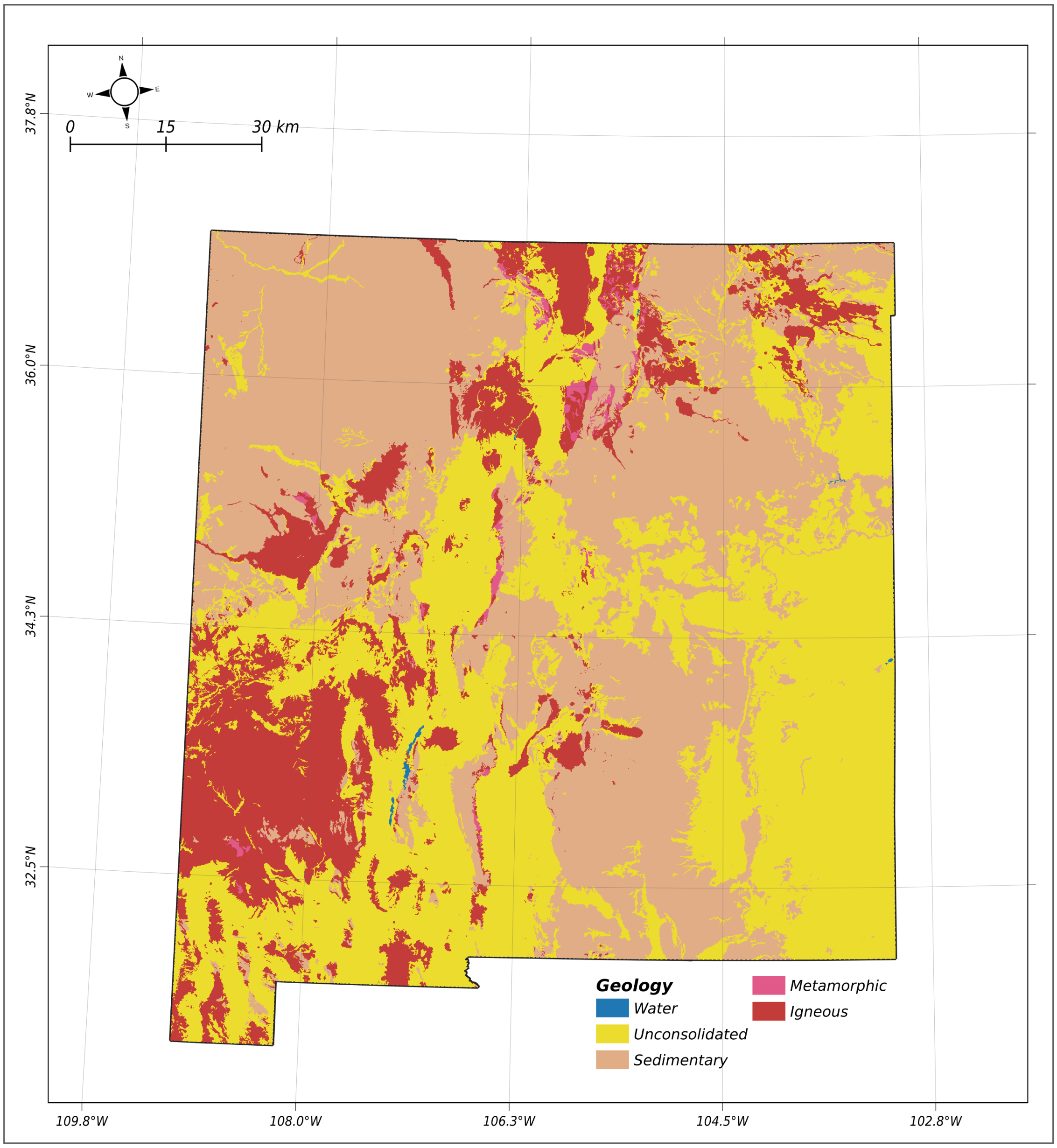

Figure 4: Generalized geology of New Mexico, reclassified into lithological groups relevant to groundwater recharge potential.

potential due to their high permeability. This geology layer thus provided a lithological control in the GIS–AHP model, complementing other thematic layers such as slope, drainage density, and lineament density in the assessment of groundwater recharge potential.

4.5 Land Cover

Land cover exerts a strong influence on groundwater recharge by mediating the balance among infiltration, evapotranspiration, and surface runoff. Vegetated surfaces tend to enhance infiltration by slowing runoff and increasing soil–water interactions, whereas impervious urban areas restrict infiltration and promote rapid runoff. Agricultural lands can contribute to recharge via irrigation return flow but may also limit infiltration through soil compaction. Characterizing land cover is therefore essential for identifying recharge potential zones.

National Land Cover Database (NLCD) at 30 m spatial resolution was used, derived from Landsat imagery (U.S. Geological Survey, 2024). Native NLCD classes were grouped into broader hydrogeologic classes for suitability analysis. Barren land, shrubland, and grassland were treated as more favorable for recharge because of minimal canopy interception and low imperviousness. Forested areas were assigned moderate to high suitability, reflecting enhanced infiltration through rooting and litter layers but higher evapotranspiration. Agricultural lands were classified as moderately suitable given their dependence on irrigation and management practices. Wetlands were considered less favorable for direct vertical percolation due to persistent saturation, and urban/developed lands were least suitable because impervious surfaces inhibit infiltration.

The reclassified land cover layer was incorporated into the AHP framework as a key thematic input. Figure 5 shows that shrubland and grassland (reclassified bin values 45–61) dominate much of the state, especially in central and southwestern regions, and are favorable for recharge due to permeable soils and limited impervious cover. Forested lands (61–78) occur mainly in the northeastern highlands, with additional patches in the southwestern and central upland regions which provide moderate to high suitability depending on evapotranspiration losses and local soils. Agricultural areas (28–45), mainly in the eastern plains and the Rio Grande Valley, show moderate recharge potential, though outcomes depend on irrigation and tillage. In contrast, urban areas (≤ 28) around Albuquerque, Santa Fe, and Las Cruces display low suitability due to extensive impervious surfaces. Water bodies and wetlands (> 78), while spatially limited, indicate high surface-water presence but typically limited direct vertical recharge because of saturation.

Including land cover in the multi-criteria overlay ensures that both natural and human-modified surface conditions are explicitly represented, capturing how vegetation, farming, and urbanization modify infiltration opportunities across the state.

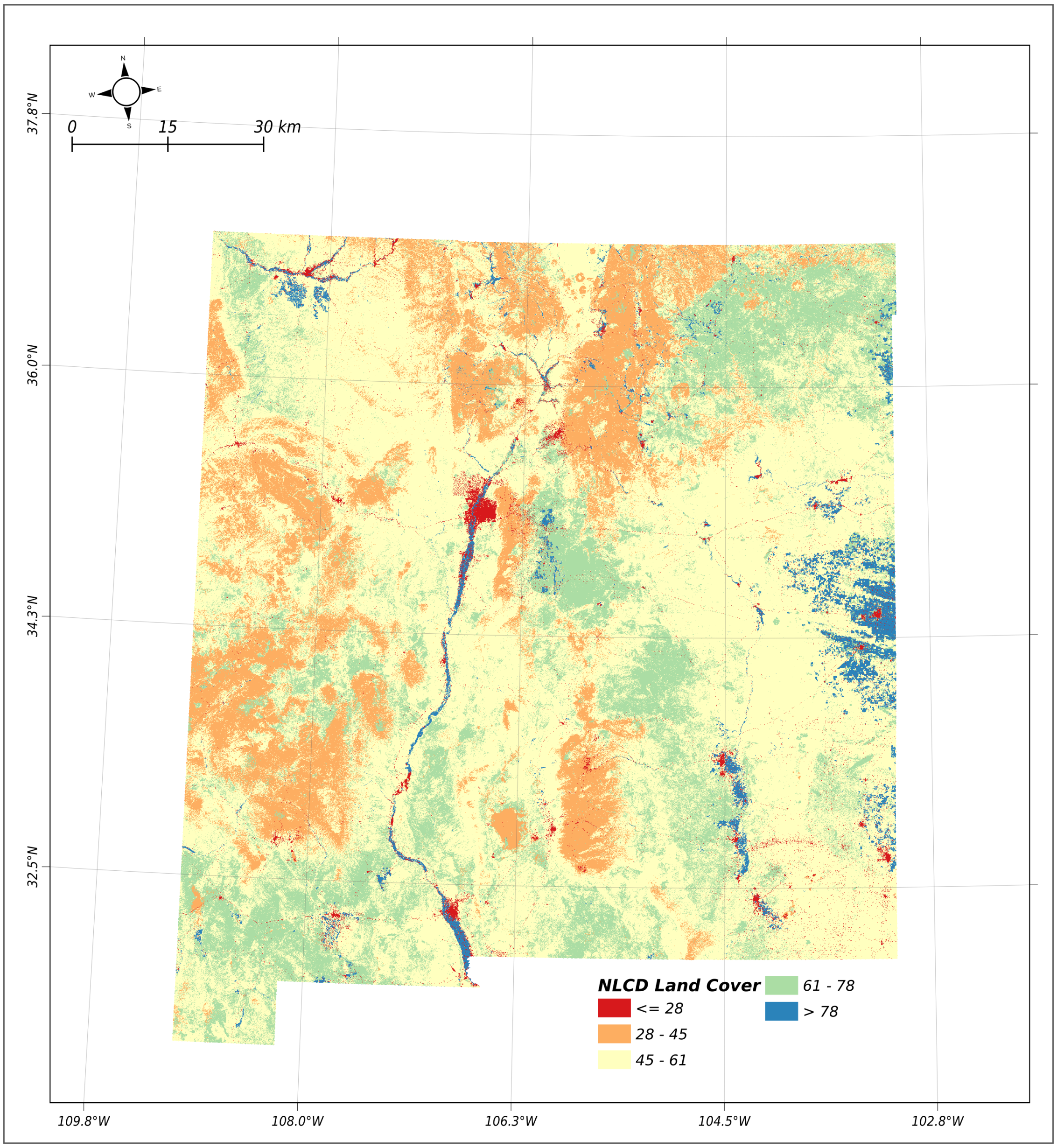

Figure 5: Land cover of New Mexico, reclassified into groundwater-recharge suitability categories based on NLCD.

4.6 Soil Group

Soil characteristics exert a fundamental control on groundwater recharge by regulating infiltration capacity, hydraulic conductivity, and water retention. Infiltration is generally higher in coarse-textured soils such as sandy or gravelly deposits, while fine-textured soils like clay have lower permeability and restrict percolation. Consequently, soil group classification serves as a critical input in groundwater potential mapping, as it reflects the relative ease with which water can move through the vadose zone into aquifers.

In this study, soil data were obtained from the Global Hydrologic Soil Group dataset provided by NASA Earthdata through the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (NASA Earthdata Search, 2025). The dataset provides spatially explicit soil attributes, including hydrologic soil groups, across New Mexico. For analytical purposes, soils were grouped into four broad hydrologic categories: Group A soils (high infiltration rates, typically sand and gravel), Group B soils (moderate infiltration, sandy loams), Group C soils (low infiltration, loams with moderate clay content), and Group D soils (very low infiltration, clayey or shallow soils). Additionally, compound groups such as A/D, B/D, and C/D were considered where drainage conditions depend on the presence of artificial improvements.

The soil group layer was reclassified into recharge suitability classes based on

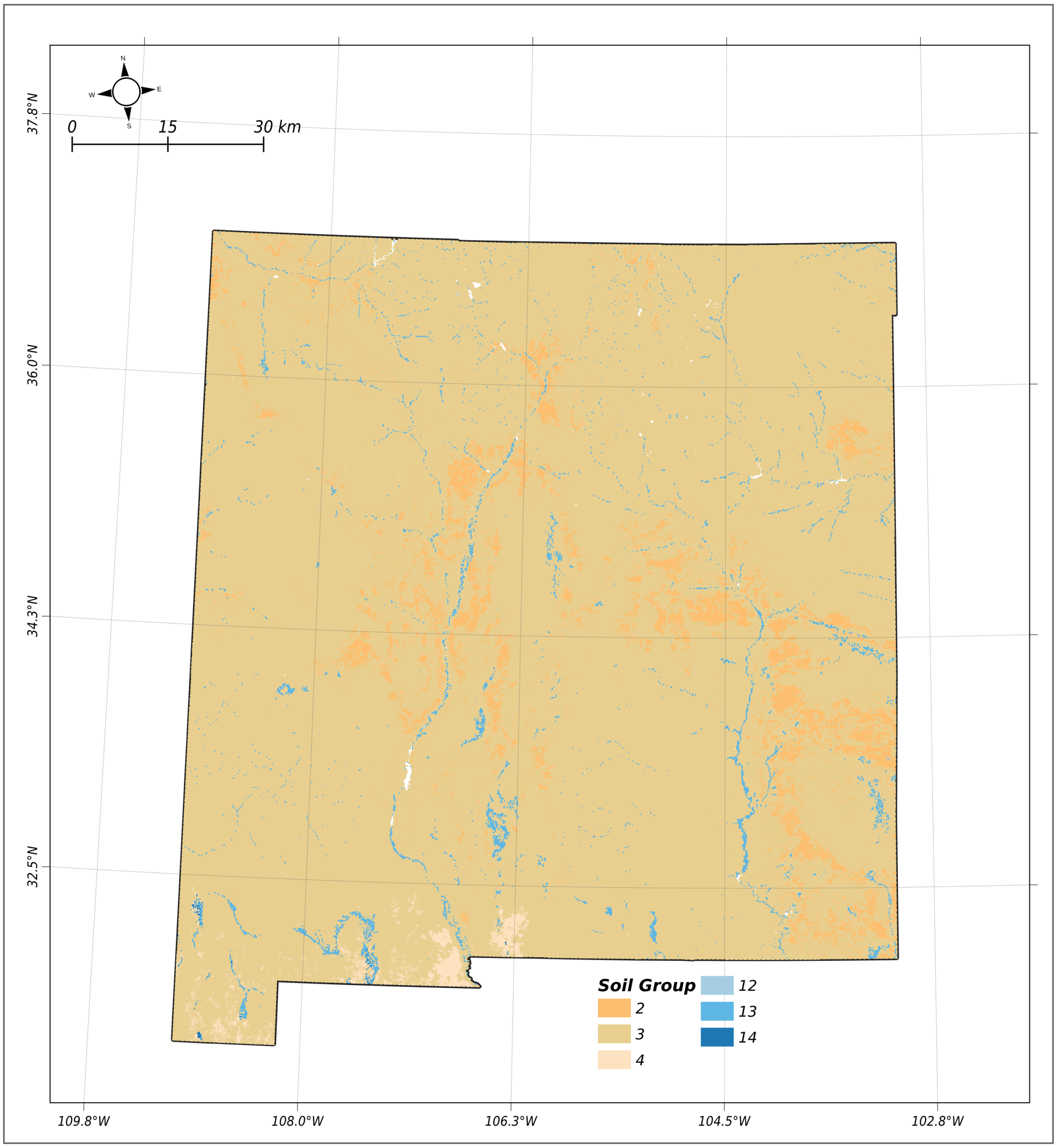

Figure 6: Soil group distribution across New Mexico, derived from USDA NRCS SSURGO database and reclassified according to infiltration capacity.

infiltration capacity. Group A soils were assigned the highest recharge potential due to their coarse texture and high permeability, followed by Group B soils with moderate suitability. Groups C and D were considered less suitable due to their higher clay content and restricted infiltration rates. These classifications were consistent with hydrologic interpretations used in previous groundwater potential studies.

Figure 6 shows the spatial distribution of hydrologic soil groups across New Mexico. The numeric codes (2, 3, 4, 12, 13, 14) correspond to the standard NRCS hydrologic soil groups: Group A (2), Group B (3), Group C (4), and Group D (12–14). Much of the state is dominated by Group C and D soils, which are associated with relatively low infiltration capacity, particularly in the eastern plains and central basins. Pockets of Group A and B soils occur along river valleys and alluvial fans, especially in the Rio Grande Valley and parts of southern New Mexico, where recharge potential is greater. By incorporating this soil information into the Analytical Hierarchy Process (AHP) framework, the model explicitly accounted for one of the most direct controls on groundwater recharge, ensuring that variations in infiltration capacity across the state were represented in the analysis.

4.7 Geomorphology

Geomorphology plays a crucial role in groundwater recharge studies, as landform types significantly influence surface–subsurface hydrological interactions, including runoff, infiltration, and storage. Flat areas and valleys tend to favor infiltration by allowing longer residence time for precipitation, while steep slopes and ridges are associated with rapid runoff and reduced infiltration. Similarly, footslopes and hollows often act as zones of water accumulation, increasing the likelihood of percolation into the subsurface. Thus, integrating geomorphic forms into groundwater potential mapping ensures that terrain controls are explicitly represented in the analysis.

In this study, geomorphological features were extracted from a 10 m resolution Digital Elevation Model (DEM) using the `r.geomorphon` module in GRASS (GRASS Development Team, 2024). The geomorphon approach is a machine-vision technique that classifies terrain into landform elements based on local patterns of topographic relief. Unlike traditional slope- or curvature-based terrain classification, which relies on fixed window sizes, geomorphons utilize visibility-based analysis of a pixel and its eight directional line-of-sight neighbors. This produces a ternary pattern (higher, lower, or equal relative elevation) for each pixel, which is then matched against an exhaustive library of 498 possible landform patterns. These patterns are consolidated into ten common geomorphic forms: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit.

For the present work, the `r.geomorphon` parameters were optimized for New Mexico's topographic setting, with a search radius of 11 cells and a flatness threshold of 1°. These settings ensured appropriate recognition of both broad valley structures and localized slope breaks. The resulting raster map was validated against visual inspection of DEM-derived hillshades to confirm the realism of landform delineations.

The reclassified geomorphic map was then integrated into the Analytical Hierarchy Process (AHP) framework for recharge potential assessment. Valleys, flats, hollows, and footslopes were assigned higher suitability values because of their favorable infiltration conditions, while ridges, peaks, and steep slopes were assigned lower suitability due to their tendency to generate surface runoff.

Figure 7 illustrates the spatial distribution of geomorphological forms across New Mexico. The map shows that valleys and flats dominate the central basins and river corridors, providing hydrologically favorable recharge settings, while ridges and peaks are concentrated in the highland regions of northern and southwestern New Mexico, where runoff dominates.

4.8 Rainfall

Rainfall is one of the most critical drivers of groundwater recharge, as it provides the primary source of water available for infiltration into the subsurface. Spatial

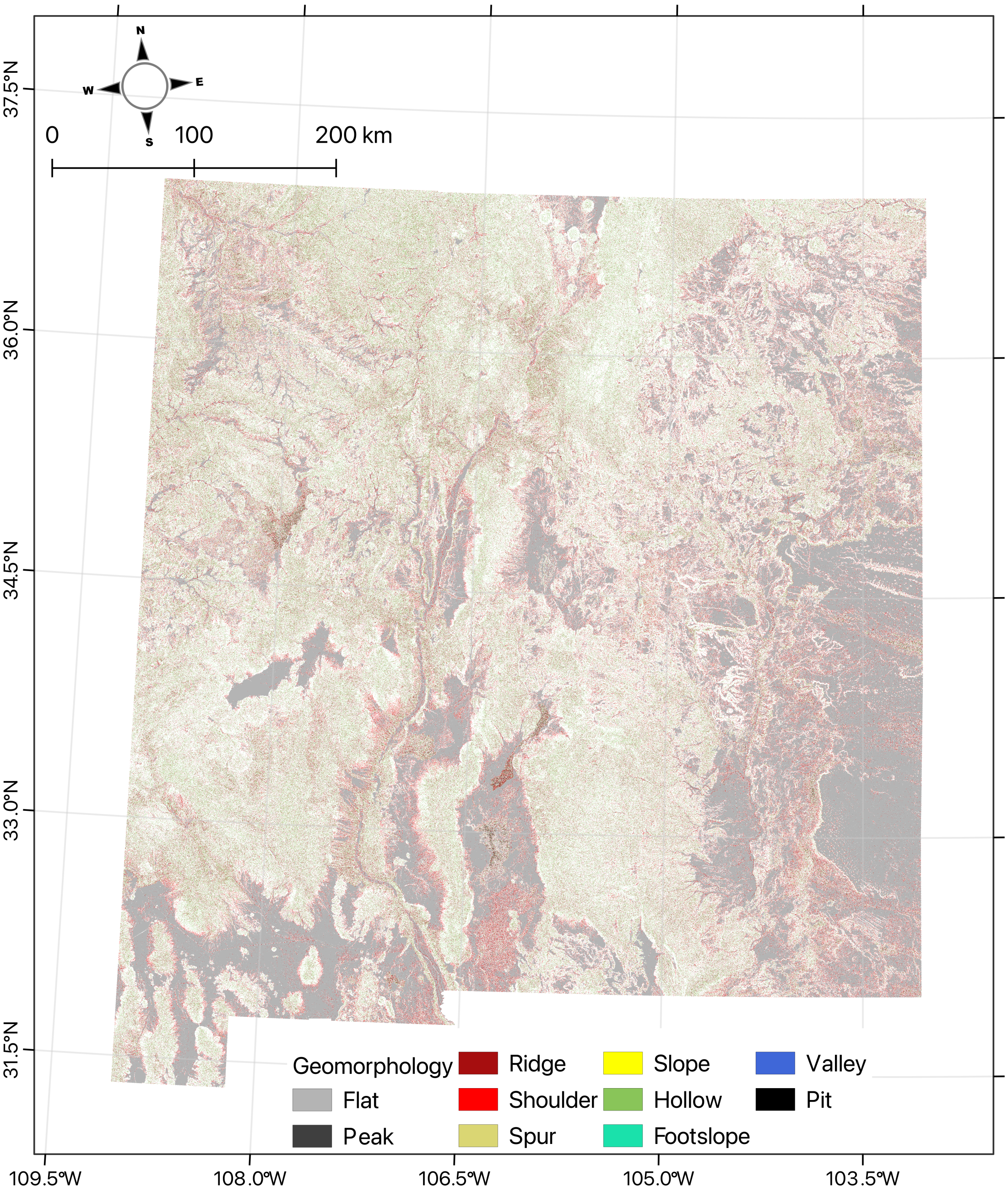

Figure 7: Geomorphological landform classification of New Mexico.

and temporal variability in precipitation strongly influences recharge distribution, with higher rainfall generally leading to greater recharge potential, provided that soil and geological conditions allow infiltration. Conversely, areas of low precipitation are often recharge-limited due to insufficient water input. Therefore, rainfall was incorporated as a key thematic layer in the groundwater recharge potential mapping.

For this study, precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group, which produces high-resolution gridded climate datasets for the United States. The PRISM Climate Group, Oregon State University (2025) dataset integrates point measurements from weather stations with a DEM to account for topographic effects on precipitation distribution. Long-term mean annual precipitation (1991–2020) at a spatial resolution of 800 m was used, which provides a representative baseline for hydroclimatic conditions across New Mexico.

The precipitation raster was reclassified into five recharge suitability categories to reflect its role in groundwater replenishment: very low ($\leq$ 270 mm), low (270–330 mm), moderate (330–375 mm), high (375–420 mm), and very high ($>$ 420 mm). Areas with higher precipitation were assigned higher suitability values because they provide greater water input for potential recharge. However, the contribution of rainfall to recharge is also moderated by other factors such as slope, soil, and land cover, which determine whether rainfall infiltrates or is lost

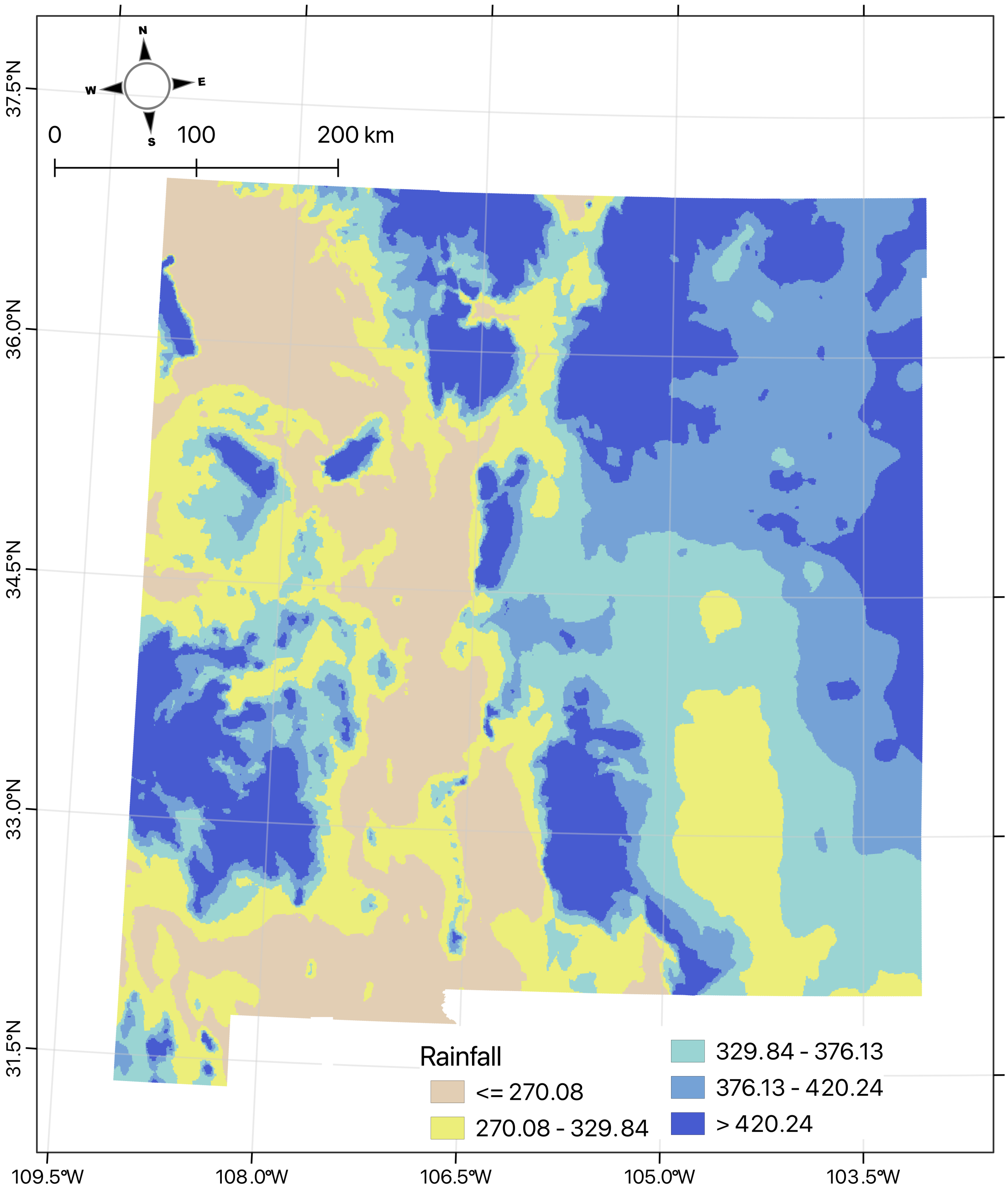

Figure 8: Mean annual precipitation (1991–2020) across New Mexico, derived from the PRISM Climate Group dataset.

as runoff.

Figure 8 shows the spatial distribution of mean annual rainfall across New Mexico. The eastern plains and northern highlands receive the highest precipitation (> 420 mm), making them favorable for recharge, while the southwestern and central basin regions receive less than 270 mm annually, representing very low recharge potential. The spatial pattern highlights the strong climatic gradients across the state and underscores the importance of integrating rainfall with geomorphic and hydrogeologic factors in assessing groundwater recharge potential.

4.9 Future Rainfall Projections: NEX-GDDP-CMIP6

Future rainfall scenarios for New Mexico were derived from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset, which provides bias-corrected, high-resolution ($0.25^\circ \sim 25$ km) climate projections based on Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations. The dataset includes outputs for multiple Shared Socioeconomic Pathways (SSPs), developed in support of the IPCC Sixth Assessment Report (AR6). The bias correction and downscaling procedures account for regional topographic influences and ensure consistency with observed historical climatology, making this dataset suitable for hydrological and recharge-related assessments (NASA Center for Climate Simulation, 2025).

For this study, precipitation (`pr`) data from the ACCESS-CM2 model under

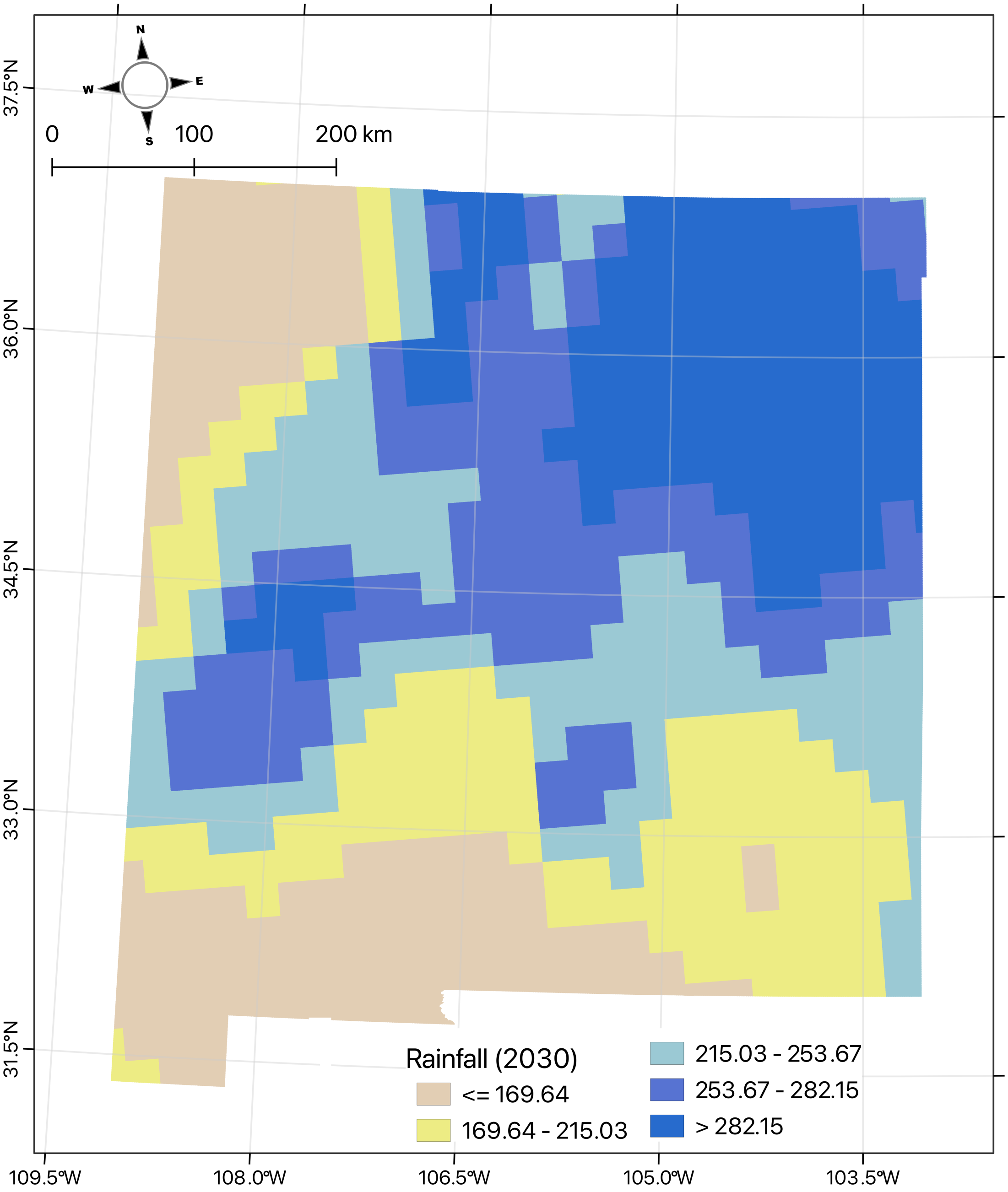

Figure 9: Projected average annual rainfall for New Mexico in the 2030s (ACCESS-CM2, SSP2-4.5).

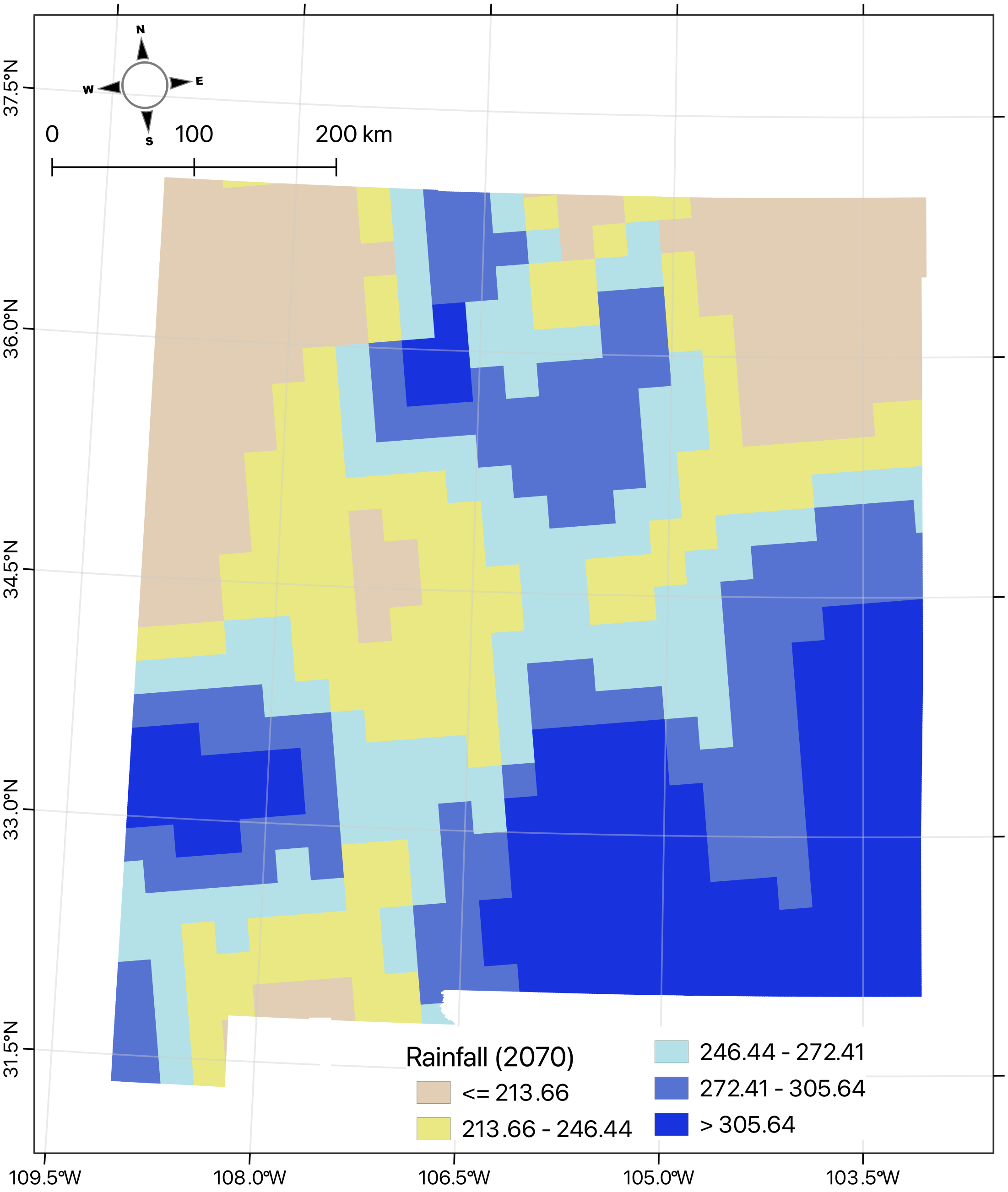

Figure 10: Projected average annual rainfall for New Mexico in the 2070s (ACCESS-CM2, SSP2-4.5).

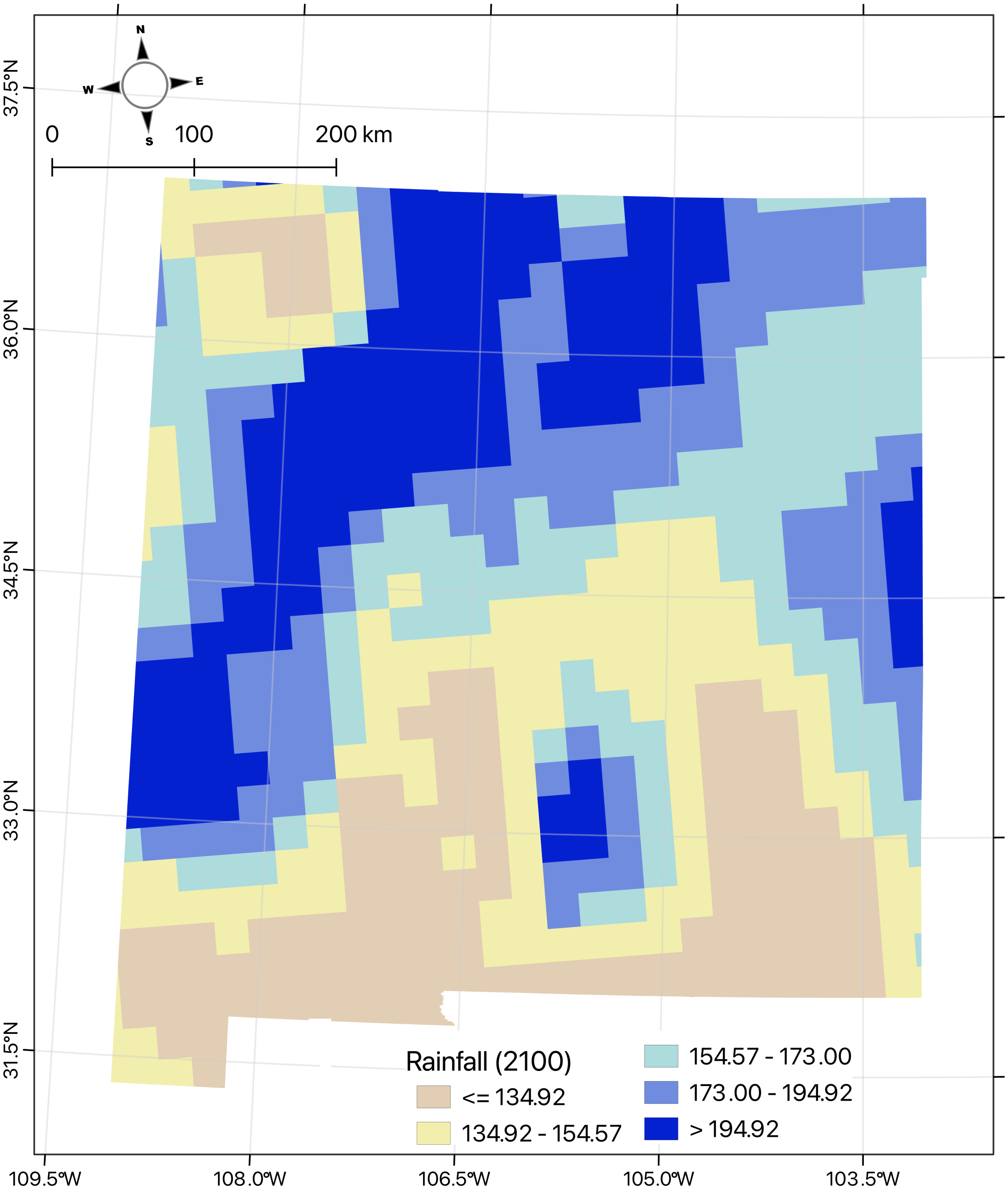

Figure 11: Projected average annual rainfall for New Mexico in the 2100s (ACCESS-CM2, SSP2-4.5).

the SSP2-4.5 scenario were selected. NetCDF files were obtained from the NASA Center for Climate Simulation (NCCS) THREDDS server(NASA Center for Climate Simulation, 2025). Daily precipitation values were aggregated into annual totals, and three representative years were selected to illustrate future time horizons: near future (2030), mid-century (2070), and end-century (2100).

The spatial distributions of projected rainfall are shown in Figures 9–11. In the near future (2030s), rainfall is projected to range from less than 170 mm in southern basins to more than 280 mm in the northeastern region (Figure 9). By mid-century (2070s), rainfall exhibits greater spatial heterogeneity, with central and southern basins receiving less than 220 mm annually, while the southeastern zone exceeds 300 mm (Figure 10). Toward the end of the century (2100s), a pronounced decline is observed in southern and southwestern New Mexico, where rainfall decreases below 150 mm, while certain northeastern pockets remain relatively wetter with values above 190 mm (Figure 11).

These results indicate a long-term drying trend in southern and southwestern New Mexico, coupled with a northward shift of relatively wetter conditions. Such changes carry important implications for groundwater recharge: regions with declining rainfall will likely experience reduced recharge potential, whereas northern zones may continue to sustain moderate recharge rates. The integration of these projections with geomorphic and hydrogeologic variables is thus essential for accurately delineating future groundwater recharge potential zones.

5 Results

The spatial analysis of groundwater recharge potential across New Mexico under current and future climate scenarios reveals clear temporal and geographic patterns. The recharge zones delineated for 2025, 2030, 2070, and 2100 are presented in Figures 12–15. These maps integrate multiple controlling factors, including slope, geology, soil type, drainage density, lineament density, land cover, and precipitation, to illustrate the spatial variability of recharge potential.

In the baseline year 2025 (Figure 12), the state is predominantly characterized by moderate and moderately good recharge zones, which collectively account for most of New Mexico's land area. Favorable recharge areas are visible mainly in the northeastern, north-central, and southwestern regions, where permeable soils, sedimentary formations, and structural lineaments coincide with moderate rainfall. Conversely, very low and low recharge zones are concentrated in the southern and southeastern parts of the state, where steep slopes, clay-rich soils, and high drainage density restrict infiltration. These results provide a baseline reference for evaluating future changes.

By 2030 (Figure 13), the spatial distribution of recharge potential remains broadly similar to 2025, though favorable zones become slightly fragmented and low recharge areas expand marginally in southern and southeastern regions. Despite a modest decline in favorable zones, moderate and moderately good cate-

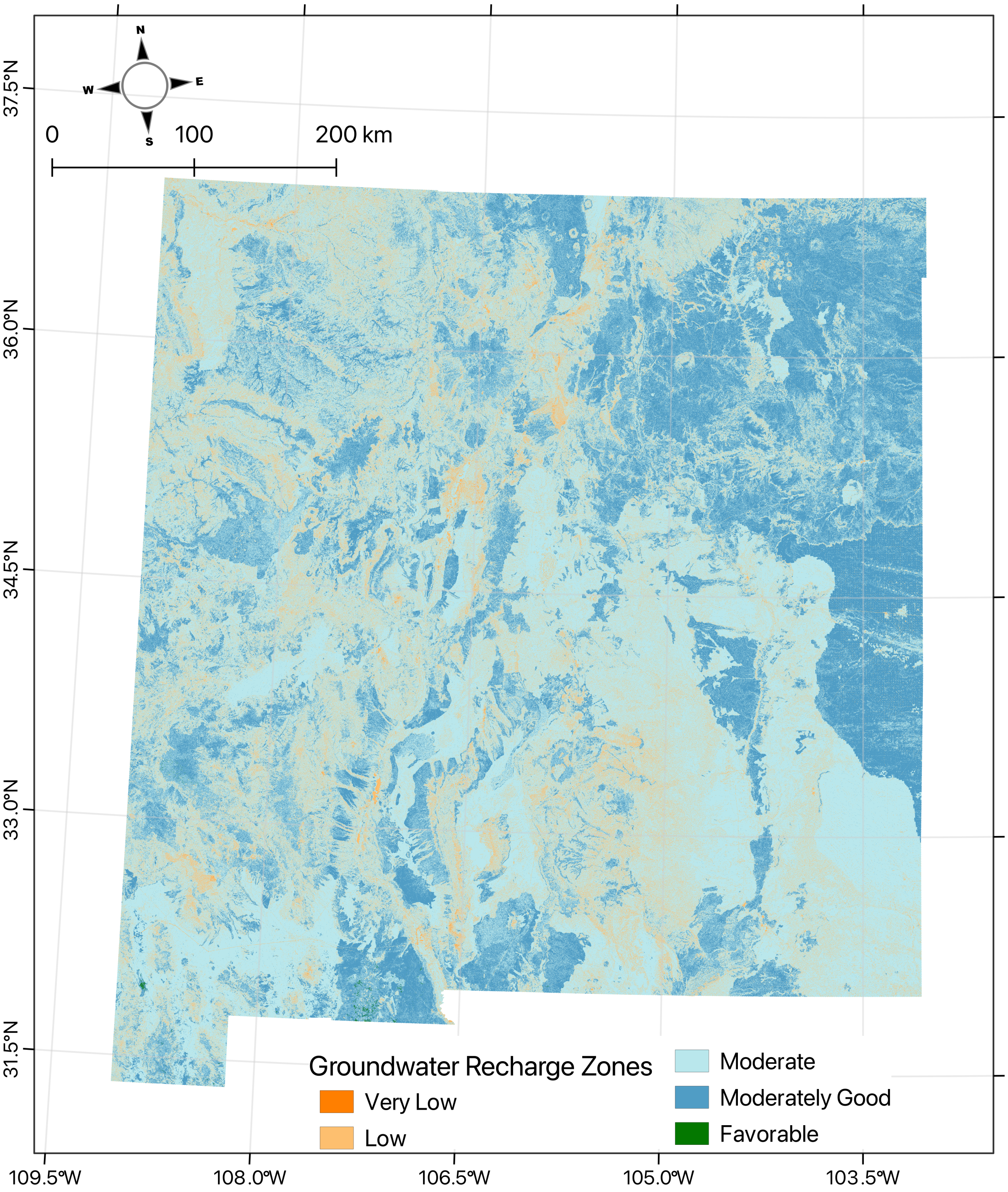

Figure 12: Groundwater recharge zones for New Mexico in 2025 (baseline).

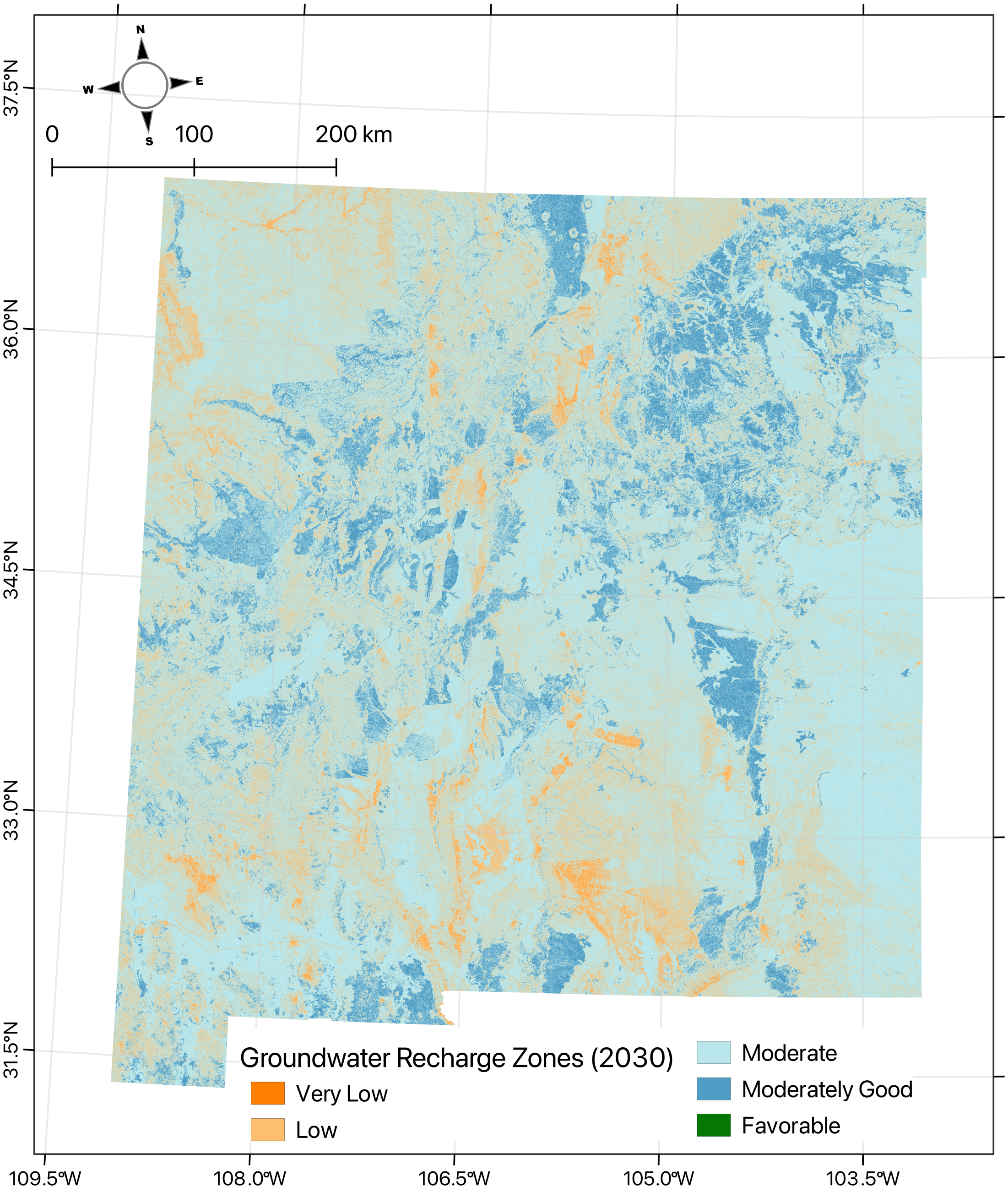

Figure 13: Groundwater recharge zones for New Mexico in 2030.

gories continue to dominate, reflecting the enduring influence of geomorphological and structural factors that promote infiltration.

The 2070 projection (Figure 14) shows a clearer shift, with favorable zones contracting and becoming increasingly discontinuous. Low and very low recharge areas expand in the northeastern, southwestern, and southeastern pockets, indicating the effects of reduced precipitation and intensified evapotranspiration. While moderately good zones persist, they are more spatially fragmented compared to earlier periods. Central New Mexico maintains moderate recharge conditions, likely sustained by valley geomorphology and structural lineaments that enhance infiltration pathways.

By 2100 (Figure 15), the contraction of favorable recharge zones becomes more pronounced, with only small isolated patches remaining in select north-central and southwestern regions. The low and very low recharge zones dominate large portions of the southern and eastern areas, coinciding with the strongest projected rainfall reductions. Moderate recharge zones remain present but are increasingly encroached upon by less favorable conditions.

Overall, the comparison from 2025 to 2100 demonstrates a progressive decline in favorable recharge zones, driven primarily by reduced precipitation and higher evapotranspiration. The findings align with previous studies reporting declining groundwater recharge potential under climate change scenarios (Dar et al., 2021; Baghel et al., 2023; Lavanya and Muthukumar, 2024). These results emphasize

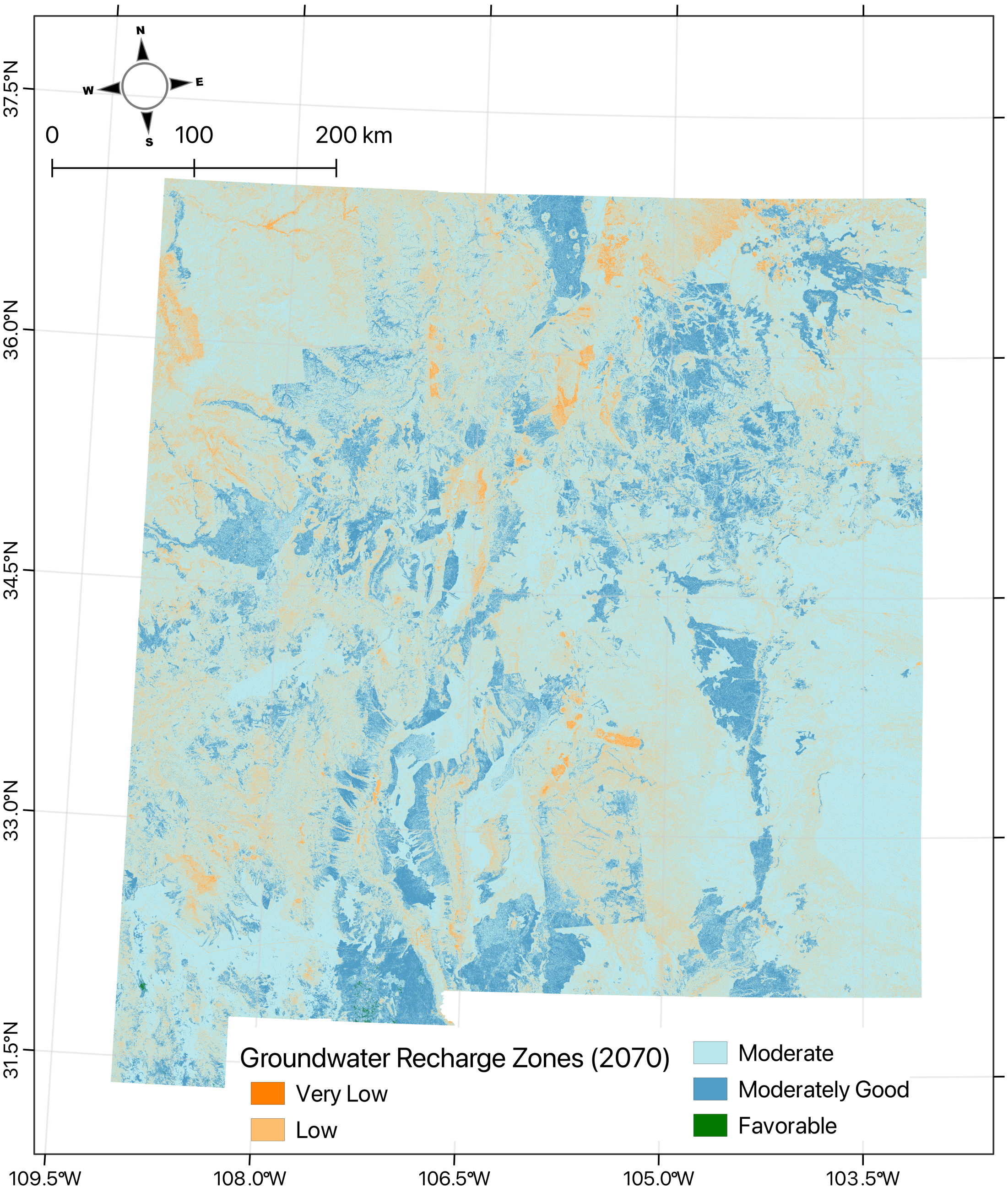

Figure 14: Groundwater recharge zones for New Mexico in 2070.

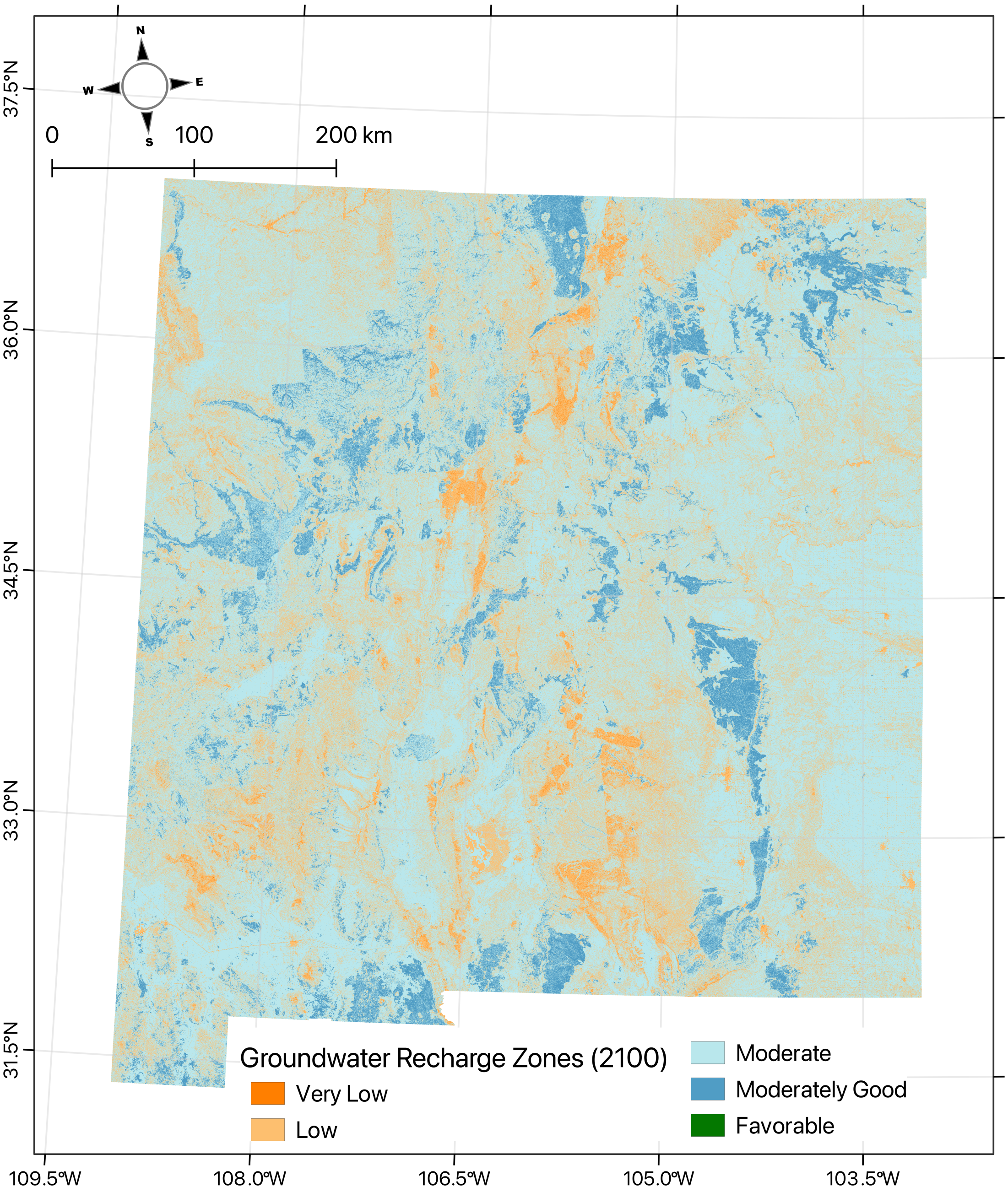

Figure 15: Groundwater recharge zones for New Mexico in 2100.

the growing vulnerability of New Mexico's groundwater resources and underscore the need for adaptive, climate-responsive water management strategies.

6 Conclusion

This study applied a GIS–AHP based multi-criteria framework to delineate groundwater recharge potential zones across New Mexico under present and projected climate conditions. By integrating hydrological, geological, geomorphological, soil, and climatic variables, the analysis provides a spatially explicit understanding of recharge opportunities across a structurally complex and climatically diverse region.

The findings demonstrate that recharge potential is shaped by the interaction of physical and climatic controls. Areas with gentle slopes, permeable soils, sedimentary formations, and relatively low drainage density consistently support higher recharge, whereas steep terrain, clay-dominated soils, and high drainage density limit infiltration and favor runoff. Structural features such as lineament density were especially important in highlighting regions where faulting and fracturing enhance secondary porosity and subsurface water movement.

Current recharge potential, derived from PRISM precipitation and land characteristics, is dominated by moderate to moderately good zones, especially in northeastern and southern pockets of New Mexico. However, projections using CMIP6 downscaled climate data indicate a progressive decline in favorable recharge areas. By 2030, favorable zones persist but are geographically constrained. By 2070, they shrink considerably, and by 2100, much of the state shifts to moderate or low recharge classes, with favorable conditions limited to isolated patches. These results are consistent with global findings of reduced recharge under warmer and drier climates, highlighting the growing vulnerability of groundwater resources.

The implications are significant for water management and climate adaptation. Recharge potential maps provide decision-support tools for prioritizing artificial recharge projects, sustainable land-use planning, and aquifer protection. The results also emphasize the importance of integrating structural and geomorphological indicators with hydrological and climatic variables when assessing groundwater resources. Most importantly, the progressive decline in favorable recharge zones underscores the urgency of adaptive management strategies that explicitly account for climate change impacts.

This study has limitations. The spatial resolution of input datasets constrained the detail of the analysis, and finer-scale studies incorporating hydrogeological field data, transmissivity, and well hydrographs would improve accuracy. The AHP weighting method, while widely applied, is based on expert judgment and may introduce subjectivity. Future work should explore machine learning and other data-driven approaches for parameter weighting and validation, alongside expanded monitoring of recharge processes.

In conclusion, groundwater recharge in New Mexico is expected to become increasingly constrained under future climate scenarios. While structural and geological conditions continue to provide localized recharge opportunities, the overall decline in favorable zones toward 2100 highlights the vulnerability of groundwater resources in an already water-stressed state. The framework presented here contributes to sustainable groundwater management by integrating geospatial analysis, climate projections, and multi-criteria decision-making, and it offers a replicable approach for other arid and semi-arid regions facing similar challenges.

7 Discussion

This study highlights the complex interplay of intrinsic land surface characteristics and extrinsic climatic forcing in shaping groundwater recharge in New Mexico. By integrating geomorphological, geological, soil, land cover, and climatic parameters within a GIS–AHP framework, the analysis provides not only a spatial delineation of recharge zones but also critical insights into the processes that govern their variability across an arid to semi-arid setting.

A clear inverse relationship between drainage density and recharge potential emerged from the analysis. Areas with sparse drainage networks were consistently mapped as favorable for infiltration, as limited channelization allows longer residence time for water to percolate into the subsurface. In contrast, high drainage density, particularly in steep mountain terrains, was associated with rapid runoff and limited recharge opportunities. These results align with earlier studies in arid and semi-arid regions (Dar et al., 2021; Baghel et al., 2023), confirming the role of drainage density as a primary geomorphic control on groundwater recharge.

Structural features also played a critical role. Zones of high lineament density, particularly in north-central and southwestern New Mexico, were identified as favorable recharge areas due to enhanced secondary porosity and permeability along fractures and faults. These findings are consistent with previous research in tectonically active regions such as southern India (Arulbalaji et al., 2019), where lineament mapping has been used effectively as a proxy for groundwater storage. The correspondence between lineament density and slope-derived structural breaks in this study underscores the importance of geological discontinuities in creating preferential infiltration pathways.

Topographic slope further influenced recharge potential. Gentle to moderately sloping terrains ($\leq 8^\circ$) were consistently associated with higher recharge potential, while steep slopes ($> 25^\circ$) were mapped as unfavorable due to the dominance of surface runoff. These findings support established hydrological understanding and are consistent with Baghel et al. (2023), who emphasized slope as a decisive factor in groundwater potential mapping using AHP-based methods.

Soil and geology contributed additional spatial variation. Sandy and loamy soils, typically linked with unconsolidated sediments and sedimentary formations, were favorable for infiltration, while clayey soils and igneous or metamorphic formations corresponded with lower recharge potential due to reduced hydraulic conductivity. This distinction is particularly significant for New Mexico, where large portions of the landscape are underlain by volcanic and crystalline bedrock that naturally limits recharge despite occasional high rainfall events.

Land cover patterns revealed the suppressive influence of urbanization. Major urban centers such as Albuquerque and Las Cruces consistently fell within low or very low recharge zones due to impervious surfaces that limit infiltration. Conversely, grasslands, shrublands, and agricultural areas provided more favorable recharge conditions. These results are in agreement with studies in other western U.S. regions, where land-use change has been shown to significantly alter recharge processes (Li et al., 2021).

Climate emerged as the most dynamic and influential driver of recharge variability. Under current conditions, PRISM rainfall data indicate moderate to moderately good recharge across much of central and northern New Mexico. However, downscaled NEX-GDDP-CMIP6 projections under SSP2-4.5 suggest a progressive reduction in favorable recharge zones through the end of the century. By 2030, favorable conditions persist but are spatially limited; by 2070, they contract significantly; and by 2100, most of the state transitions to moderate or low recharge categories, with only scattered favorable patches remaining. This trajectory demonstrates the increasing vulnerability of recharge to climate-induced precipitation declines and rising evapotranspiration, consistent with global findings by Lavanya and Muthukumar (2024) and others.

The observed temporal decline in favorable recharge highlights the urgency of integrating climate adaptation into groundwater management strategies. Given New Mexico's heavy reliance on groundwater for domestic, agricultural, and industrial use, reduced recharge could accelerate aquifer depletion unless proactive interventions are implemented. Potential strategies include artificial recharge, managed aquifer recharge (MAR), sustainable land-use planning, and conservation-oriented agricultural practices.

The study also underscores the utility of GIS–AHP for groundwater management in complex hydroclimatic regions. The integration of multiple thematic layers into a weighted framework allowed for a nuanced representation of recharge potential that accounts for both surface and subsurface processes. Nonetheless, the method has limitations. The AHP process depends on expert judgment for assigning weights, which introduces subjectivity, even if cross-validation with literature and hydrogeological data lends credibility. Furthermore, the resolution of input datasets varied; while a 10 m DEM provided sufficient topographic detail, soil, geology, and climate datasets were coarser and may obscure finer-scale processes. Additionally, aquifer-specific properties such as transmissivity, storativity, or groundwater table fluctuations were not explicitly incorporated and could improve future assessments.

Despite these limitations, the study contributes to growing evidence that groundwater recharge in arid and semi-arid regions is simultaneously shaped by opportunity and constraint. Opportunity arises from favorable conditions such as permeable soils, sedimentary formations, gentle slopes, and structural lineaments, while constraints stem from steep terrain, impermeable lithologies, urban expansion, and declining rainfall under climate change. The balance between these forces will define the sustainability of groundwater resources in the decades ahead. Ultimately, the findings emphasize the need for integrated, climate-resilient groundwater management strategies that recognize both the physical and climatic controls on recharge and prepare for a future where natural replenishment may become increasingly scarce.

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