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WATER RESOURCES MANAGEMENT IN SITUATIONS OF WATER SCARCITY: HYDROLOGICAL AND CLIMATIC INSIGHTS FROM THE GUADALUPE BASIN

GESTIÓN DE LOS RECURSOS HÍDRICOS EN SITUACIONES DE ESCASEZ DE AGUA: PERSPECTIVAS HIDROLÓGICAS Y CLIMÁTICAS DE LA CUENCA DEL GUADALUPE

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Water Resources Management in Situations of Water Scarcity: Hydrological and Climatic Insights from the Guadalupe Basin

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ABSTRACT

The present study examines water resource management in the Guadalupe Basin, Baja California, a Mediterranean semi-arid region characterized by high climatic variability, limited surface water availability, and strong dependence on groundwater. The primary objective of the study was to evaluate the climatic water balance and its implications for groundwater recharge. To this end, a Geographic Information System (GIS) framework was utilized, incorporating hydroclimatic, geomorphological, geological, and vegetation variables. The Thornthwaite–Mather method was employed to analyze the data. The results obtained demonstrate a marked east–west hydroclimatic asymmetry. The high-elevation regions of the Sierra de Juárez exhibit higher precipitation, lower evapotranspiration, and more favorable conditions for recharge, primarily due to infiltration through fractured bedrock and forested soils. Conversely, the lowland valley areas experience persistent water deficits, high evapotranspiration rates, and limited recharge, despite the presence of permeable alluvial sediments. Vegetation has been shown to play a critical role in the regulation of infiltration and soil moisture retention. The basin functions as a tripartite hydrological system, comprising recharge, transition, and storage-limited zones. These findings underscore the vulnerability of groundwater resources to climate change and anthropogenic pressure, underscoring the importance of safeguarding mountain recharge areas to ensure long-term regional water sustainability.

Keywords: climatic water balance, thornthwaite-mather method, groundwater recharge, semi-arid Mediterranean basin, Guadalupe basin

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Gestión de los Recursos Hídricos en Situaciones de Escasez de Agua: Perspectivas Hidrológicas y Climáticas de la Cuenca del Guadalupe

RESUMEN

El presente estudio examina la gestión de los recursos hídricos en la Cuenca Guadalupe, Baja California, una región semiárida mediterránea caracterizada por una alta variabilidad climática, disponibilidad limitada de agua superficial y una fuerte dependencia del agua subterránea. El objetivo principal del estudio fue evaluar el balance hídrico climático y sus implicaciones para la recarga de agua subterránea. Para ello, se utilizó un marco de Sistema de Información Geográfica (SIG), que incorporó variables hidroclimáticas, geomorfológicas, geológicas y de vegetación. Se empleó el método de Thornthwaite-Mather para analizar los datos. Los resultados obtenidos demuestran una marcada asimetría hidroclimática este-oeste. Las regiones de mayor altitud de la Sierra de Juárez presentan mayor precipitación, menor evapotranspiración y condiciones más favorables para la recarga, principalmente debido a la infiltración a través de roca madre fracturada y suelos forestales. Por el contrario, las zonas bajas de los valles experimentan déficits hídricos persistentes, altas tasas de evapotranspiración y recarga limitada, a pesar de la presencia de sedimentos aluviales permeables. Se ha demostrado que la vegetación desempeña un papel fundamental en la regulación de la infiltración y la retención de humedad del suelo. La cuenca funciona como un sistema hidrológico tripartito, que comprende zonas de recarga, transición y almacenamiento limitado. Estos hallazgos ponen de manifiesto la vulnerabilidad de los recursos hídricos subterráneos al cambio climático y a la presión antropogénica, subrayando la importancia de proteger las zonas de recarga de montaña para garantizar la sostenibilidad hídrica regional a largo plazo.

Palabras clave: balance hídrico climático, método Thornthwaite-Mather, recarga de aguas subterráneas, cuenca mediterránea semiárida, cuenca de Guadalupe

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INTRODUCTION

In the context of sustained global population growth and accelerating land-use transformation, pressure on fragile ecosystems is expected to intensify substantially in the coming decades (Rockström et al., 2009; Vörösmarty et al., 2010). These dynamics have exposed persistent deficiencies in land-use planning and territorial organization, particularly in regions characterized by limited natural resource availability (Wu et al., 2011; Bengtsson et al., 2006; He, 2018). One of the most significant consequences of these deficiencies is the intensified exploitation of surface and groundwater resources, especially to sustain irrigated agriculture and expanding urban systems. As a result, water availability has declined markedly in many arid and semiarid regions, as evidenced by the reduction of ephemeral streamflows, declining groundwater levels, and, in extreme cases, the abandonment of agricultural activities. Water vulnerability has thus emerged as a central constraint affecting food production, energy generation, domestic supply, industrial development, and ecosystem conservation (Abbaspour et al., 2015; Martínez Austria et al., 2019; Fernández-Mejuto et al., 2021).

Global climate change has further amplified these pressures by altering the fundamental drivers of the hydrological cycle. Rising air temperatures, increasingly irregular precipitation regimes, and a growing frequency of extreme events—particularly prolonged droughts—have been widely identified as key factors intensifying evaporative demand at both regional and basin scales (Burke & Brown, 2008; Orlowsky & Seneviratne, 2013; Trenberth, 2014; Jones et al., 2022). In semiarid environments, these trends reduce the fraction of precipitation that effectively contributes to soil moisture storage and groundwater recharge. Under such conditions, the accurate estimation of evapotranspiration becomes a critical component of hydrological assessments, as evapotranspiration regulates the partitioning of precipitation between atmospheric losses, surface runoff, and subsurface infiltration, thereby influencing the balance between water supply and demand in water-limited basins (Droogers, 2000; Lascano & Van Bavel, 2007).

Mediterranean-climate basins are particularly sensitive to these dynamics due to their pronounced seasonality, strong hydrothermal gradients, and reliance on winter precipitation for groundwater replenishment (Scanlon et al., 2006; Viviroli et al., 2020).

In such systems, recharge processes are temporally constrained and spatially heterogeneous, often concentrated during short winter periods when precipitation coincides with low potential evapotranspiration. Recharge is typically favored in high-elevation sectors where cooler temperatures, reduced evaporative demand, and denser vegetation promote soil moisture retention and deep percolation. In contrast, lowland areas frequently experience persistent climatic water deficits, even in the presence of highly permeable alluvial sediments, because elevated temperatures and strong evaporative demand rapidly deplete soil moisture. Understanding how climatic, geomorphological, and ecological gradients interact to structure the spatial distribution of groundwater recharge is therefore essential for anticipating future water availability under conditions of climate variability and land-use change.

In semiarid regions, such as northwestern Mexico, groundwater is often the principal and only reliable source of water for domestic supply, agriculture, and economic development. The long-term sustainability of aquifer systems is, in turn, linked to water security and to the capacity of societies to maintain stable and equitable access to water resources. Consequently, scientific identification of recharge zones, hydroclimatic controls, and aquifer vulnerability is imperative not only for environmental management but also for supporting sustainable water governance under increasing climatic and anthropogenic pressures (Vörösmarty et al., 2010; Abbaspour et al., 2015; IPCC, 2021).

Within this context, the Guadalupe Basin, located in northwestern Baja California, Mexico, represents a paradigmatic example of a Mediterranean semiarid watershed experiencing increasing water stress. The basin exhibits pronounced topographic gradients, a marked east–west hydroclimatic asymmetry, and heterogeneous land-use patterns dominated by agriculture, viticulture, and expanding urban development. These characteristics make the basin particularly sensitive to changes in precipitation regime, temperature, vegetation cover, and land management practices, all of which exert strong control on evapotranspiration rates, runoff generation, and infiltration efficiency (Scanlon et al. 2002).

The present study applies the Thornthwaite–Mather climatic water-balance model in combination with spatial and multi-criteria analysis to evaluate groundwater recharge potential across the Guadalupe Basin.

The analytical framework integrates key hydroclimatic variables, including precipitation, temperature, potential evapotranspiration, and climatic water balance, together with geomorphological attributes such as slope and elevation, vegetation patterns, and geological controls, within a Geographic Information System (GIS). This integrative approach is particularly suitable for data-scarce semiarid regions, where physically based hydrological models are often constrained by limited meteorological and hydrogeological observations.

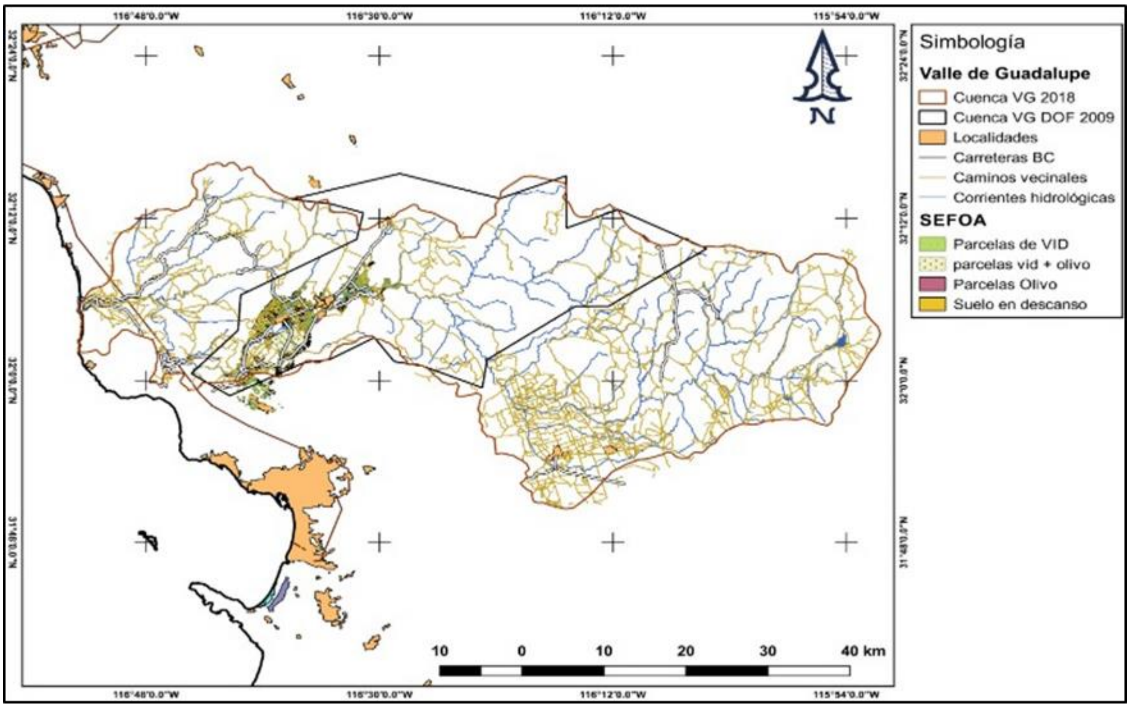
Accordingly, the central research question addressed in this study is how climatic, geomorphological, and ecological controls interact to govern the spatial organization of groundwater recharge potential under semiarid Mediterranean conditions (Wada et al. 2012; Valdes-Abellan et al. 2020). To address this question, the study pursues three specific objectives: (i) to characterize the spatial variability of key hydroclimatic drivers across the basin; (ii) to analyze the role of geomorphology and vegetation in shaping contrasting hydrological responses along elevation gradients; and (iii) to assess the implications of these spatial patterns for groundwater recharge potential and long-term water availability. By integrating climate, geomorphology, ecology, and hydrology, this work provides a robust scientific basis for climate-resilient water management and sustainable territorial planning in one of the most strategically important basins of northwestern Mexico.

Study Area

The Guadalupe Basin is located in the northwestern part of the State of Baja California, between parallels 31° 51' and 32° 15' north latitude and meridians 115° 52' and 116° 51' west longitude (Beltrán, 2001). As illustrated in Figure 1, the relationship between the two variables is evident. The geographical area under consideration encompasses an approximate area of 2,400 square kilometers, inclusive of the estuary (Hernández-Rosas & Mejía-Vázquez, 2003). The area can be divided for the purposes of study as follows: the north is divided by the Tecate-El Carrizo and Descanso-Los Medanos hydrological basins; to the east, it is divided by the Laguna Salada hydrological basin; to the south, it is divided by the Ensenada-El Gallo and San Carlos hydrological basins; and to the west, it is divided by the Pacific Ocean (Campos Gaytán, 2008; Salgado et al., 2012; Figueroa-Núñez and Campos-Gaytán, 2018; CONAGUA, 2014).

The surface runoff of the Guadalupe Basin originates in the Sierra Juárez, traverses the Ojos Negros and Guadalupe valleys, and ultimately reaches the Pacific Ocean near the town of La Misión.

Figure 1. Location of the Guadalupe Basin in Baja California



Geology

The Guadalupe Basin's geological structure is indicative of the extensive and complex tectonomagmatic evolution of the Peninsular Ranges Batholith, which serves as the basin's fundamental physical framework, giving rise to its hydrological processes. According to Regional Geological Mapping (INEGI, 2006), four major lithological assemblages have been identified: intrusive igneous rocks, extrusive volcanic sequences, metamorphic complexes, and unconsolidated Quaternary sediments. Each of these units exhibits distinctive hydraulic characteristics that control groundwater input, storage, and subsurface flow pathways across the basin (see Figure 2).

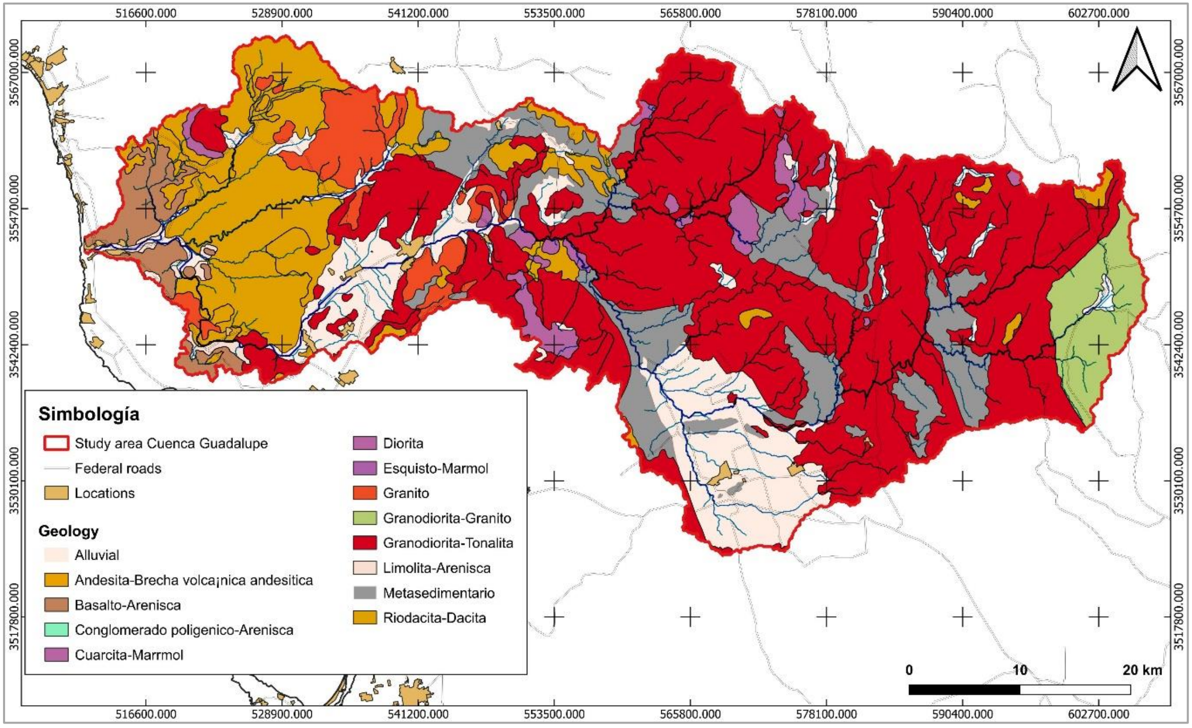
Intrusive igneous rocks represent the most extensive lithological group in the region. The crystalline highlands that border the basin are composed of granodiorites, granites, diorites, and gabbros. Despite the fact that these plutonic units possess a negligible degree of primary porosity, they are capable of acquiring secondary permeability through the processes of jointing and fault-related fracturing. This fracture network frequently serves as the primary mechanism that facilitates deep percolation during climatic conditions that are conducive to such processes. This phenomenon has been observed in fractured-bedrock aquifers within the Coast Ranges of California and in granitic terrains of central Chile (Scanlon et al., 2002; Figueroa-Núñez & Campos-Gaytán, 2018). In this regard, the fractured igneous uplands of the Guadalupe Basin function as both runoff-producing areas and localized recharge domains, where the high density of fractures enables effective downward infiltration.

West of El Porvenir, extrusive volcanic rocks, primarily andesites, rhyolites and various volcanic tuffs, are widespread and represent the remnants of Mesozoic volcanic activity associated with arc systems in the region. The hydraulic behaviour of these rocks varies considerably. Massive or densely welded tuffs form effective hydraulic barriers, whereas fractured or brecciated lava flows may allow more efficient infiltration. As Houser et al. (2015) demonstrate, analogous heterogeneity has been documented in the Trans-Mexican Volcanic Belt. In this region, contrasts in vesicularity, cooling history, and fracture development strongly influence infiltration patterns.

Metamorphic units, including schists, slates, and gneisses, are predominantly located to the east of El Porvenir and represent some of the oldest crustal materials within the basin. The foliated textures, low primary porosity, and restricted transmissivity of these minerals render them effective hydrogeological barriers, capable of constraining lateral groundwater flow. This phenomenon is analogous to that observed in the Sierra San Pedro Mártir and certain regions of southern California, where metamorphic terrains compartmentalize aquifer systems and restrict basin-scale groundwater movement (Daesslé et al., 2020).

The most hydrologically significant deposits, however, are the unconsolidated Quaternary sediments that fill the Guadalupe Valley. Alluvial deposits are defined by their composition of gravels, sands, silts, and interbedded sandstones. These deposits are distinguished by their high porosity and permeability. These wetlands function as the primary groundwater reservoir for agricultural and domestic use, thereby supporting ecological baseflows. Comparable valley-fill aquifers in other Mediterranean semiarid regions, such as the Segura Basin in Spain and the Santa Ana Basin in California, perform similar roles as key groundwater-storage and recharge systems (Valdes-Abellan et al., 2020; Scanlon et al., 2002).

Figure 2. Geological map of the Guadalupe Basin



Structurally, the geometry of the basin is significantly influenced by the San Miguel and Ojos Negros fault systems. These fault zones have a profound influence on the formation of valleys, regulating the accumulation of sediment and creating vertical conduits that facilitate enhanced hydraulic connectivity between bedrock and overlying alluvium. As demonstrated in numerous hydrogeological studies across northern Baja California (Saiz-Rodríguez, 2019; Daesslé et al., 2020), such structures are of great importance as preferential recharge pathways. The contrasting geomorphic expressions of the basin's lithologies – namely, steep crystalline uplands, dissected volcanic plateaus, metamorphic ridges, and broad alluvial fans – produce a heterogeneous hydrogeological landscape that directly controls the distribution of runoff, infiltration, and groundwater storage. The geological framework of the Guadalupe Basin collectively establishes the physical foundation for its hydrological functioning, generating sharp contrasts between low-permeability crystalline highlands and highly permeable alluvial aquifers. These lithologic and structural controls are fundamental for understanding the basin's response to climatic variability, recharge dynamics, and groundwater vulnerability.

Climate

According to the Köppen climate classification system, as modified by García (1970) and adapted to Mexico's climatic conditions, CONAGUA (2014a) classifies the climate as semiarid. The climate is distinguished by elevated temperatures and diminished precipitation levels in the drier regions adjacent to the mountain ranges, with more substantial rainfall in the west. In the elevated regions of the basin, specifically the high and middle topographic zones, the climatic classification is designated as "BS ks," distinguished by a winter precipitation index that exceeds 36%. The observed climatic diversity is primarily attributable to the cool winds that enter the continent from the northeast. The region's winds are moderately humid, leading to minimal precipitation, with the exception of the highest elevations within the basin, which are situated above 1,500 meters above sea level. In these elevated regions, average annual temperatures remain below 12°C (CNA, 2004). The maximum temperatures range from 39°C to 45°C between July and September, while the minimum temperatures range from -13°C to -14°C, particularly in the mountainous regions and in the eastern part of the valley. The mean annual temperature ranges from 15°C to 18°C, and evaporation rates range from 88 mm/year to 570 mm/year (CNA, 2001). Another aspect of arid climates with deep water tables, especially when precipitation is concentrated in small areas, is that they can create localized runoff that then infiltrates downstream, resulting in less runoff than in humid areas (Tarboton, 2003). The mean annual precipitation range in the highest regions is between 300 and 400 millimeters. A decline in precipitation is observed from winter to summer (INEGI, 2006).

Vegetation

The Guadalupe Creek Basin is situated within the Mediterranean phytogeographic region, where the winters are mild and humid, and the summers are warm and dry. The region's biodiversity is marked by a variety of endemic and restricted-range species, with its ecosystems primarily consisting of coastal scrub, chaparral, and temperate forests (Riemann and Ezcurra 2005; Myers, 2020). In lower-altitude areas proximate to the coast, coastal scrub communities predominate, with species such as Artemisia californica, Adenostoma fasciculatum, and Eriogonum fasciculatum, which are adapted to arid conditions and shallow soils. In higher elevations and more humid environments, chaparrals develop, composed of shrub species such as Ceanothus sp., Rhus ovata, and Quercus dumosa, which have adapted to fire and drought. In the elevated regions of the basin, characterised by deeper soils and enhanced water availability, temperate oak forests (Quercus agrifolia, Quercus engelmannii) and mixed forests with conifers, such as Pinus coulteri and Pinus jeffreyi, have been established (Riemann and Ezcurra 2005; Morrone 2019; González-Barrera 2014).

Despite its notable biodiversity, the coastal Mediterranean region of Baja California is among the most threatened in the state, facing accelerated habitat fragmentation due to a combination of agricultural expansion, tourism, industry, and uncontrolled urban growth. These factors contribute to ecosystem degradation and the risk of losing the germplasm of native species, many of which have restricted distributions or small populations (Riemann and Ezcurra 2005). The introduction of invasive exotic species, such as Brassica nigra and Eucalyptus camaldulensis, also poses a significant challenge to the conservation of native flora. These species have the capacity to displace native species and modify the ecological structure of natural habitats (Garcillán et al. 2013).

Hydrology and Hydrogeology

The hydrology and hydrogeology of the Guadalupe Basin are the result of a combination of factors, including steep topographic gradients, a highly heterogeneous geological framework, and the distinct seasonality of its semiarid Mediterranean climate. The basin is situated within Hydrological Region 1 (RH01) of northwestern Baja California, constituting a component of the Tijuana River–Maneadero Creek subregional system. The body of water under consideration exhibits a westward drainage pattern toward the Pacific Ocean, facilitated by a well-organized exoreic drainage network that spans five Strahler orders (see INEGI, 2010b; Sánchez-Montoya et al., 2009). Surface runoff originates along the western slopes of the Sierra de Juárez, where elevations approach 1,800 m a.s.l., and flows through a succession of geomorphological units from the Ojos Negros Valley to the agricultural and viticultural landscapes of the Guadalupe Valley before reaching the coast at La Misión. The principal channels (El Barbón, Agua Caliente, and Guadalupe creeks) collectively constitute more than 138 km of interconnected drainage, facilitated by tributaries such as Los Barrancos, Jamatay, La Casita, and Las Bellotas.

Hypsometric patterns in the basin (see Figure 3) reveal a striking elevation contrast, ranging from sea level along the coast to a maximum of 1,900 meters on the eastern highlands.

This topographic gradient exerts strong control over hydrological behavior. High-elevation areas are distinguished by steep slopes, shallow soils, and rapid runoff generation, whereas low-relief alluvial valleys offer conducive conditions for water accumulation, infiltration, and groundwater recharge (Auerswald et al., 2024; Gnann et al., 2022). These dynamics are characteristic of semiarid Mediterranean mountain systems, where crystalline highlands function as runoff production zones and valley-fill sediments act as the primary recharge and groundwater-storage domains (Scanlon et al., 2002).

From a hydrogeological perspective, the basin is composed of two primary groundwater domains. The first of these corresponds to fractured-bedrock aquifers developed within the crystalline and metamorphic rocks of the Peninsular Ranges Batholith. The aquifers in question are predominantly unconfined, relying on secondary permeability created by the San Miguel and Ojos Negros fault systems and associated splays. Such structural pathways have been demonstrated to augment vertical percolation and have been identified as pivotal recharge mechanisms in northern Baja California, as well as in analogous geological settings in southern California (Daesslé et al., 2020; Figueroa-Núñez & Campos-Gaytán, 2018). These elements function as hydraulic links between mountain slopes and deeper paleo-aquifers.

Conversely, the extensive Guadalupe Valley encompasses the basin's primary alluvial aquifer. The system under scrutiny is comprised of gravels, sands, and silts of a coarse texture, which exhibit high porosity and hydraulic conductivity. These characteristics enable substantial groundwater storage and response to both diffuse and focused recharge events during periods of precipitation. As in the Segura Basin (Spain), Santa Ana Basin (California), and central Chile, these valley-fill aquifers serve as key hydrological buffers in regions with pronounced climatic seasonality, helping to sustain water availability under fluctuating hydrometeorological conditions (Valdes-Abellan et al., 2020; Scanlon et al., 2002).

From a hydrological perspective, the basin functions as a coupled mountain-valley system. The Sierra de Juárez functions as both a runoff source and a recharge zone, while the mid-slope areas facilitate flow redistribution through channels and subsurface pathways.

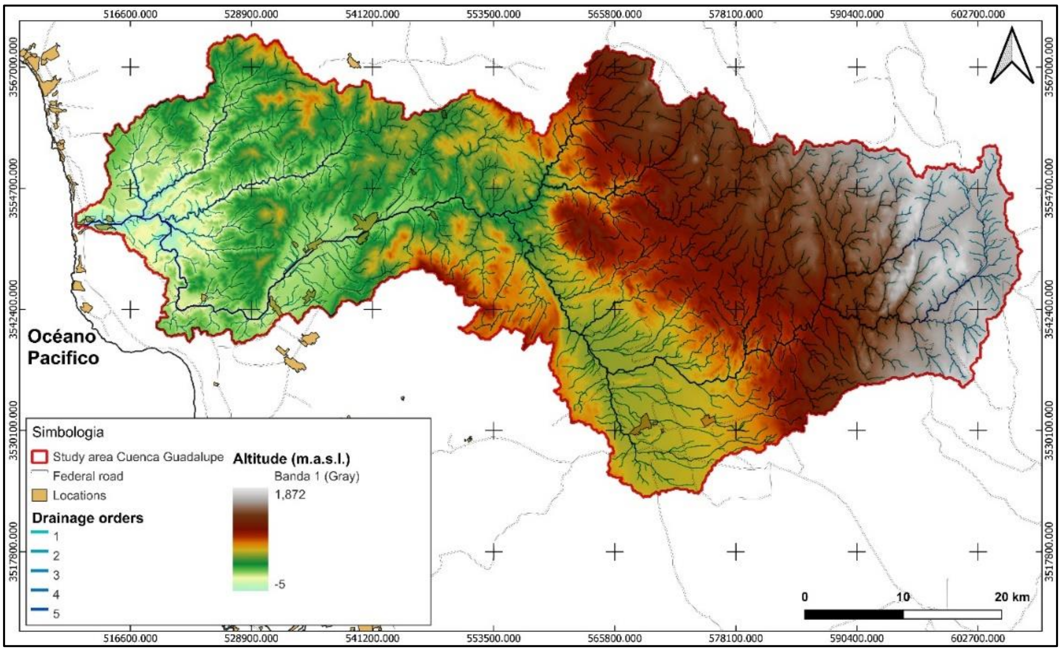
The Guadalupe Valley, which consists of permeable sediments, functions as a pivotal nexus where the processes of groundwater replenishment and extraction converge. This renders the area the most vulnerable within the basin, particularly in view of the pressure exerted by intensive agricultural pumping, industrial extraction, soil compaction resulting from vineyards and grazing, and the removal of native vegetation. These alterations, driven by anthropogenic activities, have been shown to diminish the capacity for infiltration, augment surface runoff, and erode the resilience of aquifers during periods of drought (Salgado Tránsito et al., 2012; Daesslé et al., 2006).

The hydroclimatic factors further exacerbate the spatial contrasts within the basin. The hydrological regime is distinguished by its heightened sensitivity to interannual variability, as demonstrated by the predominance of winter-dominated precipitation and elevated summer PET. Recent regional studies have indicated a decline in winter rainfall, an increase in the frequency of extreme droughts, and rising temperatures.

These trends pose a threat to recharge processes in mountainous areas and accelerate groundwater decline in lowlands (IPCC, 2021; Molina-Navarro et al., 2016).

The hydrological and hydrogeological functioning of the Guadalupe Basin is governed by the interplay of topographic gradients, structural geological features, and sedimentary properties. The phenomenon of steep relief exerts a significant influence on the processes of runoff generation and flow routing. In contrast, the presence of faulting and fracture networks serves to delineate the preferential pathways for vertical groundwater recharge. Highly permeable valley-fill sediments play a central role in controlling groundwater storage capacity and extraction dynamics. Characterizing the interactions among these controls is essential for quantifying aquifer vulnerability, evaluating the feasibility of recharge enhancement strategies, and delineating priority areas for sustainable water management under evolving climatic and land-use pressures.

Figure 3. Hypsometric map and drainage network of the Guadalupe Basin**.**



METHODOLOGY

Spatial Maps

The spatial maps developed in this study provide an integrated visualisation of the climatic, topographic, and ecohydrological gradients that control water availability, runoff generation, and recharge potential across the Guadalupe Basin. The creation of these maps involved a rigorous process that utilised geospatial interpolation, terrain modelling, and thematic GIS integration. This integration entailed the amalgamation of various data sources, including precipitation, temperature, potential evapotranspiration (PET), climatic water balance (CWB), vegetation, slope, and geological data. Collectively, these layers establish the spatial context necessary for interpreting basin-scale hydrological dynamics under semiarid Mediterranean conditions.

The interpolation of climatic variables was conducted utilising Inverse Distance Weighting (IDW), a methodology that has been extensively employed in mountainous semiarid basins characterised by sparse meteorological station coverage. IDW has been shown to preserve local variability and demonstrate reliable performance under conditions of steep climatic gradients (Molina-Navarro et al., 2016; Valdes-Abellan et al., 2020). The resulting climatic surfaces capture the dominant hydroclimatic gradient of the basin, with higher winter precipitation and lower PET in the elevated eastern Sierra de

Juárez and warmer, drier conditions in the western lowlands. Derived terrain features from the digital elevation model (see Figure 3) reveal steep mountain fronts, which are conducive to rapid runoff, transitional mid-elevation slopes with mixed hydrological responses, and low-relief alluvial plains where residence times increase and infiltration becomes more favourable (Auerswald et al., 2024; Gnann et al., 2022). These topographic structures have been observed to mirror ecohydrological behaviour that has been documented in Mediterranean mountain systems (Eagleson, 2002).

Vegetation cover (see Figure 4) has been demonstrated to modulate soil-moisture retention and evapotranspiration dynamics (Guo et al., 2017; Salgado Tránsito et al., 2012). Forests and chaparral at higher elevations have been shown to enhance moisture storage and delay desiccation during winter, whereas agricultural and disturbed lowland areas exhibit reduced infiltration and higher runoff coefficients. The intersection of degraded land cover, elevated PET, and negative CWB underscores the combined influence of land-use change and climate forcing. The spatial datasets presented in Figures 3 and 4 reveal a structurally coherent hydroclimatic system, in which high-elevation eastern sectors serve as the main recharge zones, intermediate slopes shape lateral redistribution and soil-moisture cycling, and permeable lowlands function as infiltration environments constrained by high evaporative demand (Scanlon et al., 2002; Houze, 2012). These maps form the foundation for the integrated hydroclimatic interpretation presented in Sections 4.1–4.7.

The Thornthwaite-Mather Method

The empirical formula for water balance is the process of accounting for water in the soil by Thornthwaite and Mather (1955). They introduced the term potential evapotranspiration (PET), and it is based on temperature and latitude and determines that the latter constitutes a good index of energy in a specific place. The PET must be corrected using a coefficient that considers the number of days in the month and hours of light per day, depending on the latitude, to obtain the final PET according to Thornthwaite (mm/month).

Determine the monthly Heat Index **(i):**

$$i = \left(\frac{t}{5}\right)^{1.514}$$

From the monthly average temperature **(t)**.

Determine the annual Heat Index **(I)**:

Adding the 12 values of **i.**

$$I = \sum i$$

Determine the "uncorrected" monthly ET using the formula

$$ET_{(uncorrected} = 16\left(\frac{10 * t}{I}\right)^{a}$$

Where:

ET (uncorrected) Potential evapotranspiration at monthly level in mm/month, for months of 30 days and 12 hours of sunshine (theoretical)

I = Annual Heat Index

T = Monthly average temperature in °C

a= function of the annual heat index (I), calculated with

$$a = 675 * 10^{-9} * I^{3} - 771 * 10^{-7} * I^{2} + 1792 * 10^{-5} * I + 0.49239$$

Make corrections for the number of days in the month and the number of hours of sunshine.

$$ET = ET_{(uncorrected)} * \frac{N}{12} * \frac{a}{30}$$

Where:

ET = Corrected potential evapotranspiration

N = Maximum number of hours of sunshine, depends on the month and latitude

D = Number of days in a month: 30

The methodology was developed to facilitate recharge assessment in semiarid basins where available climatic data is limited. The integration of the Thornthwaite–Mather model with geospatial analysis provides a stable structure for estimating climatic recharge potential under conditions where data is scarce. This approach is widely utilised in regions where station density is inadequate for physically based models such as Penman–Monteith or distributed hydrological simulations (Scanlon et al., 2002). In order to enhance the robustness of the study, multiple datasets (namely, NASA EARTHDATA, WorldClim 2.0, and CONAGUA station records) were integrated and harmonised with a view to reducing temporal and spatial uncertainty. The employment of standardised soil moisture parameters, slope-derived runoff indices, and land-cover weighting serves to further enhance the internal consistency of the model. The climatic variables obtained included maximum, minimum, and average temperature, relative humidity, wind speed, precipitation, extraterrestrial radiation, and sunshine hours. The data were then organized, structured, and systematised in databases, following appropriate calculation methods to determine reference evapotranspiration (ETo).

Processing of Climate Information

The processing of climate data was conducted using the QGIS Geographic Information System (GIS), employing spatial analysis tools to generate thematic layers depicting temperature, radiation, sunshine hours, and relative humidity. The calculation of ETo was achieved by establishing a relationship between sunshine hours and other climate variables, in accordance with the method originally outlined by Thornthwaite and Mather (1957). The model was fed with a 30-year series of climate records obtained from meteorological stations, ensuring representativeness in the hydrological analysis. Subsequently, the interpolated climatic surfaces were harmonized with terrain derivatives to ensure spatial continuity across the basin.

Notwithstanding the dearth of long-term hydrometric and groundwater observations in the basin, several indirect validation procedures were implemented to enhance methodological robustness. Firstly, simulated potential evapotranspiration (PET) values were compared against regional estimates reported for semiarid Mediterranean climates, showing consistency with reference ranges documented in southern Spain, California, and central Chile (Guo et al., 2017; Valdes-Abellan et al., 2020). Secondly, precipitation fields derived from gridded datasets were cross-checked with available station records from CONAGUA and CICESE, confirming that spatially interpolated values fall within observed seasonal ranges. Thirdly, the spatial patterns of climatic recharge potential correspond with the previously reported fluctuations in groundwater levels within the Guadalupe Valley aquifer, particularly in areas where mixing processes and deep percolation have been documented (Daesslé et al., 2020). While it is recognized that these validation steps do not supplant direct hydrogeological measurements, it is contended that they enhance confidence in the internal coherence of model outputs and their applicability under conditions where data is scarce.

Slope Analysis

Slope analysis was performed using a Digital Elevation Model (DEM). Slope was defined as the maximum rate of change in altitude of each Digital Elevation Model (DEM) cell relative to its neighboring cells. The methodology proposed by Van Zuidam (1986) was utilized for the classification of slopes. Subsequently, the values obtained were adjusted to conform to geomorphological standards. The classification resulting from this process is presented in Table 1.

The processing of geographical data in Geographic Information Systems (GIS) facilitated the generation of slope maps and the identification of drainage patterns, thereby enabling the assessment of runoff in the basin. In order to achieve this objective, a range of geospatial analysis techniques were employed, including raster reclassification methods and spatial interpolation techniques. The advent of Geographic Information System (GIS) tools has precipitated substantial advancements in the realm of data collection and processing.

Table 1. Slope ranges taken from Van Zuidam (1985)

Slope coverage (modified from FAO 2006) and area coverage in percentage

Slope classes	Slope (°)	Area coverage	Area ratio (%)
Level slope	<1	16,758.12	7.00%
Very gentle sloping	01-feb	6,578.02	2.75%
Gently sloping	02-may	8,810.12	3.68%
Sloping	05-oct	66,256.02	27.69%
Strongly sloping	oct-15	48,680.68	20.35%
Moderately steep	15 - 30	31,971.90	13.36%
Steep	30 - 45	53,489.97	22.36%
Very steep	> 45	6,692.00	80.00%
		239,236.98	100.00%

RESULTS AND DISCUSSION

Morphometric analysis of slopes

The morphometric structure of the Guadalupe Basin has been revealed to be characterised by a highly heterogeneous topography, with slopes ranging from 0° to 56.93°. The topography exerts fundamental control over runoff generation, infiltration potential, soil stability, and groundwater recharge. Gentle slopes, defined as those with a gradient of less than 5°, comprise approximately 42% of the basin, predominantly situated in the southwestern alluvial valleys and agricultural terraces. In this region, the presence of deep, coarse- to medium-textured soils has been observed to impede overland flow, prolong residence time, and substantially enhance infiltration (see Figure 4A). These low-gradient sectors function as natural infiltration corridors and represent the most favourable environments for focused and diffuse recharge. Comparable recharge dynamics in low-relief alluvial plains have been documented in semiarid Mediterranean basins of southern Spain, California, and central Chile, where permeable sediments and gentle slopes promote infiltration even under strong seasonal water deficits (Scanlon et al., 2002; Valdes-Abellan et al., 2020).

Conversely, the precipitous inclines (>20°) in the eastern and central regions adjacent to the Sierra de Juárez facilitate expeditious runoff, impede infiltration due to the shallow nature of the soils, and expedite the process of erosion. These steep sectors function as runoff-generation zones where precipitation is rapidly redistributed downslope before substantial infiltration can occur, a behaviour consistent with well-established hydrologic responses in mountainous terrains worldwide (Eagleson, 2002; Auerswald et al., 2024). Despite the generally unfavourable conditions on steep slopes, localised recharge is possible where major fault systems, such as the San Miguel and Ojos Negros faults, create vertical permeability contrasts. As demonstrated in the relevant literature, fractured zones – defined by the presence of fissures or fractures in the rock matrix – exhibit an increased capacity for percolation in igneous and metamorphic rocks that are characterised by low permeability. This enhanced percolation process is a significant factor in the contribution to deep groundwater accumulation (Daesslé et al., 2020; Figueroa-Núñez & Campos-Gaytán, 2018).

Vegetation Controls on Hydrological Processes

These slope-controlled patterns are closely linked to the spatial distribution of vegetation cover (Figure 4B), since chaparral and forest-dominated slopes generally exhibit higher soil aggregation and moisture retention, whereas degraded or agricultural surfaces on gentle slopes show reduced infiltration capacity. It is imperative to incorporate vegetation into the interpretation of slope morphology to facilitate comprehension of the spatial differentiation of runoff and recharge zones across the basin. The spatial configuration of slopes establishes a hierarchical hydrological system within the basin, wherein steep highlands function as zones of runoff production, intermediate slopes act as transfer corridors that redistribute flow laterally and longitudinally, and low-relief alluvial plains serve as accumulation and recharge environments. This morphometric organisation provides a foundation for the recharge patterns derived from the water balance analysis and elucidates the concentration of infiltration potential in the western and central basin sectors.

In the upper echelons of the Sierra de Juárez, the presence of oak-pine forest patches has been observed to enhance soil-moisture retention. This phenomenon is attributed to the presence of thicker organic layers, lower temperatures, and reduced PET levels in these regions. Consequently, the recharge window is extended, resulting in a prolonged period of water accumulation. These forested zones function as hydrological buffers that facilitate percolation into fractured bedrock, thereby strengthening mountain-block recharge processes, as observed in other semiarid mountainous regions (Valdes-Abellan et al., 2020; Houze, 2012). The riparian vegetation along the Guadalupe, Agua Caliente, and Jamatay creeks plays a critical role in stabilising channel banks, maintaining soil moisture, and promoting focused infiltration during high-flow events. The existence of vegetated corridors has been demonstrated to enhance groundwater and surface water connectivity and to enhance recharge opportunities within the drainage network. This phenomenon has been observed in Mediterranean streams on a global scale (Sánchez-Montoya et al., 2009).

Conversely, agricultural lands, vineyards, orchards, and areas with disturbed or compacted soil, especially in the western and central lowlands, have reduced infiltration capacity due to the removal of vegetation, soil disturbance, and mechanized land management practices. The alterations have been demonstrated to engender an augmentation in runoff coefficients, a diminution in soil water storage, and an escalation in the basin's hydrological vulnerability (Salgado Tránsito et al., 2012). The spatial overlap of these degraded areas with zones of high PET and negative climatic water balance (see Figures 4C-4D) further increases the susceptibility of these areas to moisture deficits and rapid runoff generation.

Post-disturbance landscapes, including burned slopes and areas dominated by invasive grasslands, pose significant hydrological challenges. The increasing frequency of wildfires in Mediterranean ecosystems of Baja California has been shown to reduce canopy cover, increase soil hydrophobicity, and trigger extreme runoff responses during subsequent precipitation events (Pulido-Chávez et al., 2023; Sample, 2022). These processes substantially decrease infiltration efficiency and accelerate erosion, particularly across mid-slope terrains.

Vegetation in the Guadalupe Basin forms a well-defined ecohydrological hierarchy. High-elevation oak–pine forests function as primary recharge zones, while chaparral-covered slopes regulate soil moisture dynamics and lateral flow redistribution. Riparian corridors maintain localized infiltration pathways and enhance surface–groundwater connectivity (Smith et al., 2022). In contrast, agricultural or degraded lowland areas exhibit reduced infiltration capacity and increased runoff generation. As discussed in Sections 4.3–4.6, these vegetation–hydrology interactions are fundamental for interpreting the climatic water balance and the spatial organization of groundwater recharge potential.

Climate water balance

The hypothesis that temperature gradients reinforce this spatial behaviour has been demonstrated. The mean annual temperature in the lower basin is recorded as exceeding 18–20°C. This has the effect of increasing potential evapotranspiration (PET) and reducing water availability for infiltration. Conversely, temperatures in the highlands are below 12–14°C, which enhances water retention and slows evaporation. The thermal regime exerts a direct influence on vegetation distribution, soil moisture persistence, and the duration of the hydrological recharge period (see Figure 4B). During the summer months, the presence of strong warming, persistent high-pressure systems, and near-zero precipitation has been observed to result in severe soil desiccation, amplified PET, and extremely low infiltration efficiency, even during isolated storm events.

The distribution of precipitation, temperature, and seasonal hydroclimatic factors collectively delineates a recharge landscape characterised by spatial asymmetries, including high-elevation recharge corridors and lowland deficit zones. This imbalance underscores the imperative for the conservation of montane recharge regions, the maintenance of vegetation cover across slope gradients, and the implementation of land use practices that enhance infiltration and minimise soil compaction in mid- and low-elevation areas.

Recent studies have demonstrated that vegetation cover has a significant impact on the spatial behaviour of CWB. Forested regions and areas with mature chaparral vegetation have been observed to moderate soil desiccation, increase interception, and enhance infiltration during winter precipitation events.

Conversely, agricultural fields, vineyards, degraded soils, and urbanized or disturbed areas demonstrate diminished infiltration capacity and elevated runoff coefficients. These modified landscapes have been shown to have a substantial impact on local CWB values, often resulting in shifts towards more negative balances. This phenomenon can be attributed to a decline in soil water storage accompanied by increased evaporative losses (Salgado Tránsito et al., 2012).

It is evident that anthropogenic activities exert a substantial influence on shifts in CWB. The processes of land clearing, soil compaction, road construction and vegetation removal disrupt natural infiltration zones and redirect surface flow pathways. These disturbances have the effect of reducing the hydrological buffering capacity of mid- and low-elevation zones, which historically served as recharge corridors.

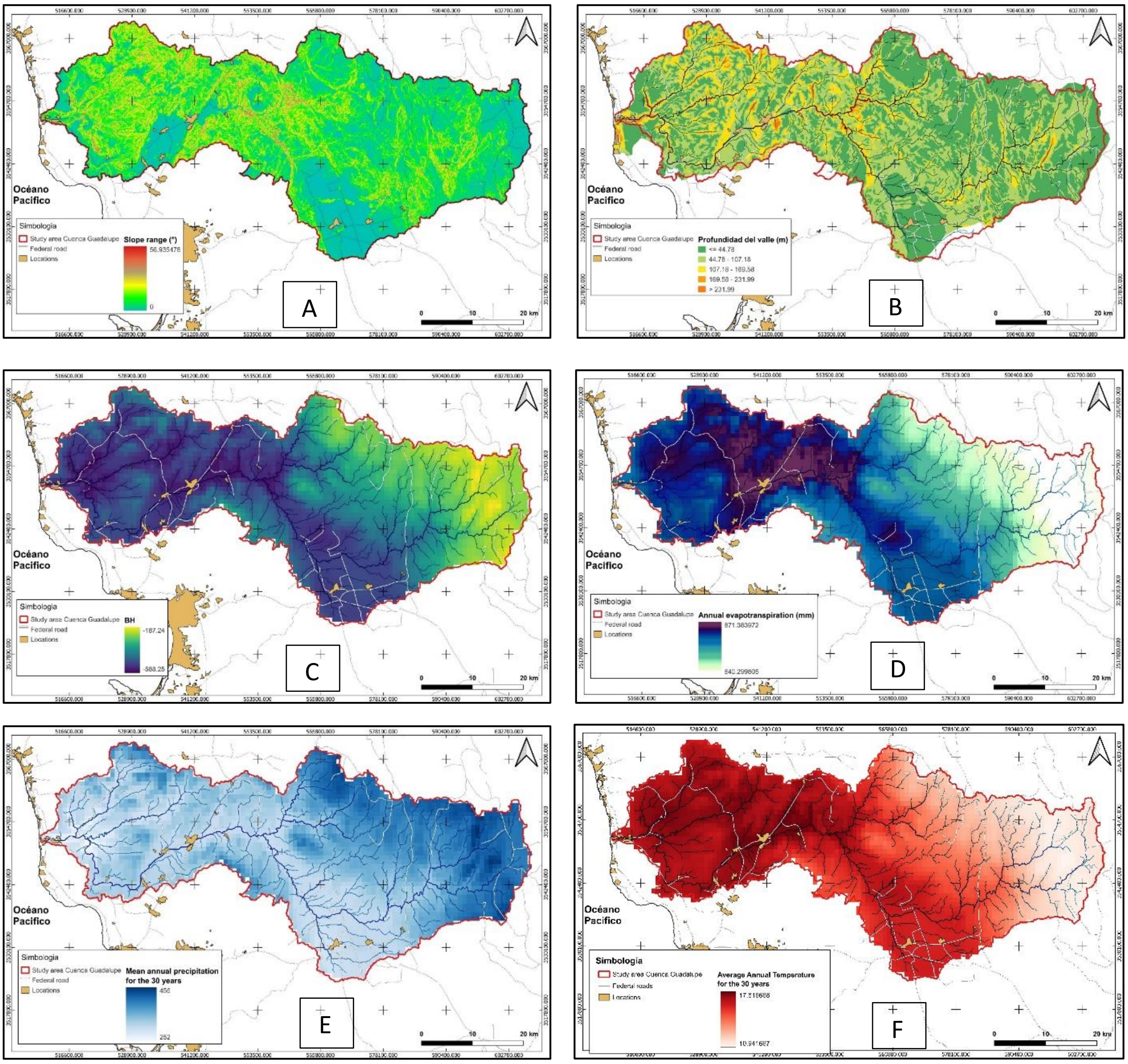
The spatial distribution of the CWB demonstrates the basin's structural vulnerability to water deficits and emphasises the necessity of preserving high-elevation recharge zones. The restoration of vegetation cover, the prevention of soil degradation, and the improvement of land-use management in mid- and lowland sectors are of the utmost importance in order to sustain soil-water storage, reduce runoff losses, and reinforce the basin's hydrological resilience in the face of ongoing climate variability.

Potential Evapotranspiration and Hydrothermal Gradients

Potential evapotranspiration (PET) exerts a predominant influence on soil moisture dynamics, vegetation stress, and groundwater recharge efficiency in semiarid Mediterranean basins. In the Guadalupe Basin, the spatial distribution of PET demonstrates a distinct west-east asymmetry in hydrothermal conditions, which is directly associated with temperature, solar radiation, elevation, and land cover patterns (Figure 4D). The western and central lowlands have the highest PET values, reflecting warmer conditions, lower humidity, and extensive disturbed or agricultural soils. The aforementioned factors have been demonstrated to engender an escalation in evaporative demand, a acceleration in surface drying, and a reduction in the annual infiltration window (Eagleson, 2002).

Conversely, the elevated eastern sectors of the Sierra de Juárez demonstrate a significant decline in PET levels, attributable to cooler temperatures, reduced solar exposure, and denser vegetation. The prevailing hydroclimatic conditions have been demonstrated to engender prolonged soil moisture retention, delay the onset of vegetation growth, and increase the likelihood that winter infiltration will reach deeper subsurface pathways (Valdés-Ábellan et al., 2020). The combination of low PET, higher precipitation (Figure 4E), and organic-rich soils in forested areas creates optimal conditions for groundwater replenishment.

Figure 4.



A) Slope degrees, B) Basin depth, C) Climatic water balance, D) Simulated evapotranspiration,
E) Average annual water flow over a 30-year period, F) Average annual ambient temperature over a 30-year period.

This phenomenon aligns with the documented mountain-block recharge processes prevalent in Mediterranean regions worldwide (Houze, 2012). Furthermore, research has demonstrated a correlation between soil texture and the outcome of PET. The presence of Coarse-grained alluvial sediments in valley bottoms promote rapid infiltration during winter precipitation events; however, their low water-retention capacity makes them highly susceptible to evaporative losses under elevated temperature conditions. This renders them highly sensitive to evaporative demand. Conversely, soils with a finer texture or higher organic content – such as those found in forested uplands – demonstrate increased moisture retention capacity. This capacity provides a buffering effect against the impact of PET. This enhanced capacity is attributed to the stabilisation of soil-water storage throughout transitional seasons (Gnann et al., 2022). These interactions serve to reinforce the spatial differentiation observed in the climatic water balance (Figure 4C), where negative values predominate in regions with high PET.

Annual Precipitation and Temperature

The annual precipitation in the Guadalupe Basin exhibits pronounced spatial asymmetry, driven primarily by orographic forcing, elevation gradients, and seasonal atmospheric circulation. Basin-wide estimates indicate annual precipitation ranging from approximately 206 to 456 mm, with maximum values concentrated in the eastern highlands of the Sierra de Juárez. Orographic uplift in this sector has been shown to enhance cloud formation and intensify winter precipitation events (Figure 4E). Documented precipitation patterns in other Mediterranean mountain systems are analogous, with elevation-induced gradients generating a spatial concentration of recharge potential within high-altitude zones (Houze, 2012; Eagleson, 2002).

The eastern and northeastern sectors, with elevations exceeding 1,500 meters above sea level, receive the highest precipitation levels, typically over 450 millimeters per year. When combined with lower temperatures and reduced PET (see Figure 4D), these conditions significantly enhance soil moisture retention, extend the recharge window, and promote both diffuse and focused infiltration in permeable zones.

Conversely, the western and central lowlands receive less than 250 mm annually and exhibit persistent climatic deficits (Jones et al., 2022, reinforcing their limited recharge capacity under high evaporative demand. These hydrometeorological asymmetries, typified by uplands with high recharge and lowlands with high discharge, are a hallmark feature of Mediterranean basins experiencing climatic water stress. In these regions, valley floors and coastal plains are becoming increasingly vulnerable to warming and drying trends (Valdés-Ábellan et al., 2020). Seasonality exerts a substantial influence on the basin's hydrological regime, with over 85% of annual precipitation occurring during the winter months (November–March) and being predominantly associated with Pacific frontal systems.

This precipitation accumulation underscores the significance of optimal soil moisture timing, as evidenced by the findings that recharge is maximised when winter precipitation coincides with low PET and increased soil saturation. During periods of drought, comparative analyses of semiarid watersheds in California and northern Chile (Molina-Navarro et al., 2016) have demonstrated that the delayed arrival or decreased intensity of winter storms substantially impacts annual recharge.

Integrated Spatial Analysis of Hydroclimatic Drivers

An integrated spatial analysis of slopes, vegetation cover, climatic water balance (CWB), potential evapotranspiration (PET), precipitation, and temperature reveals the interconnected nature of the Guadalupe Basin's hydrogeomorphology. Its hydrological functioning is collectively determined by topography, climate, soils, and ecological patterns (Figures 4A–4F). The spatial alignment of these variables reveals a persistent east-west hydroclimatic asymmetry characteristic of Mediterranean semiarid basins. In these basins, elevation, winter-dominated precipitation, and hydrothermal gradients govern infiltration, runoff generation, and recharge potential (Eagleson, 2002; Molina-Navarro et al., 2016).

In the eastern highlands of the Sierra de Juárez, several favorable factors converge: high winter precipitation (Figure 4E), cooler temperatures, low PET (Figure 4D), and dense chaparral and oak-pine forest cover (Figure 4B). These combined conditions reduce evaporative demand, enhance moisture retention, and prolong the period during which infiltration can occur. The fractured bedrock typical of these areas further enhances vertical percolation, facilitating recharge processes consistent with those observed in the mountains of Mediterranean regions in Spain, California, and Chile (Houze, 2012; Valdés-Ábellan et al., 2020). This region clearly functions as the main recharge engine of the basin.

Mid-slope terrains serve as transitional ecohydrological zones where infiltration, runoff redistribution, and soil-vegetation interactions occur. Slopes with a gradient of 7 to 20 percent are characterized by dense chaparral vegetation that intercepts runoff and promotes partial infiltration. However, the hydrological behavior of these slopes is highly sensitive to land disturbance. Vineyard expansion, road construction, soil compaction, and vegetation clearing can rapidly shift these terrains from partially infiltrating to runoff-dominated conditions. These threshold responses have been extensively documented in semiarid Mediterranean catchments under anthropogenic influence, where minor disturbances can significantly alter infiltration pathways and water storage dynamics (Gnann et al., 2022).

The western and central alluvial plains have the lowest CWB values due to high PET, high temperatures, and shallow winter precipitation. Despite containing coarse, highly permeable sediments that are conducive to infiltration, the geologically recent valley floors of these areas experience rapid soil evaporation following winter storms due to the lowlands' strong evaporative demand. This limits the effectiveness of infiltration and reduces the proportion of winter rainfall that contributes to groundwater replenishment. Similar dynamics have been observed in Mediterranean lowland basins, where high permeability does not result in high recharge under warm, dry climatic conditions (Valdés-Ábellan et al., 2020).

Analysis of the data reveals that the Guadalupe Basin is organized into three hydrological subsystems. First, the recharge-dominant highlands have low PET and high winter precipitation. Second, the transition-dominant mid-slopes control lateral redistribution. Third are the storage-limited lowlands, where PET-driven dedication restricts recharge. This tripartite organization is characteristic of Mediterranean climate regions worldwide. It provides a scientific basis for identifying priority zones for conservation, recharge, protection, and climate-resilient management (IPCC, 2021).

Comparative Discussion: Hydrological Dynamics of the Guadalupe Basin in an International Mediterranean Context

When examined within an international Mediterranean framework, the Guadalupe Basin's hydrological behaviour reveals a high level of consistency with well-documented patterns in semiarid, mountain-fed basins across California, central Chile, southern Spain, Israel, and Turkey. One of the strongest parallels that can be drawn is the dominance of winter precipitation, which typically accounts for over 80% of annual rainfall and coincides with the lowest potential evapotranspiration (PET). This seasonal synchrony is imperative for the effective replenishment of groundwater reserves, a phenomenon that has been observed across all Mediterranean regions. This phenomenon is especially pronounced in the Guadalupe Basin, where the frequency and intensity of winter storms have a direct impact on the annual potential for recharge (Houze, 2012; Eagleson, 2002). It is evident that a reduction in, delay to, or weakening of winter rainfall has a substantial impact on infiltration and recharge efficiency.

This phenomenon has been observed in a variety of geographical locations, including California's coastal basins, Chile's Andean foothills, and Spain's interior catchments (Molina-Navarro et al., 2016). The geomorphological structure of the Guadalupe Basin is analogous to that of Mediterranean basins on a global scale. These basins exhibit a distinctive three-part hydrological organisation (Jones et al., 2022). The organisation of this system is characterised by steep, high-elevation runoff production and recharge zones, transitional mid-slopes that control lateral redistribution, and low-relief alluvial plains that serve as sediment accumulation and extraction areas (Jones et al., 2022). In the Guadalupe Basin, the majority of winter recharge is attributable to the Sierra de Juárez. Concurrently, the chaparral-covered midlands regulate slope hydrodynamics, and the western alluvial plains exhibit high PET and reduced infiltration. These patterns bear a strong resemblance to those previously observed in the Segura Basin (Spain), the Maipo Basin (Chile), and the Santa Ana River watershed (California) (Gnann et al., 2022; Valdés-Ábellan et al., 2020).

The interaction between vegetation and hydrology further aligns the basin with global Mediterranean behaviour. Chaparral ecosystems in Baja California are distinguished by pronounced summer evapotranspiration, profound root systems, and heightened vulnerability to fire. These characteristics are shared with chaparral in California and matorral in Chile. This vegetation type is characterised by significant fluctuations in soil moisture levels between the winter and summer periods, resulting in distinct transitions in the ecosystem's hydrological balance. Concurrently, oak-pine forests flourish at higher altitudes and demonstrate hydrological functions analogous to those observed in Mediterranean mountain forests in Europe and South America. As demonstrated in the relevant literature, these forests have been observed to reduce temperatures, decrease PET, stabilise soils and enhance infiltration (see Guo et al., 2017; Houze, 2012).

The phenomenon of climate change has been demonstrated to engender additional parallels. The contemporary Mediterranean climate is characterised by increased temperatures, intensified heat waves, and potential reductions in winter precipitation. These climatic shifts are likely to shorten recharge windows and increase evaporative demand (IPCC, 2021). These alterations directly impact the Guadalupe Basin, where warming trends are expected to exacerbate soil moisture deficits in the lowlands and increase hydrological dependence on high-elevation recharge zones.

This structural vulnerability bears a striking resemblance to those previously documented in the Segura Basin in Spain, the central valleys of Chile, and the inland watersheds of California.

It is evident that numerous Mediterranean regions have devised adaptive water management strategies that have the potential to inform decision-making processes in the Guadalupe Basin. These strategies include the protection of mountain recharge zones, the restoration of mid-slope vegetation, the reduction of soil compaction in lowland agricultural areas, the implementation of managed aquifer recharge (MAR) systems, and the incorporation of climate forecasts into water allocation planning (Scanlon et al., 2016; Dillon et al., 2020).

The hydroclimatic configuration of the Guadalupe Basin supports these interventions and underscores the necessity of an ecohydrologically informed governance approach.

Limitations & Uncertainty

Notwithstanding the integrative framework applied in this study, several methodological and data-related limitations introduce uncertainty in the estimation of precipitation, evapotranspiration, and groundwater recharge in the Guadalupe Basin. It is imperative to acknowledge these limitations to establish a comprehensive contextual framework for interpreting the results and informing future research directions. Firstly, the sparse distribution of long-term meteorological stations in the region necessitated the use of gridded climatological products, such as Legates and Willmott's (1990) gauge-corrected precipitation dataset and WorldClim 2.0 climatology. While these datasets have been extensively utilised in the field of hydrological research, it has been observed that they possess the capacity to attenuate extreme events and underestimate spatial variability within mountainous terrain. This phenomenon is particularly pronounced in the Sierra de Juárez, where marked altitudinal variations give rise to substantial microclimatic contrasts that are not adequately captured by coarsely interpolated surfaces.

Secondly, the Thornthwaite-Mather water balance model estimates potential evapotranspiration (PET) and relies heavily on air temperature as a proxy for available energy. It is evident that this empirical formulation does not explicitly incorporate aerodynamic variables, such as wind speed, vapor pressure deficit, or net radiation. As Lascano and Van Bavel (2007) have previously observed, these simplifications may introduce biases in PET estimation when compared to physically based models, such as the Penman-Monteith model. Additionally, the parameters that govern the transition between actual evapotranspiration and recharge (i.e., soil storage parameters) introduce uncertainty because they are derived from generalized soil descriptions rather than site-specific hydraulic measurements.

In Mediterranean semiarid environments of northwestern Mexico, reference evapotranspiration calculated using the FAO Penman–Monteith method commonly ranges between 7.5 and 9 mm day^{-1} during summer months in the Valle de Guadalupe and adjacent viticultural valleys (Macías-Carranza et al., 2021). Numerous comparative studies have demonstrated that temperature-based approaches such as Thornthwaite tend to underestimate potential evapotranspiration relative to the physically based FAO Penman–Monteith formulation, particularly under conditions of high radiation and low atmospheric humidity typical of semiarid climates (Allen et al., 1998; Droogers, 2002; Xu, 2002). Although the Thornthwaite method remains suitable for data-scarce basins and for spatially comparative analysis, these documented differences suggest that absolute PET values derived in this study should be interpreted as conservative estimates, while the spatial patterns and hydroclimatic gradients remain robust.

Thirdly, the use of inverse distance weighting (IDW) to interpolate climatic and topographic variables has been demonstrated to result in the creation of spatial artefacts, a phenomenon that is especially prevalent in areas characterised by steep relief transitions or sparse data. Despite its computational efficiency and widespread use, IDW assumes isotropic spatial continuity, neglecting terrain barriers and preferential climatic gradients (Wang & Liu, 2006). Fourthly, the study lacked direct groundwater abstraction data, pumping records, isotopic tracers, and geophysical estimates of infiltration. This limitation resulted in a restricted validation of recharge estimates. Consequently, the water balance indicates climatic recharge potential rather than actual recharge under prevailing extraction pressures. It is conceivable that extraction pressures are considerably lower in overexploited systems, as evidenced in analogous semiarid aquifers (Daesslé et al., 2020).

Finally, it is imperative to acknowledge the uncertainties arising from rapid land use changes, including vegetation degradation, soil compaction, and urban expansion, which must be given due consideration. These factors modify the partitioning of runoff and infiltration. It is evident that static land-cover datasets are incapable of fully capturing the evolving dynamics under consideration. Consequently, these datasets may have a substantial impact on recharge estimation. In spite of the aforementioned uncertainties, the integrated hydrological-climatic approach developed here provides a reliable initial diagnosis of water availability and stress in the Guadalupe Basin. It is recommended that future research incorporate expanded climate monitoring networks, tracer-based recharge validation, soil hydraulic characterisation, and coupled surface-groundwater models. These additions would serve to reduce uncertainty and strengthen predictive capability.

A qualitative sensitivity analysis was performed to evaluate the influence of key parameters on model outputs. Variations of ±10% in temperature and precipitation resulted in proportional changes in PET and water balance estimates. These results are consistent with sensitivities reported in other semiarid basins (Guo et al., 2017). The findings indicated that soil storage capacity exerted the most significant influence on recharge estimates. This result underscores the necessity for enhanced precision in subsequent field measurements of this parameter. Despite its simplifications, this sensitivity assessment provides insight into the relative contributions of climatic and edaphic uncertainties to overall recharge estimation.

Implications for Sustainable Water Management

The hydroclimatic structure identified in the Guadalupe Basin provides critical scientific insight into the spatial controls governing groundwater recharge and highlights key priorities for sustainable water resources management in semiarid Mediterranean environments. The strong dependence of recharge on the high-elevation sectors of the Sierra de Juárez underscores the strategic importance of mountain recharge areas as fundamental components of regional water security. These upland zones exhibit favorable hydroclimatic conditions, including lower potential evapotranspiration, higher winter precipitation, and enhanced soil moisture retention. Collectively, these conditions promote deep percolation and aquifer replenishment. As demonstrated in extant literature, recharge in mountainous regions has been shown to exhibit a high degree of similarity in Mediterranean basins worldwide. In these basins, highland recharge is identified as the primary source of groundwater renewal (Scanlon et al., 2002; Viviroli et al., 2020; Valdes-Abellan et al., 2020).

The identification of recharge-dominant highlands and storage-limited lowlands has important implications for land-use planning and aquifer sustainability.

Anthropogenic disturbances, such as the removal of vegetation, soil compaction associated with agriculture, vineyard expansion, and infrastructure development, have the potential to significantly reduce infiltration capacity and alter natural recharge processes. These impacts have been previously documented in the Guadalupe Valley aquifer, where intensive land use and groundwater extraction have contributed to declining water levels and increased aquifer vulnerability (Daesslé et al., 2006; Salgado Tránsito et al., 2012; Díaz-Gutiérrez et al., 2024). The preservation of vegetation cover, particularly oak–pine forests and chaparral ecosystems, plays a critical role in maintaining soil structure, regulating evapotranspiration, and enhancing recharge efficiency. Consequently, the restoration and conservation of vegetation have been identified as pivotal management strategies to enhance hydrological resilience in semiarid watersheds (Guo et al., 2017; Scanlon et al., 2016).

Furthermore, the results underscore the structural limitations of lowland aquifer zones, where high evaporative demand and persistent climatic water deficits constrain natural recharge despite the presence of permeable sediments. This finding suggests that groundwater extraction in these areas may exceed long-term recharge capacity under current and projected climatic conditions. A plethora of studies have documented analogous imbalances between recharge and extraction in multiple semiarid aquifers across the globe. These imbalances have been identified as a predominant catalyst for groundwater depletion and long-term water insecurity (Wada et al., 2012; IPCC, 2021).

These findings underscore the imperative for adopting integrated water management approaches that explicitly incorporate spatial recharge dynamics into decision-making processes. Strategies such as the protection of recharge zones, regulation of groundwater abstraction, restoration of degraded landscapes, and implementation of managed aquifer recharge systems have been successfully applied in Mediterranean-climate regions to enhance groundwater sustainability and mitigate water stress (Scanlon et al., 2016; Dillon et al., 2020). The spatial framework developed in this study provides a scientifically robust basis for identifying priority conservation areas, optimizing land-use planning, and supporting climate-resilient water management strategies in the Guadalupe Basin.

The integration of hydroclimatic, geomorphological, and ecological information presented here contributes to a more comprehensive understanding of groundwater vulnerability and reinforces the importance of science-based water management to ensure long-term sustainability under conditions of increasing climatic variability and water demand (Abbaspour et al., 2015; Viviroli et al., 2020).

CONCLUSIONS

The integrated hydroclimatic, geomorphological, and ecohydrological assessment of the Guadalupe Basin reveals a strongly differentiated watershed that exhibits the defining characteristics of Mediterranean semiarid systems. The integrated analysis of slope gradients, vegetation cover, climatic water balance, potential evapotranspiration (PET), and winter-dominated precipitation reveals that groundwater recharge, runoff generation, and soil moisture dynamics exhibit spatial structuring and are governed by elevation-driven hydrothermal gradients. The basin functions as a tripartite hydrological system, comprising recharge-dominant highlands, mid-slope transition zones that regulate lateral redistribution, and lowland sectors characterized by storage limitations and persistent hydroclimatic stress. This functional organization is consistent with Mediterranean basins worldwide, where elevation, seasonality, and evaporative demand govern hydrological behavior (Eagleson, 2002; Molina-Navarro et al., 2016; Valdes-Abellan et al., 2020).

The eastern high-elevation sectors of the Sierra de Juárez function as the primary recharge corridors of the basin. These regions are distinguished by elevated winter precipitation, diminished PET, temperate temperatures, and dense oak–pine and chaparral vegetation. These conditions contribute to the prolongation of soil moisture availability and promote deep percolation. The presence of fractured crystalline bedrock further enhances vertical infiltration, thereby supporting mountain-block recharge processes analogous to those documented in Mediterranean mountain systems of California, Chile, and southern Spain (Houze, 2012; Scanlon et al., 2002; Daesslé et al., 2020). Conversely, the western and central lowlands experience elevated PET, higher temperatures, and reduced precipitation, resulting in persistent negative climatic water balance values. This condition increases long-term aquifer vulnerability under projected warming trends. (IPCC, 2021; Valdes-Abellan et al., 2020).

Vegetation emerges as a pivotal ecohydrological regulator across the basin. Forested and chaparral-covered uplands have been shown to enhance soil structure, moisture retention, and infiltration efficiency during the winter recharge period. Conversely, agricultural lands, vineyards, compacted soils, and disturbed surfaces in lowland areas exhibit reduced infiltration capacity and accelerated runoff generation. These contrasts underscore the imperative of preserving and reviving native vegetation to ensure hydrological connectivity and mitigate the repercussions of rising PET under climate change (Guo et al., 2017; Gnann et al., 2022; Salgado Tránsito et al., 2012).

From a water management perspective, the results indicate that long-term groundwater sustainability in the Guadalupe Basin cannot be achieved through interventions focused solely on valley floors or extraction zones. An effective management approach must explicitly acknowledge the structural dependence of the aquifer system on recharge areas located at higher elevations. The preservation of mountain recharge corridors, the maintenance of vegetation cover on slopes, and the limitation of land-use changes that disrupt infiltration pathways are therefore essential requirements for basin-scale hydrological resilience. Decisions pertaining to agricultural expansion, urban development, road construction, and vegetation clearing directly influence recharge efficiency and aquifer vulnerability in semiarid Mediterranean environments (Scanlon et al., 2016; Dillon et al., 2020).

These findings underscore the pressing need to incorporate recharge zone protection and hydroclimatic spatial variability into regional water management strategies. It is imperative to acknowledge the paramount importance of preserving high-elevation recharge areas within the Sierra de Juárez, as this is instrumental in ensuring the long-term sustainability of aquifers. Consequently, land-use regulation in mid-slope and valley sectors is imperative to avert further reductions in infiltration capacity caused by vegetation removal, soil compaction, and agricultural intensification. A review of comparable semi-arid Mediterranean regions indicates that groundwater sustainability is contingent upon the protection of recharge areas, the restoration of degraded landscapes, and the implementation of adaptive management strategies such as managed aquifer recharge and vegetation conservation (Scanlon et al., 2016; Dillon et al., 2020; Viviroli et al., 2020). The incorporation of hydroclimatic controls into land-use planning and groundwater governance is imperative to enhance water security and climate resilience in the Guadalupe Basin.

A comparison of the Guadalupe Basin with other regions confirms that it shares the fundamental attributes of Mediterranean-climate watersheds. These include strong seasonality, winter-dependent recharge, hydrothermal asymmetry, and heightened sensitivity to warming trends (Eagleson, 2002; Houze, 2012; IPCC, 2021).

Comparable regions have implemented adaptive strategies, including managed aquifer recharge, reforestation of critical slopes, reduction of soil compaction in agricultural areas, and protection of riparian corridors. These strategies have been identified as viable pathways for enhancing recharge and mitigating long-term water stress (Scanlon et al., 2016; Dillon et al., 2020).

Methodologically, this study demonstrates that integrating climatic water-balance modeling with geomorphological, ecological, and spatial analyses provides a robust and transferable framework for identifying relative recharge patterns in data-scarce semiarid regions. Although the Thornthwaite–Mather approach does not quantify absolute recharge volumes, its integration with terrain, vegetation, and hydroclimatic gradients provides a scientifically sound foundation for strategic planning. The Guadalupe Basin offers a paradigmatic example of the hydrological challenges confronted by Mediterranean semiarid environments, thereby providing transferable insights for climate-resilient water management and sustainable territorial planning.

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