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"Vegetation Structure in Recharge and Discharge Areas of a Karstic Landscape in the Ciénega de Tamasopo, San Luis Potosí, Mexico."

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I. Chapter 1. Foundations

I.1. Introduction

Wetlands are ecosystems widely studied due to the importance and variety they present; they are defined as land covered by shallow water permanently or intermittently, which provides ideal conditions for the development of diverse ecosystems of great ecological, economic and social importance.

Wetlands are areas in which water is the main controlling factor of the environment, fauna and flora associated with it, and the wide diversity of this type of ecosystem reflects in the definition provided by the Ramsar convention: "areas of marsh, fen, peatland or water, whether natural or artificial, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" (Abarca, 2001; Ramsar Convention Secretariat, 2013).

Wetlands are among the most productive environments of the world (Ramsar Convention Secretariat, 2013) and are habitats of a diversity of species of flora and fauna. They provide ecosystem services such as control of inundation and storm protection, in addition to their recreational and economic value with activities such as fishing.

According to Zedler and Kercher (2005), around 9 percent of earth's surface is covered by some type of wetland, with a total extension of approximately 12.8 million km^2. Nonetheless, indiscriminate exploitation and anthropogenic pressures on wetland continues, altering key ecological processes that have led to the reduction of the area and resilience of this ecosystems (Agardy *et al.*, 2005).

As part of the efforts for the management and conservation of wetlands, in 1971 the Convention on Wetlands of International Importance, also known as the Ramsar Convention, was established. This convention is an intergovernmental treaty that provides the framework for the conservation and wise use of wetlands and their resources (Ramsar Convention, 2015). In México, the Ramsar treaty came into force on November 4 of 1986 and in 2008 the Ciénega de Tamasopo wetland was declared a Ramsar site of international importance (Torres, 2008).

The Ciénega de Tamasopo wetland (also known as Ciénega de Cabezas) is located in the microbasin No. 40, in the Tamuín river basin, which is part of the Panuco hydrological region (CAN, 1998; INEGI, 2002). It is considered a lentic system since its waters have little to almost no movement and is one of the last wetlands of tropical subhumid climate of San Luis Potosí (Torres, 2008). It has great ecological importance as habitat of native flora and fauna, in addition to its social value, since it supplies at least 14 communities in its microbasin with water. However, the intensification of sugarcane cultivation, which was reinforced in 1982 to meet the demand of the Ingenio Alianza Popular, led to the conversion of forested areas into agricultural land and the drainage of wetland soils for crop establishment. These changes expanded the agricultural area, increased the wetland's primary productivity, and ultimately created a hypertrophic state (Rodríguez del Río, 2024).

The Ciénega de Tamasopo wetland is fed both by surface water, through rainfall, and by groundwater, as the karst formations (composed of highly soluble rocks) that are abundant in the micro-basin facilitate groundwater flow.

To analyze in detail the way water flows temporally and spatially, above and below the ground in the microbasin, the groundwater flow systems theory (FST) proposed by Toth (1999) is used. This theory proposes a systemic analysis to evaluate the interaction of groundwater with other components of the environment, including vegetation, soil, and geomorphology of the terrain, among others (Gardea, 2019). The FST describes three main flow systems on the spatial scale, each with specific characteristics: local, intermediate and regional. Each of these flows has a recharge, transit and discharge zone.

Recharge zones are areas where rainwater infiltrates with a vertical flow favored by gravity. They are generally located in topographically high areas and have deep water tables. The discharge zones are areas where water emerges as the water table reaches the surface, expressing as springs, lakes, streams or flooded soils (Peñuela & Carrillo, 2012).

Within the microbasin, there are karstic formations known as sinkholes (depressions that form when water washes sediment down into cracks and voids in karst bedrock) which are considered recharge zones since their topographic characteristics makes them great for rainwater collection, therefore, have been established as one of the main areas to analyze in the present study.

Peñuela and Carrillo (2012) point out how important it is to identify and study the groundwater recharge and discharge zones, as a tool for the design of conservation plans of critical hydrological areas. They emphasize in vegetation being one of the principal superficial indicators of these zones as it has been shown to exhibit specific characteristics for each of these places.

Vegetation ecology studies are one of the main supports for the planning, management, and conservation of ecosystems. To achieve this, it is first necessary to know the richness and floristic composition of the sites to be analyzed, and then to perform an analysis of the vegetation structure, to assess the density, frequency, abundance, and importance value of the species that make up the plant communities. Additionally, information on biological diversity is obtained based on indices such as Shannon's index (Álvarez *et al.*, 2006). These studies must also consider ecosystem components (especially aspects of climate, soil, bedrock, etc.) as analyzing the interactions between these components and the vegetation will provide a better understanding of the dynamics and conservation status of the studied areas (Álvarez *et al.*, 2006).

I.2. Justification

The water crisis is a problem that has been increasing over time, making it necessary to seek effective solutions for the conservation of water bodies. In Mexico, 38.7% of water for human consumption comes from aquifers (IMTA, 2019), whose recharge is regulated by the groundwater flow system described by Toth, emphasizing the recharge and discharge zones. Within these zones, vegetation plays a key role in the interactions between groundwater and surface water systems due to its direct and indirect influence on infiltration. Therefore, studying vegetation in these priority zones provides relevant information for ecosystem preservation

There are no floristic studies for the microbasin in which the Ciénega de Tamasopo is located, although several studies made in different locations around the study site have floristic lists; nonetheless the total richness of the vegetation in this region is far unknown. The Ciénega de Tamasopo is a Ramsar site, and in addition to its ecological importance as an area of great biological diversity, it represents an important source of income for the local inhabitants, whose main economic activities depend on the water supply and plant resources of the wetland. These activities, primarily sugar cane cultivation and livestock farming, have driven accelerated land-use changes that have altered the dynamics of the wetland, particularly the recharge and discharge zones. This is why the analysis of vegetation and its interaction with groundwater flow systems in ecologically important areas such as recharge and discharge zones become an important tool for the conservation of wetlands, providing real, clear, and reliable information for the establishment of programs aimed at the systemic management of natural resources.

This research is part of the multidisciplinary project A1-S-27598 “Evaluation of the process of eutrophication and environmental alteration that affects the RAMSAR site Ciénega de Tamasopo (SLP) as a basis for proposing its comprehensive management.” One of the objectives of the project is to create a conceptual model of the groundwater flow system in a subhumid karst environment, integrating the most important plant species for the ecological communities of the water recharge and discharge areas. Through this model, it is expected to obtain a greater understanding of the dynamics that supply the Ciénega de Tamasopo wetland to achieve the conservation of the site.

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I.3. Objective

To characterize and analyze the vegetation structure and floristic composition based on the groundwater recharge and discharge zones of the Ciénega de Tamasopo wetland, San Luis Potosí, México.

I.3.1. Specific objectives

1. To elaborate a floristic list of the water recharge and discharge zones of the Ciénega de Tamasopo wetland.
2. To analyze the community diversity of the vegetation in the water recharge and discharge zones of the Ciénega de Tamasopo wetland.
3. To characterize and analyze the vegetation structure based on the water recharge and discharge zones of the Ciénega de Tamasopo wetland.

I.4. Literature review

I.4.1. Ramsar wetlands

Wetlands are defined by the Ramsar Convention as areas where water is the primary factor controlling the environment and the associated flora and fauna. Wetlands occur where the water table is at or near the surface of the land, or where the land is covered by shallow water (Ramsar Convention Secretariat, 2013).

They are ecosystems of great environmental, social, and economic importance, as they serve as water supply sources for the population, provide ecosystem services such as flood control and storm protection, are habitats of great biodiversity of flora and fauna, and serve as sources of income through activities such as fishing and tourism (Zedler & Kercher, 2005; Ramsar, 2018).

The exact percentage of the Earth's surface covered by wetlands is not known. According to the estimate by the UNEP World Conservation Monitoring Centre, it is around 570 million hectares (5.7 million km^2), approximately 6% of the Earth's surface (Ramsar Convention Secretariat, 2013).

The 2018 Ramsar Wetland Outlook reported that wetland area continues to decline, with conversion and loss continuing in all parts of the world (Convention on Wetlands, 2021). Worldwide, wetlands have been degraded either by direct alteration or through the consequences of changes to their necessary environmental, and especially hydrological, inputs (Maltby, 2009).

Natural wetlands are in long-term decline around the world; between 1970 and 2015, inland and marine/coastal wetlands both declined by approximately 35% globally. By region, the decline varies from 12% in Oceania to 59% in Latin America (Ramsar Convention, 2018).

This is why the Convention on Wetlands was created on February 2, 1971, adopted in the Iranian city of Ramsar, and has since become commonly known as the Ramsar Convention. This convention was developed to draw international attention to the rate at which wetlands were disappearing, partly due to a lack of understanding of the important role of these ecosystems.

Now, there are more than 2,400 Ramsar sites worldwide, covering a total area of over 2.5 million square kilometers. Mexico is one of the member countries with the most designated sites, with 142 sites (Ramsar Convention, 2024).

I.4.2. Ciénega de Tamasopo wetland

The Ciénega de Tamasopo wetland, also known as Ciénega de Cabezas, is located in the municipality of Tamasopo in the state of San Luis Potosí. This place can be legally identified since 1935, the year in which the waters of the El Trigo or Cabezas stream were declared national property according to declaration number 137, published by the Official Gazette of the Federation (DOF by its Spanish acronym), due to their status as permanent springs (Zapata, 2011).

The Ciénega de Tamasopo wetland supplies water to the surrounding communities, such as Cabezas, Oscuranas, Cofradía, San Isidro, Verástegui, La Copa, Tamaginique, La Esperanza, 20 de Noviembre, La Ceibita, Capuchinas, El Detalle, Agua de Piedras, Joya de los Novillos, Emiliano Zapata, among others (Pérez, 2017).

Since this wetland is an important collector of rainwater, combined with the variety of soil groups in its basin, it provides suitable conditions for sugarcane production, an agriculturally significant activity for the community (Torres, 2008; Tapia-Goné *et al.*, 2010).

On February 2, 2008, the Ciénega de Tamasopo was designated as a "Wetland of International Importance" (Ramsar Site No. 1814) for being one of the few wetlands that exist in the Sierra Madre Oriental region and the Huasteca Potosina region. This was done in an effort to halt deterioration and promote the conservation of the ecosystem.

The impact of agriculture on the wetland as the principal economical source started in the 1970's and has maintained until this day, with the over-extraction of water resources due to the high demand for water during each vegetative growth season of each planting cycle, as well as the increased periods of drought in the area. An analysis of satellite information indicates a loss of approximately 574 hectares of the wetland since the 1970s due to the expansion of sugar cane agriculture and livestock farming (Rocha, 2019).

I.4.3. Previous studies in the Ciénega de Tamasopo wetland.

The importance of the Ciénega de Tamasopo is reflected in the number of studies of different disciplines that has been made in the zone, each of which has as an objective to contribute to the conservation of the wetland.

In the hydrogeochemical section, the studies by Zapata Sánchez (2011), Pérez Castillo (2017), Krienen *et al.* (2017), Rocha Vázquez (2019), Centeno Herrera (2023), and Rodríguez del Río (2024) are noteworthy.

Zapata Sánchez (2011), within the project "Evaluation of the Eutrophication Process and Alteration Affecting the Ramsar Site Ciénega de Tamasopo (SLP), as a Basis for Proposing Its Integrated Management," characterized the soils in the groundwater recharge and discharge zones through their physical and chemical properties and elemental concentrations. The results indicated that the soils are rich in macro- and micronutrients, derived from both natural and anthropogenic factors. Furthermore, elements such as As, Ba, and V exceeded the maximum permissible limits in all samples, as stipulated by NOM-147-SSA1-2004, a consequence of agricultural and livestock activities occurring near the Ciénega de Tamasopo.

Pérez Castillo (2017) conducted a study on the biogeochemical dynamics of elements (C, N, Fe, and S) between the water and sediment of the Ciénega de Tamasopo wetland to determine whether alterations in sedimentation rates have affected the wetland's biogeochemical functions. Additionally, water quality was monitored by measuring physicochemical parameters in the 11 springs of the wetland. The study also determined that the water in the area belongs to the bicarbonate/sulfate-calcium family, which is related to the karstification process (the dissolution of the calcareous substrate due to rainwater infiltration) of the "Sierra Calcárea" landform system.

Krienen *et al*. (2017) analyzed the water from the wetland and compared it to that of a nearby area located in the same valley, known as Rio Verde. They found that the water is bicarbonate-calcium and bicarbonate-sulfate and concluded that, while the two areas share a common origin, they lack hydraulic connectivity.

Rocha Vázquez (2019) evaluated the water quality in the Huasteca Karst zone, which includes the Ciénega de Tamasopo, using water quality indices. The study concluded that, overall, the composition of groundwater is suitable for human consumption.

Centeno Herrera (2023) determined the accumulation rates of contaminants and organic matter in the wetland. The study linked the increase in accumulation rates to the period when communities were established (Cabezas was settled in 1959) and/or the practice of sugarcane agriculture. It also suggested a potential anthropogenic contribution of Cr due to the use of agrochemicals.

Rodríguez del Río (2024) analyzed the concentration profiles of substances present in the interstitial water at the water-sediment interface of the wetland, aiming to identify variations in water quality and the chemical processes in which these substances participate. Additionally, the study evaluated the variables that could influence changes in the productivity of the Ramsar site. The research findings indicated an alteration in the primary productivity of the wetland, possibly linked to substances derived from agricultural activities and the use of agrochemicals. Furthermore, water quality parameters were identified, suggesting an impact from human settlements, likely due to the infiltration of wastewater.

Regarding land-use changes and their effects on the wetland, notable studies include those by Tapia *et al.* (2010), Saldaña (2011), Galindo (2012), and Zubieta (2012).

Tapia *et al.* (2010) analyzed the potential land use of the Ciénega de Tamasopo through soil characterization at 20 sampling points. The study classified the soil into four different categories based on its potential use: Agricultural (2.58%), suitable for any crop; Agricultural and livestock (43.85%), appropriate for limited crops; Forests and forest crops, with very severe limitations and primarily suitable for forests and reserve lands (17.69%); and finally, protection soils and/or natural reserves (35.85%), suitable only for sustaining natural flora and fauna.

Saldaña (2011) analyzed data from a meteorological station located in the 20 de Noviembre community within the Ciénega de Tamasopo basin to evaluate potential microclimatic changes due to land-use change. The study compared temperatures and precipitation during the periods 1973–1990 and 1991–2008. The observed trend indicated an increase in temperature and a decrease in precipitation, suggesting that desiccation and land-use change influenced these variations, which were most pronounced in the spring season.

Galindo (2012) and Zubieta (2012) analyzed the current and potential land use by measuring soil parameters in the communities of El Sabino and the Peña Amarilla-La Tinaja fraction, respectively, within the Ciénega de Tamasopo.

Regarding flora and fauna diversity, notable studies include Escobedo-Galván *et al.* (2011), which monitored *Crocodylus moreletii*; Sahagún *et al.* (2013), which conducted an inventory of bird species to determine potential geographic distribution patterns; Carranza *et al.* (2016), which studied the orchids of the wetland, and Castillo Ipiña (2022), who developed a management plan proposal for the conservation of the *Crocodylus moreletii* in the Ciénega de Tamasopo as a strategy for ecosystem conservation, thereby determining the area's economic, social, and ecological potential.

Also noteworthy is the study conducted by Cruz (2023), who monitored environmental and biological parameters, including the physicochemical properties of water samples, and used freshwater snail shells as biomarkers to assess the ecological risk in the aquatic ecosystem of the wetland. The study identified herbicides, metalloids, and heavy metals, and monitoring was carried out seasonally and by site type (conserved, semi-impacted, and impacted).

I.4.4. Studies on Vegetation in Groundwater Flow Systems

Vegetation plays a key role in the interactions between groundwater and surface water systems, as it influences several components of the water balance, such as runoff, evapotranspiration, precipitation, and infiltration (Le Maitre *et al.*, 1999; Kurc & Small, 2007).

Various studies have focused on the interactions between vegetation and groundwater, as well as their application in groundwater flow system models. Kim and Jackson (2012) studied recharge areas to conduct a global analysis of recharge processes, and the vegetation types associated with them. They analyzed the effects of vegetation on water recharge and linked these effects to climatic and soil parameters.

Studies such as those by Finch (1998), Keese *et al.* (2005), and Döll and Fiedler (2005) have incorporated vegetation into groundwater recharge models at various scales. However, most of these studies have found, or assumed, that the relationship is secondary compared to the effects of abiotic factors such as climate and soil.

Peñuela and Carrillo (2012) demonstrated the importance of discharge areas in defining recharge areas and highlighted the utility of the groundwater flow systems theory for understanding groundwater dynamics. They noted a lack of studies in Mexico linking hydrogeochemical conditions with surface environmental parameters (vegetation, topography, soil), employing the flow systems theory established by Toth. They identified vegetation as a significant surface indicator of recharge and discharge areas due to the specific characteristics exhibited in each.

Orozco Uribe *et al.* (2023) analyzed hydrogeological processes in fractured media in Jalisco by studying vegetation distribution and the precipitation-runoff response. They determined that vegetation distribution followed patterns indicating the presence of local groundwater flows and proposed a conceptual model of water movement that included the recorded vegetation.

Gardea (2019) investigated vegetation as one of the environmental elements interacting with groundwater, based on the Groundwater Flow Systems Theory (GFS). For this purpose, she sampled vegetation cover using the step-point method to understand the functioning of the "Ojo de Agua" spring in the municipality of Moctezuma, S.L.P., Mexico.

Yulistyarini (2011) evaluated vegetation quality in groundwater recharge areas in Batu City, East Java, through vegetation structure, diversity, and litter in different land-use systems (forests, eucalyptus plantations, pine plantations, and bamboo forests). The vegetation structure was described by the vertical stratification of vegetation.

Antalia (2011) identified different groundwater flow systems and their components in Loreto, Baja California. He identified recharge and discharge zones, characterized the vegetation associated with discharge areas, and collected water samples. Antalia determined that vegetation associated with discharge zones is distinctive and varies depending on the type of flow. She distinguished vegetation associated with regional flows from that associated with local flows. Using the collected data, she developed a conceptual groundwater flow model integrating vegetation, soil type, and flow type information.

I.5. Theoretical framework

I.5.5. Importance of Wetlands

When discussing the value or values of wetlands, this refers to their significance for humanity from economic, cultural, historical, religious, educational, recreational, aesthetic, or even spiritual perspectives (Cervantes, 2007). From an ecological standpoint, these values are also known as ecosystem services. The services wetlands provide are classified into four main groups: support (primary productivity, ecosystem continuity through the trophic chain), provision (water and food), regulation (temperature control, flood cycles, rainfall cycles, etc.), and cultural (recreation, landscape, and education) (Lenis-Ibarguen & Bernal, 2019).

The degradation of wetlands, driven by the rapid widening of the gap between water demand and supply, diminishes access to potable water, human health, food production, economic development, and geopolitical stability (Ramsar Convention Secretariat, 2013).

According to Cruces de Abía (2000), some of the main causes of disappearance and degradation of wetlands are:

1. Alterations in the hydrological regime
    - Overexploitation of aquifers
    - River channelization
2. Alterations in water basins
    - Desiccation
    - Siltation
3. Water quality degradation
    - Discharge of liquid waste
    - Discharge of industrial waste

I.5.6. Groundwater Flow System Theory

The Groundwater Flow System (GFS) theory proposed by Toth (1963) develops a systemic analysis and evaluation of the interaction between groundwater and other environmental components, including vegetation, soil, geomorphological aspects, among others (Gardea, 2019). This theory provides a systemic perspective of the environment, integrating various natural elements and recognizing groundwater as a geological agent responsible for a wide variety of processes and surface manifestations through contrasting natural conditions between recharge and discharge zones (Hernández-Juárez *et al.*, 2020).

The GFS allows the hydrogeological environment to be represented through a conceptual model that integrates geological, geomorphological, hydrological, edaphic, and vegetation parameters influencing the groundwater flow regime.

The GFS describes three main flow systems, each with specific characteristics: local, intermediate, and regional. Each of these flows has its distinct recharge, transit, and discharge zones.

I.5.7. Groundwater Recharge and Discharge Sites

Recharge zones possess a set of characteristics that facilitate water infiltration until it reaches the water table. A primary indicator of these zones is the hydraulic conductivity of the rock, which allows rainwater to percolate. In studies conducted in these areas (mainly in arid and dry climates), the water table is deep, and the soil is generally acidic and underdeveloped, with low organic matter content and low concentrations of sodium and salts.

In contrast, discharge zones whose properties are more visible, are located at lower topographic elevations relative to where recharge occurs. In these zones, water moves preferentially upward from the subsurface, contributing, along with surface runoff, to the formation of water bodies (lakes, river base flow, coastal lagoons, etc.).

These zones may manifest as a spring, a lake, saline soil, and/or a shallow groundwater table (Peñuela and Carrillo, 2012).

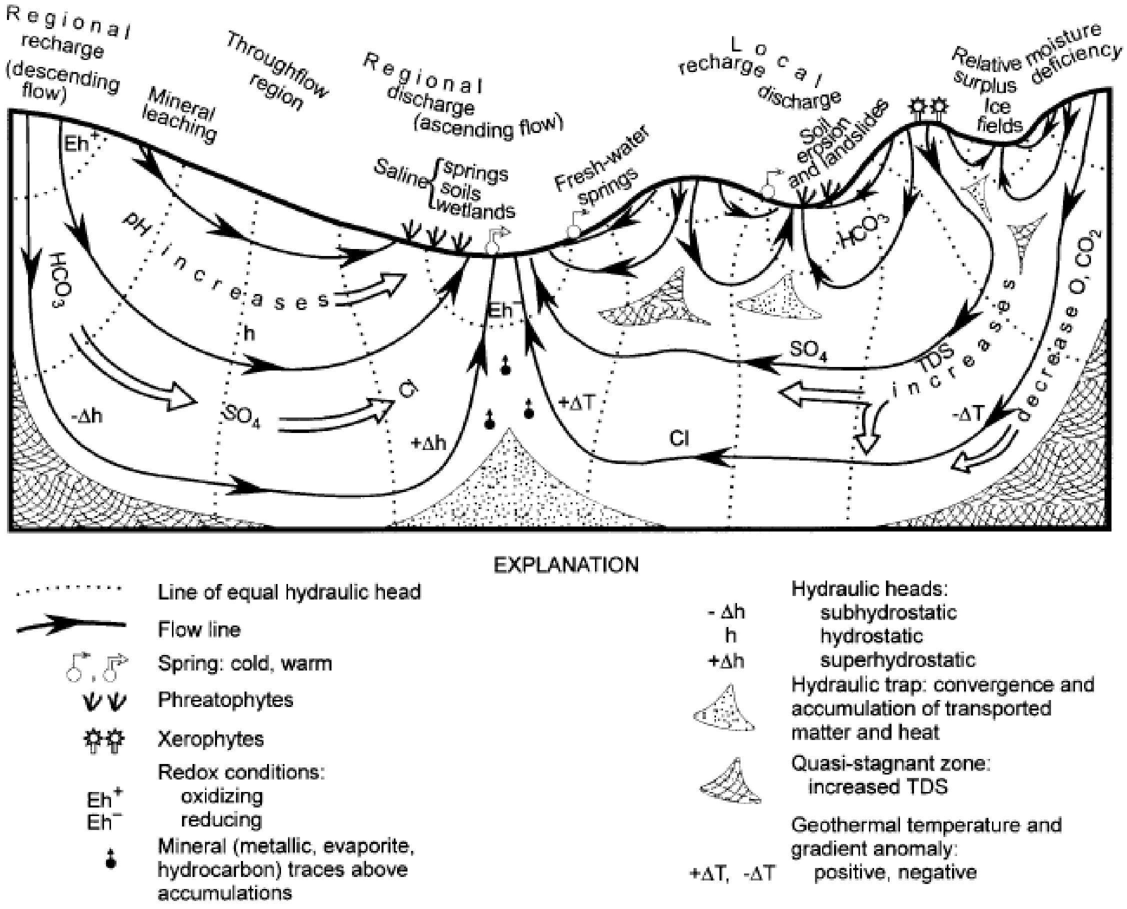


Figure I-1 . Illustrative diagram of the flow system theory proposed by Tóth, obtained from Tòth (1998)

I.5.8. Karst Formations and dolines

For billions of years, water has flowed across the surface of the emerged land, shaping and creating the relief as we know it today. Karst is the result of the action of infiltrating and runoff water on chemically soluble rocks, such as $CaCO_3$, through a slow dissolution process (Aquae Foundation, 2022). Karst is defined as "the set of original relief forms occurring in areas composed of easily soluble rocks: gypsum, limestone, dolomite, or salt" (De la Lanza-Espino, 1999).

Dolines are one of the landforms found in karst terrains. They form when water infiltrates at the intersection of two fissures, creating an area of maximum dissolution. This leads to a collapse area, resulting in a circular depression with variable diameter and depth (Tarburck, 2013).

Due to their nature, dolines are considered recharge zones, as their topographic and geological conditions make them highly efficient in capturing rainwater. Therefore, they have been identified as one of the main areas for analysis in this study.

I.5.9. Vegetation–Groundwater interaction

Vegetation plays a crucial role in the functioning and balance of the hydrological system, promoting the condensation and precipitation of moisture from the ocean, maintaining soil moisture and conditions, and forming macropores in the soil that enhance infiltration (Hernández-Juárez, 2020).

The interactions between vegetation and groundwater occur at two interconnected stages within the water cycle: a) as an influence on the processes through which precipitation infiltrates the subsurface and b) through the extraction of groundwater via deep roots or vegetation located in discharge zones. The composition and coverage of vegetation determine the proportion of rainfall that reaches the soil and can influence infiltration, percolation, and the storage capacity within soil horizons.

Vegetation effects can be both positive and negative. For instance, vegetation intercepts precipitation and transpires water absorbed through its roots, but it also facilitates infiltration, and root systems can increase percolation by creating macropores in the soil (Le Maitre *et al.*, 1999).

According to Le Maitre *et al.* (1999), some of the impacts of vegetation on groundwater are:

- Redirection of precipitation through vegetation cover. Water is evaporated or channeled into the soil via stemflow or drip flow, respectively.
- The litter on the soil surface tends to retain more water than bare soil and improves the infiltration rate.

- Roots can provide channels for preferential water flow through the unsaturated zones of the water table, particularly in low-permeability soils, thereby enhancing recharge.
- Water extraction from the soil in the unsaturated zone of the aquifer, through plant roots, reduces the amount of water that percolates into the saturated zone of the aquifer (recharge).
- Interception. This term refers to precipitation retained or absorbed by vegetation or litter, which is directly evaporated back into the atmosphere.

I.5.10. Studies on Vegetation Structure

Vegetation arises from the interaction of environmental factors affecting the set of species that coexist and interact within a continuous space. It reflects the climate, soil nature, water and nutrient availability, as well as anthropogenic and biotic factors (Matteucci & Colma, 1982).

The study of vegetation involves describing plant communities in a specific location by analyzing various attributes, such as biomass, frequency, cover, and density, among others. Vegetation sampling has been conducted for over a century, leading to the development of numerous methodologies for obtaining accurate measurements (West & Bonham, 1990).

Vegetation studies are a cornerstone for the planning, management, and conservation of ecosystems (Álvarez *et al.*, 2006). According to Matteucci and Colma (1982), such studies pursue one or more of the following fundamental objectives:

- Identifying spatial patterns, both horizontal and vertical, of individuals or species.
- Investigating population processes that influence spatial or temporal patterns.
- Detecting trends or variation classes in the similarity or dissimilarity relationships among communities or species groups.
- Establishing correlations or associations between the spatial patterns of communities or species groups and environmental variables, and formulating

hypotheses about the causal relationships between environmental factors and vegetation responses.

Vegetation structure, as defined by Dansereau (1958), refers to the spatial organization of individuals within a sample and, by extension, within a specific vegetation type.

I.6. Methodology

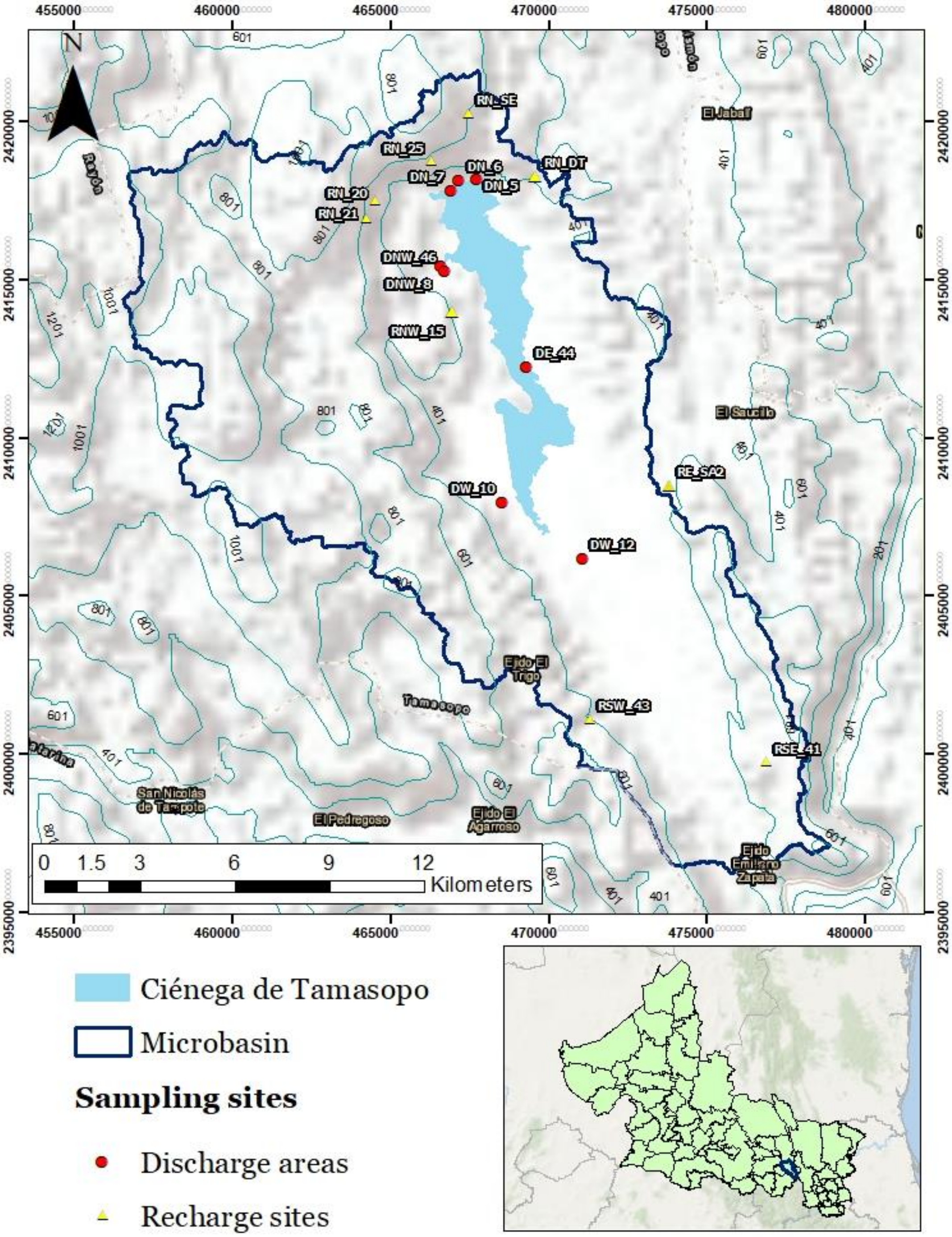
I.6.1. Description of the Study Area

I.6.1.1. Location and Delimitation of the Study Area

The Ramsar Site "Ciénega de Cabezas" is situated in the southeastern part of the Tamasopo municipality, within the coordinates 99°19’14” E, 99°16’57” W, 21°52’03” N, and 21°45’41” S. Its official boundary follows the natural limit of the waterbody of the wetland, located 40 km west of Ciudad Valles, in the state of San Luis Potosí, Mexico. This wetland spans an average area of 1,364.2 hectares, extending from Cabezas to La Copa, at the base of the Sierra Palmillas (Zapata, 2011).

Using a Geographic Information System (GIS), potential recharge and discharge zones were delineated. Recharge zones were defined as dolines located on the slopes surrounding the waterbody, while discharge zones corresponded to springs and riverbanks. Field evaluations were conducted to verify these areas, resulting in the identification of 9 recharge points (labeled with the prefix "R") and 8 discharge points (labeled with the prefix "D").

A polygon was delineated based on the micro-basin, using the hydrographic network and the digital elevation model from INEGI. This polygon encompasses the entire Ramsar Site, as well as the surrounding landforms that give rise to the ecosystem. It also covers the recharge and discharge points of the wetland, corresponding to the highest and lowest altitudes in the area.



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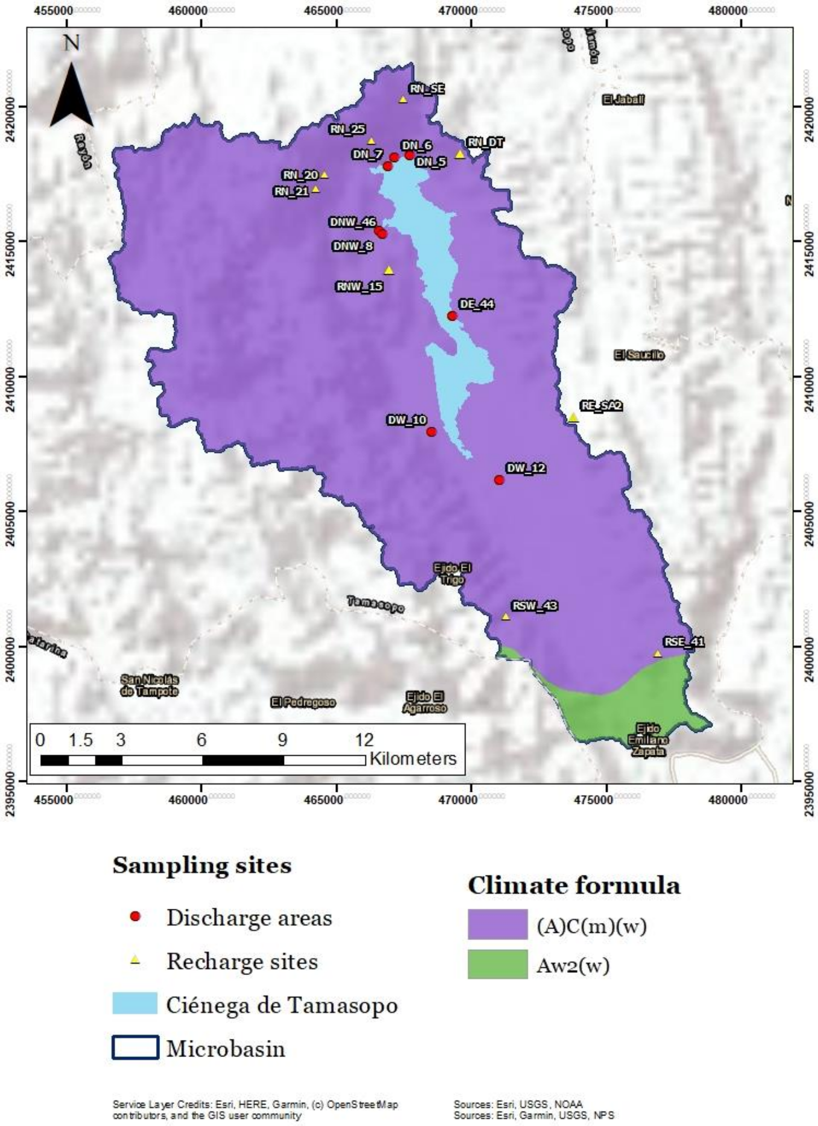
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure I-2 Study site location and sampling points

I.6.1.2. Climate

The climate formulas for the area are (A)C(m)(w), defined as a semi-warm humid climate, and Aw2(w), described as a warm subhumid climate (Fig. I-3). The average total annual precipitation reaches 1334 mm, and the average annual temperature is 24.6°C (Meteorological Station "20 de Noviembre" in the municipality of Tamasopo).

The dry and cool functional season occurs from December to April, while the warm and humid season extends from May to November (Fig. I-4).



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Sources: Esri, USGS, NOAA
Sources: Esri, Garmin, USGS, NPS

Figure I-3 Climate of the study site.

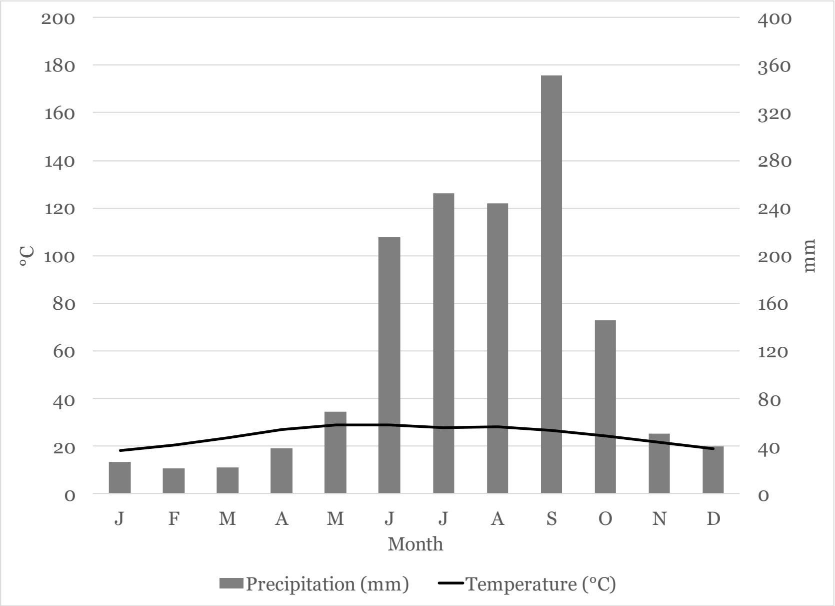


Figure I-4 Climograph of the functional seasons at the study site. Prepared with INEGI data from 1973–2020.

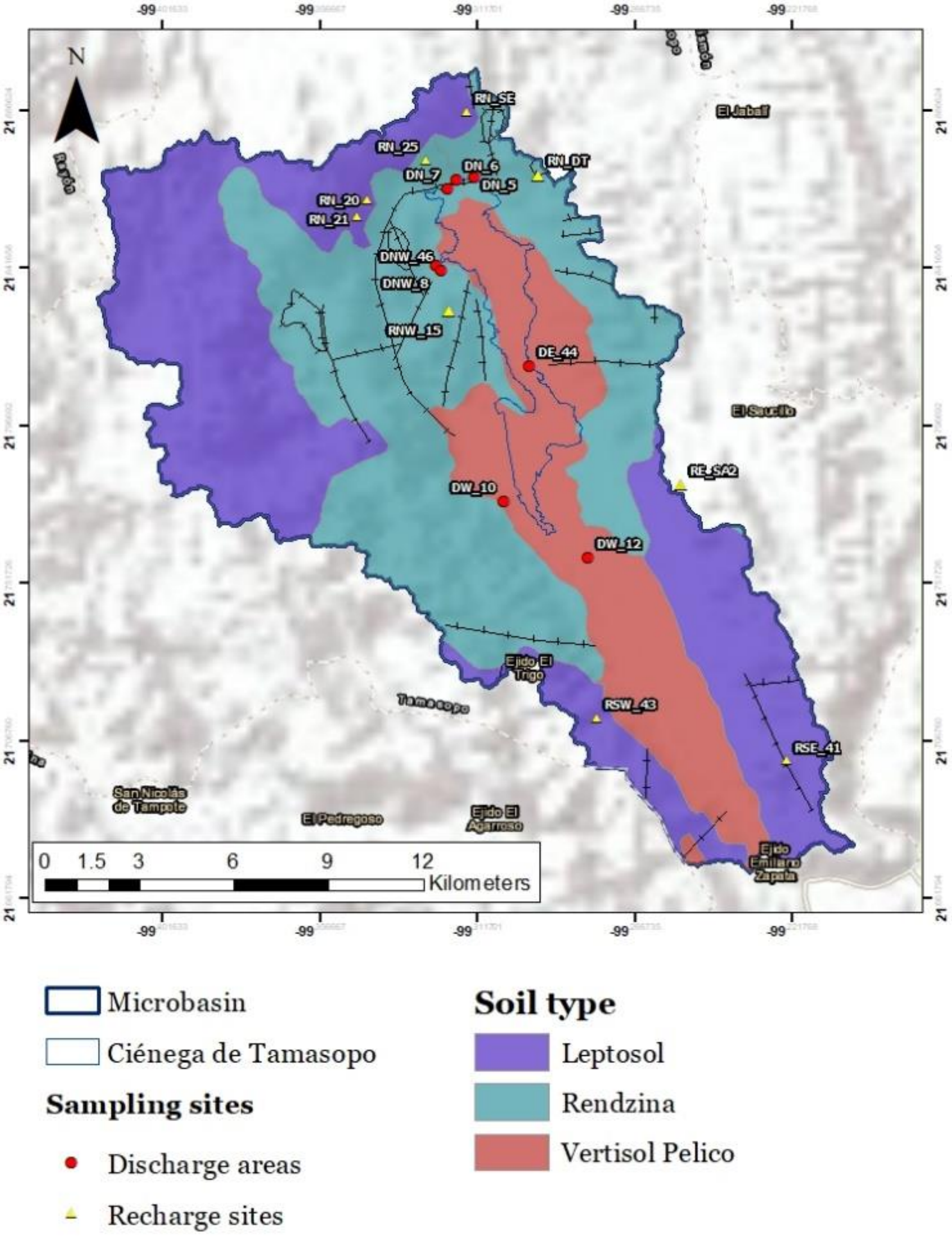
I.6.1.3. Soils

According to INEGI (2009), three dominant soil types were identified in the study area: Lithosol, Rendzina, and Vertisol (Fig. I-5).

Vertisol. Soils with 30% or more clay content in all horizons up to a depth of 50 cm. These soils are highly productive due to their natural fertility and high moisture retention (Sotelo, 2008). As nutrient deposition zones within the basin, they are the most productive soils in the area. Additionally, with a constant water supply, the O and A horizons—formed by organic matter in varying degrees of decomposition—are expected to be deep and fertile.

Rendzina. These are dark, shallow soils (10 cm to 50 cm) that lie directly over carbonate material, such as limestone. The vegetation they support varies from oak forests and oak woodlands to low and medium tropical forests (González Medrano, 2004).

Leptosol. (From the Greek lithos: stone and solum: soil, meaning "stone soil"). These are very thin soils, with thicknesses of less than 10 cm. They rest on the bedrock. Depending on the climate, they support low tropical forests or tall shrublands (González Medrano, 2004).



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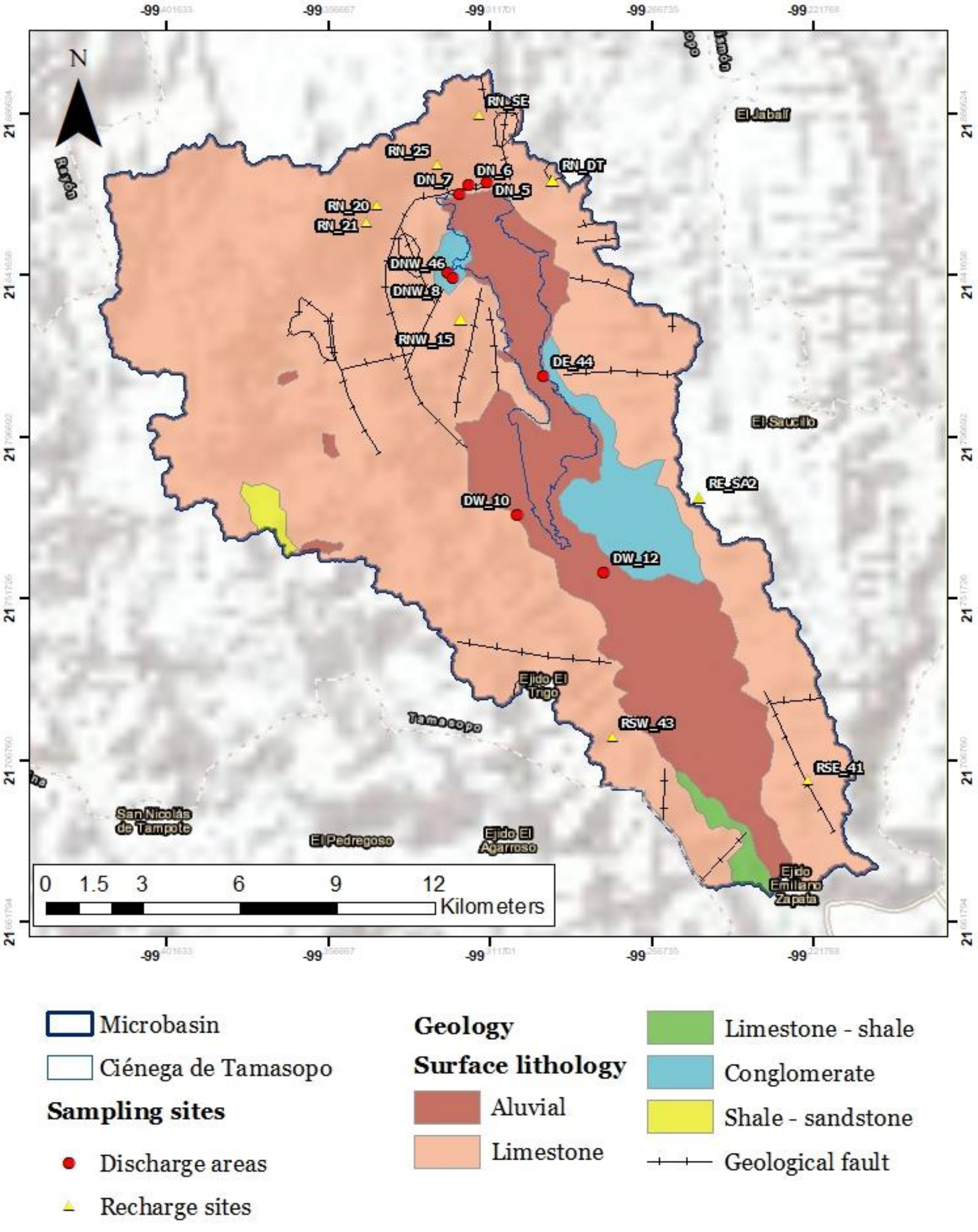
Sources: Esri, USGS, NOAA
Sources: Esri, Garmin, USGS, NPS

Figure I-5 Soil of the study area, created with INEGI data

I.6.1.4. Physiographic, Geomorphological, and Geological Characteristics

The study site is located within the Sierra Madre Oriental physiographic province, specifically in the Huasteca Karst subprovince, and in the paleogeographic unit known as the Valles-San Luis Potosí Platform. Its stratigraphic column is primarily characterized by the presence of sandy-clayey, evaporite, calcareous, and terrigenous sequences. The area features karstic sinkholes with a northwest-southeast orientation and geological features of marine sedimentary origin. The elevation ranges from 200 to 1000 meters above sea level.

The predominant rocks are sedimentary limestone (Fig. I-6), well-stratified and dating back to the Lower Cretaceous, corresponding to the Del Abra formation (reef formation). These rocks are also associated with portions of shale. In the lower-elevation areas of the site, alluvial sediments and sedimentary conglomerate rocks are present, primarily composed of gravel subjected to deposition and lithification processes, cemented with calcite, silica, or iron oxides (Pérez Castillo, 2017).



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Sources: Esri, USGS, NOAA
Sources: Esri, Garmin, USGS, NPS

Figure I-6 Geology of the study site

I.6.1.5. Vegetation and land use

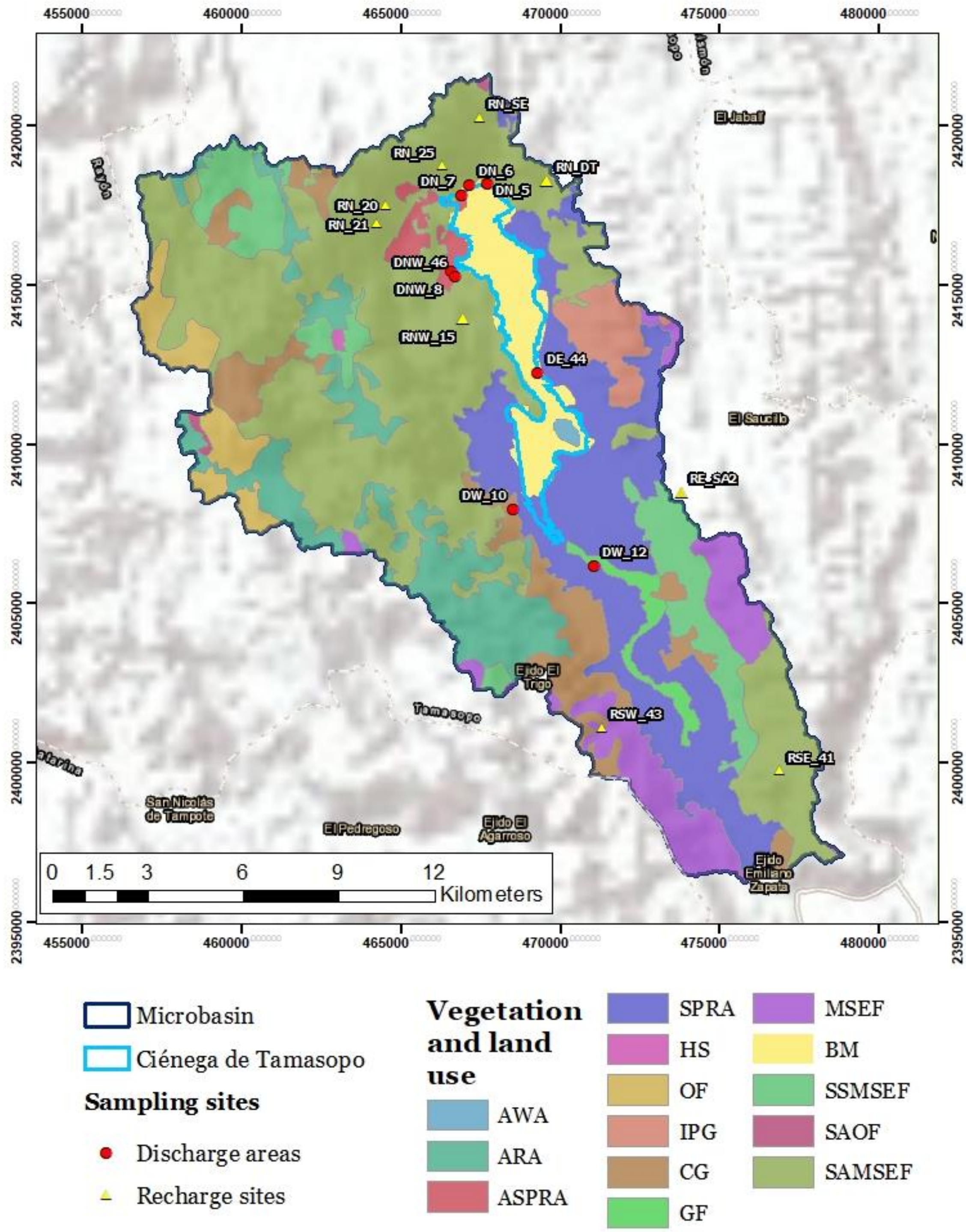
In the study area INEGI (2013) identifies 14 types of vegetation and land use:

Table I-1 Type of vegetation and land use in the study site

Type of vegetation and land use	Description
Annual* wetland agriculture (AWA)	Crops take advantage of residual soil moisture in flood-prone areas at the end of the rainy season or before it. The crop duration is less than one year.
Annual* rainfed agriculture (ARA)	Crops rely solely on rainfall. The crop duration is less than one year.
Annual and semi-permanent* rainfed agriculture (ASPRA)	Crops rely solely on rainfall. The crop cycle lasts less than one year. Crops are replanted each year and remain on the land for 2 to 10 years.
Semi-permanent* rainfed agriculture (SPRA)	Crops rely solely on rainfall. Crops remain on the land for 2 to 10 years.
Human settlements (HS)	Places where individuals or human communities establish themselves.
Oak forest (OF)	Forests formed by species of the genus *Quercus* (oaks), widely distributed.
Induced palm grove (IPG)	Vegetation dominated by palms (*Sabal*, *Brahea*, *Attalea*, etc.), generally found in tropical areas.
Cultivated grassland (CG)	Vegetation communities characterized by the dominance of grasses. Produced through agricultural practices, primarily in tropical areas.

Gallery forest (GF)	Tree vegetation in warm climates along areas with relatively higher humidity, such as riverbanks and stream edges.
Medium sub-evergreen forest (MSEF)	Tree vegetation community 20 to 30 meters tall. Between 25% and 50% of the trees lose their foliage during the dry season.
Bulrush marsh (BM)	Herbaceous vegetation found in shallow parts of water bodies in both tropical and temperate zones. Primarily composed of species of the genus *Typha* (bulrushes).
Secondary shrubby vegetation of medium sub-evergreen forest (SSMSEF)	Secondary successional phase of vegetation dominated by shrubs. It may or may not transition to a tree phase. Over time, it may resemble the original vegetation.
Secondary arboreal vegetation of oak forest (SAOF)	Secondary successional phase of vegetation dominated by trees. This is a relatively mature phase that may or may not eventually lead to a vegetation formation similar to the original one, dominated by species of the genus *Quercus* (oaks).
Secondary arboreal vegetation of medium sub-evergreen forest (SAMSEF)	Secondary successional phase of vegetation dominated by trees. This is relatively mature. Over time, it may resemble the original vegetation.

Note: The terms "annual" and "perennial" are used to refer to plant species based on their life cycle. "Annual" applies to species with a life cycle of less than a year, while "perennial" refers to species that live for more than two years and do not need to be replanted annually. The term "semi-permanent" is used to describe crops that are cultivated on the same land for a period of 2 to 10 years, being replanted each year.



Service Layer Credits: Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Sources: Esri, USGS, NOAA
Sources: Esri, Garmin, USGS, NPS

Figure I-7 Vegetation and land use of the study area. Created with data from INEGI (2013)

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II. Chapter II. Diversity and terrestrial floristic composition in water recharge and discharge areas in the Tamasopo Ciénega, San Luis Potosí, Mexico

Abstract

The Ciénega de Tamasopo wetland is a Ramsar site declared in 2008 for its ecological importance. Although it has been acknowledged as a wetland of international importance there is almost no information about the flora in the area. The vascular flora of the microbasin of Ciénega de Tamasopo was studied in the present investigation from 2022 to 2024 as a part of a vegetation structure analysis at the microbasin. Within the study area of 266.6 km^2, 65 families, 156 genera and 276 species were documented. The collection took place in groundwater recharge and discharge areas along the entire micro-basin and covered the oak forest, medium semi evergreen tropical forest, low deciduous tropical forest, gallery forest and palm groove. The families with the most species were Fabaceae, Euphorbiaceae, Malvaceae, Rubiaceae, Acanthaceae, Asteraceae, Moraceae and Solanaceae. Six introduced species were found mostly in discharge areas, around 2 % of the total registered. Within both recharge and discharge areas, 18 endemic species of México and 1 endemic of San Luis Potosí were found. Additionally, nine species in a category of risk according to the IUCN Red list were documented, of which only four were listed in the NOM-059-SEMARNAT-2010. There was a differentiation between the diversity of species of recharge and discharge areas, with recharge areas being more diverse than discharge areas. Furthermore, families like Asteraceae, Solanaceae and Rutaceae, the ones with the largest number of species in discharge areas, seem to indicate some level of disturbance, which can be attributed to the accessibility of these zones and its closeness to crops and pasture sites.

Key words: Flora, diversity, groundwater recharge and discharge, Ciénega de Tamasopo.

II.1. Introduction

Mexico is considered an exceptional area for floristic diversity and endemism. With a total terrestrial surface of almost two million kilometers squared, the country encompasses a broad elevational gradient, from very high mountains (the tallest being Citlaltépetl volcano, also known as Pico de Orizaba, with 5,610 m at the summit) to extensive coastal plains bordering both the Atlantic and Pacific Oceans. The climatic, geologic, and topographic complexity of the country provides a scenario conducive to the existence of an astonishing vegetational mosaic almost unrivaled (Villaseñor, 2022).

The Mexican flora is one of the richest of the world with 23,314 native species and 11,600 endemic species of which at least 3,225 are located in the seasonally dry tropical forest habitat (Rzedowski & Calderón, 2013; Villaseñor, 2016).

Within the country, San Luis Potosí state is one of the principal zones of diversification of vegetal species. The geographical ubication of the state, where both Neotropical and Nearctic regions converge, in addition with its orography, locate San Luis Potosí in a privilege spot that reflects in multiple and rich vegetal communities that go from desert scrublands of the Altiplano to seasonal tropical forest in the Huasteca (De Nova, 2018).

The total richness of the vascular plants estimated in the state is around 4,485 to 5,413 species, representing approximately 21 % of the national overall (Villaseñor, 2016; De Nova, 2018). This diversity locates San Luis Potosí in the seventh place, just after Oaxaca, Chiapas, Veracruz, Jalisco, Guerrero and Michoacan, despite being the 15th in territorial extension (De Nova, 2018).

In San Luis Potosí state, there are 12 floristic studies (Calderón, 1960; Reyes-Agüero *et al.*, 1996; García Sánchez *et al.,* 1999; Romero y García-Moya, 2002; González *et al.,* 2007; Fortanelli *et al.,* 2014; Castillo, 2015; Torres-Colín *et al.,* 2017; López-Palacios *et al.,* 2018; De Nova *et al.*, 2019: Morales *et al.*, 2020; De Nova *et al.*, 2023), but none made in Ciénega (wetland) de Tamasopo. The Ciénega de Tamasopo is one of the last wetlands located in the neotropical region of San Luis Potosí, in the municipality of Tamasopo. It was declared a Ramsar site in 2008 for being considered a wetland of international importance (Torres, 2008). This wetland is feed by a groundwater flow system favored by the karstic formations that exist along the basin (Zapata, 2011; Krienen, 2017; Pérez, 2017; Rocha, 2019; Centeno, 2023).

The importance of wetlands as a habitat for unique and priority flora and fauna has been widely demonstrated (Cruces de Abia, 2000; Babinger, 2002; RAMSAR, 2013; López-Gómez, 2024). Wetland plant species exhibit a wide range of morphological, physiological, and reproductive adaptations, enabling them to tolerate excess moisture and liquid saturation or resist drought. This allows them to survive in dry conditions, as well as in semi-saturated or fully flooded soils (Tiner 2012, Heynes-Silerio *et al.* 2017).

In addition, Peñuela and Carrillo (2012) have emphasized the importance of vegetation in groundwater flow systems, which is characteristic of these areas. However, studies in groundwater flow systems in Mexico have focused on dry regions. In the Ciénega de Tamasopo, INEGI (1997) reported different types of terrestrial vegetation: gallery forest, induced grassland, induced palm groves, medium sub-evergreen forest, oak forest, reed beds, secondary shrub vegetation of medium sub-evergreen forest, secondary tree vegetation of oak forest, and secondary tree vegetation of medium sub-evergreen forest. The sampling sites in recharge zones are located in the highest altitudes in the area, corresponding to oak forests and medium sub-evergreen forest vegetation, as well as secondary vegetation associated with these, in addition to induced palm groves; in discharge zones (located on the lower part of the basin, near the shore of the aquatic are), the reported vegetation corresponded to grasslands, reed beds, and gallery forests. The intermediate areas are altitudinally between discharge and recharge areas. To learn more about the characteristic species of the recharge and discharge zones of the subhumid karstic landscape present in the Ciénega de Tamasopo basin, it was necessary to conduct an inventory of the species present in each site.

Lawrence (1951) defined flora or floristic studio as “an inventory of the plants of a definite area”. Such inventory derives from the study and examination of a set of herbarium specimens collected in localities or stations within the area under study or by direct recollection an examination of a study area (Villaseñor, 2022).

The knowledge of flora and its inventory in the states of the Mexican republic is still incomplete (Villaseñor, 2003; Villaseñor, 2016), and San Luis Potosí is no exception. However, there is currently an important collection of specimens in local, national, and international herbaria, which have helped to increase the floristic knowledge of the country (Díaz-Luna & Villarreal, 1975; Llorente & Ocegueda, 2008; Martínez-Castillo & Yáñez-Espinosa, 2011; González-Elizondo *et al.*, 2017).

There are no floristic studies for the microbasin in which the Ciénega de Tamasopo is located, although several studies made in different locations around the study site have floristic lists; nonetheless the total richness of the vegetation in this region is far unknown.

The significance of understanding the flora of the Ciénega de Tamasopo microbasin lies in the critical role vegetation plays within the groundwater flow system that partially sustains the wetland. This vegetation is currently under anthropogenic pressure driven by sugarcane cultivation and livestock farming, which are the primary economic activities in the area. Additionally, during the sugarcane harvest process ("zafra"), the fields are burned to facilitate manual and mechanical harvesting (Mugica-Alvarez *et al.*, 2018; Perez *et al.*, 2023). This practice poses a significant risk to the wetland ecosystems, as inadequate controls can result in substantial loss of existing vegetation.

On March 8, 2024, a forest fire allegedly caused by poor control measures during sugarcane burning destroyed much of the flora and fauna of the wetland. However, no exact information on the extent of the damage is currently available (El Universal S.L.P., 2024; Martínez, 2024; Zacarías, 2024).

The anthropogenic pressures on this ecosystem, its designation as a wetland of international importance, and its socioeconomic value to nearby communities make this site a priority for conservation. Due to these factors, this study aims to define the flora of the Ciénega de Tamasopo and the structure of its vegetation, with flora being the focus of this chapter.

The main objective of this chapter is to document the flora present primarily in the recharge and discharge zones of the Ciénega de Tamasopo microbasin to identify key species associated with groundwater flow systems in a karst landscape. Additionally, information was gathered on other species found throughout the microbasin to enhance the understanding of the area's overall flora.

II.2. Materials and methods

II.2.1. Study area

The Ciénega de Tamasopo is located in the municipality of Tamasopo, San Luis Potosí, México. The climate classification in the area shows two types: semi-warm subhumid (A)C(m)(w) and warm subhumid $Aw_2(w)$ (INEGI, 2008). The soil variety goes from lithosol in the higher elevations to rendzina and vertisol in the lower part of the microbasin (INEGI, 2009). The study site is in the physiographic province of the Sierra Madre Oriental, in the Huasteco Karst subprovince, and within the paleogeographic unit of the Valles-San Luis Potosí Platform. The elevation ranges from 200 to 1000 m above sea level. The rocks present are mostly sedimentary, predominantly limestone (Pérez, 2017). Within the designated polygon for the Ramsar site, there are two land ownership regimes: communal (ejido, 93% of the microbasin surface) and private (6.7% of the microbasin surface). The ejidos intersecting the site include Cabezas, Capuchinas, La Esperanza, Veinte de Noviembre, El Trigo, Emiliano Zapata, San José El Viejo, and El Saucillo. Additionally, within and/or adjacent to the Ciénega de Tamasopo, there are 13 private properties totaling 1,782.23 hectares.

II.2.2. Methods

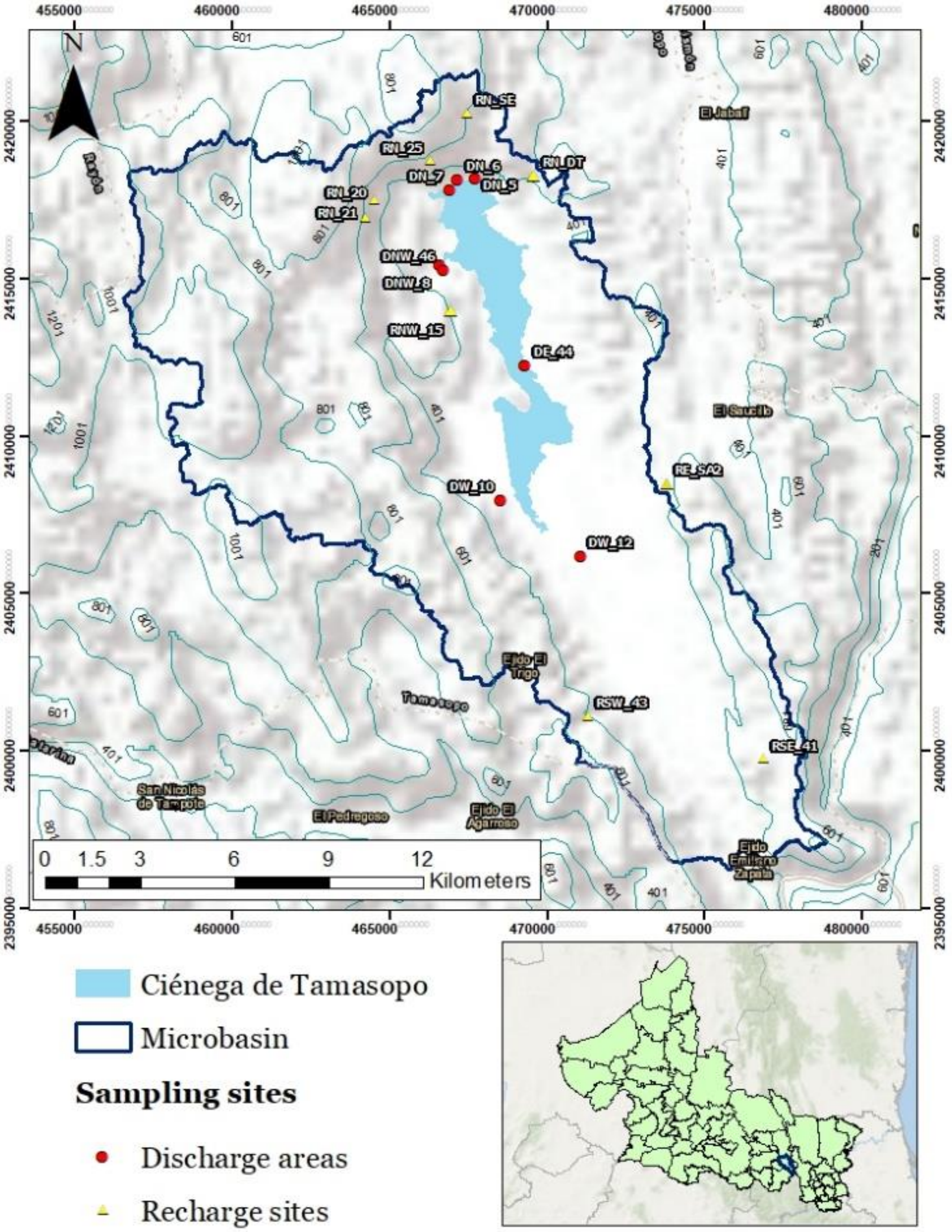
The bibliographic material (Pennington & Sarukhán, 2005; Rzedowski, 2015; Puig, 1991; Tapia *et al.*, 2010; Carranza *et al.*, 2016; Galindo, 2012; Torres, 2008; Zubieta, 2012) and herbarium records related to collections registered for the Ciénega de Tamasopo and the types of vegetation present in the area were reviewed. The databases of the Isidro Palacios Herbarium, SLPM, from Autonomous University of

San Luis Potosí (https://slpm.uaslp.mx/) and Tropicos (tropicos.org) were consulted to create a preliminary list of species in the area.

Field surveys were conducted between 2022 and 2024 in a total of 42 days, with a local guide knowledgeable about the flora of the site. The botanical collections were made in discharge and recharge zones (Figure II.1), and it also included the vegetation in the intermediate zones (intermediates altitudinally between discharge and recharge areas) and roadsides. The collection was made following the methods suggested by Lot and Chiang (1986), and the samples were subsequently processed at the facilities of the Isidro Palacios Herbarium (SLPM).

To quantify the abundance of each species specifically in recharge and discharge sites, various methods were employed. For the nine recharge sites, sampling was carried out using the following approach: two rectangular plots of 200 m^2 were established for the arboreal stratum, three rectangular plots of 10 m^2 for the shrub stratum, and three plots of 1 m^2 for the herbaceous stratum. Data collected for each individual included height, basal diameter, diameter at breast height (DBH), and coverage.

In discharge areas, due to less dense vegetation in the tree stratum, the nearest neighbor method was used, based on Matteucci and Colma (1982), while the shrub and herbaceous strata continued to be sampled using plot methods.



Service Layer Credits: Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure II-1 Botanical collection sites in the microbasin of the Ciénega de Tamasopo.

For species identification, the dichotomous keys from various fascicles of the Flora del Bajío were used, as well as the databases of the Isidro Palacios Herbarium (SLPM), Tropicos (tropicos.org), the Mexican Herbarium Network (herbanwmex.net), and the UNAM biological collection (datosabiertos.unam.mx/biodiversidad). Additionally, literature on tree species in similar vegetation types was consulted, including the preliminary catalog of wild tree species of the Sierra Madre Oriental (Rzedowski, 2015), Tropical Trees of Mexico (Pennington & Sarukhán, 1998), and Trees of Mexico (Lesur, 2017), among others.

The species were corroborated by a taxonomist at Isidro Palacio Herbarium (SLPM), and the WFO plant list was consulted to obtain the correct and updated names of the species (wfoplantlist.org).

A presence-absence matrix and an abundance matrix were elaborated containing the species and the sites they were collected; the data was used to calculate the α and β diversity. For the α diversity, the Shannon and Wiener index was calculated; this index takes into account the degree of evenness in species abundances.

$$H' = -\sum p_i \ln p_i$$

H' = Shannon index
p_i = proportion of individuals found in the *i*th species

As a complement, the Margalef richness index and the SHE diversity index were used to allow further interpretation of the obtained data. The essence of SHE analysis is the relationship between S (species richness), H (diversity as measured by the Shannon index), and E (evenness) (Magurran, 2004; Moreno, 2001; Neeson *et al.*, 2013).

For the β diversity, the presence-absence matrix was used to calculate the Whittaker diversity index and the Jaccard similarity index, these indexes are conceived as a measure of the change in diversity between samples along transects or across environmental gradients or communities (Magurran, 2004; Whittaker, 1960). The indexes were calculated using the software PAST4.

The risk status of each species was evaluated according to NOM-059-SEMARNAT-2010 (SEMARNAT, 2010) and the IUCN Red list of threatened species. Endemism and native species were verified based on the work of De Nova *et al.* (2018) and Villaseñor (2016), and invasive species were identified according to Villaseñor and Espinosa (2004).

To evaluate the sampling efficiency, species accumulation curves were generated using different estimators. To assess the completeness of the botanical collection, a presence-absence matrix was prepared and entered into the software EstimateS 9.1.0. The richness estimators Jack1, Jack2, and Bootstrap were plotted as non-parametric methods for presence-absence data (Smith & Van Belle, 1984; Lopez & Williams, 2006).

Additionally, the data were separated by recharge and discharge zones to evaluate sampling efficiency in these sites. For this, the estimators Chao1 and Chao2 were used, as they are recommended for abundance data, while the Jack1 and Bootstrap estimators were used for comparison with the total collection estimates.

II.3. Results

Within the study area of 266.6 km^2, 65 families, 156 genera and 276 species of vascular plants were documented mostly Angiosperms (97.8%). (Table II.1).

Table II-1 Number of families, genera and species according to their phylum.

Phylum	Families	Genera	Species
Angiosperms	60	150	270
Cycadophyta	1	2	2
Pinophyta	1	1	1
Polypodiophyta	3	3	3
Total	**65**	**156**	**276**

Of the families documented, the best represented per number of species were Fabaceae (24), Euphorbiaceae (14), Malvaceae (11), Rubiaceae (10) and Acanthaceae (9); the remaining families are listed in Table II.2. The first 24 families (marked with an asterisk) represent 55% of the total flora registered in Ciénega de Tamasopo, while the other families have one or two species each, making up the remaining 45%.

Additionally, Table II.2 shows families with the highest number of recorded genera. Of these, the greatest richness was concentrated in the first 13 families, representing 50.3% of the total recorded genera. Of the 156 genera registered the ones with the largest number of species were *Acalypha* (4), *Croton* (4), *Ficus* (4), *Ruellia* (4), *Centrosema* (3), *Euphorbia* (3), *Iresine* (3), *Psychotria* (3), *Quercus* (3), and *Solanum* (3).

Table II-2 Number of genera and species per family and number of species per genera (In descending order, first 40 records).

Families	Number of species	Number of genera	Genera	Number of species
Fabaceae*	24	18	*Acalypha*	4
Malvaceae*	11	9	*Croton*	4
Asteraceae*	8	8	*Ficus*	4
Rubiaceae*	10	7	*Ruellia*	4
Euphorbiaceae*	14	6	*Centrosema*	3
Acanthaceae*	9	5	*Euphorbia*	3
Apocynaceae*	5	5	*Iresine*	3
Sapindaceae*	5	5	*Psychotria*	3
Moraceae*	7	4	*Quercus*	3
Lamiaceae*	4	4	*Solanum*	3
Solanaceae*	6	3	*Bauhinia*	2
Arecaceae*	4	3	*Casearia*	2
Rutaceae*	4	3	*Chamaedorea*	2
Salicaceae*	4	3	*Citrus*	2
Verbenaceae*	4	3	*Justicia*	2
Anacardiaceae*	3	3	*Lippia*	2
Bignoniaceae*	3	3	*Lysiloma*	2
Orchidaceae*	3	3	*Mimosa*	2
Poaceae*	3	3	*Persea*	2
Amaranthaceae*	4	2	*Physalis*	2
Lauraceae*	4	2	*Pithecellobium*	2
Meliaceae*	3	2	*Psidium*	2
Myrtaceae*	3	2	*Randia*	2
Araliaceae*	2	2	*Sida*	2
Asparagaceae	2	2	*Trichilia*	2
Cannabaceae	2	2	*Achatocarpus*	1
Celastraceae	2	2	*Acrocomia*	1
Convolvulaceae	2	2	*Adelia*	1
Primulaceae	2	2	*Adiantum*	1
Rhamnaceae	2	2	*Ampelocissus*	1
Vitaceae	2	2	*Annona*	1
Zamiaceae	2	2	*Anoda*	1
Fagaceae	3	1	*Aphananthe*	1
Commelinaceae	2	1	*Ardisia*	1
Achatocarpaceae	1	1	*Asclepias*	1
Annonaceae	1	1	*Bacopa*	1
Araceae	1	1	*Beaucarnea*	1
Boraginaceae	1	1	*Beloglottis*	1
Bromeliaceae	1	1	*Bidens*	1
Burseraceae	1	1	*Brosimum*	1

II.3.3. Plant life forms

To characterize the structure of the vegetation associated with the recharge and discharge zones of la Ciénega de Tamasopo, and compare it with other conserved ecosystems, information was gathered on the life forms associated with the collected species.

Most of the species showed a tree life form (66 species, 34%), followed by herbs (61 species, 32%) both annual and perennial, shrubs (50 species, 26%) and lastly vines (16 species, 8%). The representative families of trees in the Ciénega de Tamasopo were Fabaceae, Moraceae, Malvaceae, Euphorbiaceae, Rutaceae, Lauraceae, Salicaceae, Fagaceae, Cannabaceae, Asparagaceae, Anacardiaceae and Bignoniaceae.

From the shrub life form the families Rubiaceae, Fabaceae, Euphorbiaceae, Solanaceae, Arecaceae, Primulaceae, Apocynaceae, Verbenaceae, Malvaceae, Celastraceae, Sapindaceae, Myrtaceae and Meliaceae stood out.

The representative families for the herb life form were Euphorbiaceae, Asteraceae, Acanthaceae, Malvaceae, Orchidaceae, Lamiaceae, Poaceae, Commelinaceae, Fabaceae, Amaranthaceae and Solanaceae; at last, the representative families for the vines were Vitaceae and Fabaceae.

II.3.4. Species accumulation curves

The species accumulation curves for the total botanical collections (Figure II.2) showed a sampling efficiency of 49% to 81% with the different estimators. According to the literature, for this type of data, the most accurate value under real conditions is the jackknife estimator, with an efficiency of 49%. For discharge sites (Figure II.3), sampling efficiency ranged from 55% to 85%, with the Chao2 estimator representing the real values most accurately. For recharge sites (Figure II.4), efficiency values ranged from 43% to 82% depending on the estimator used.

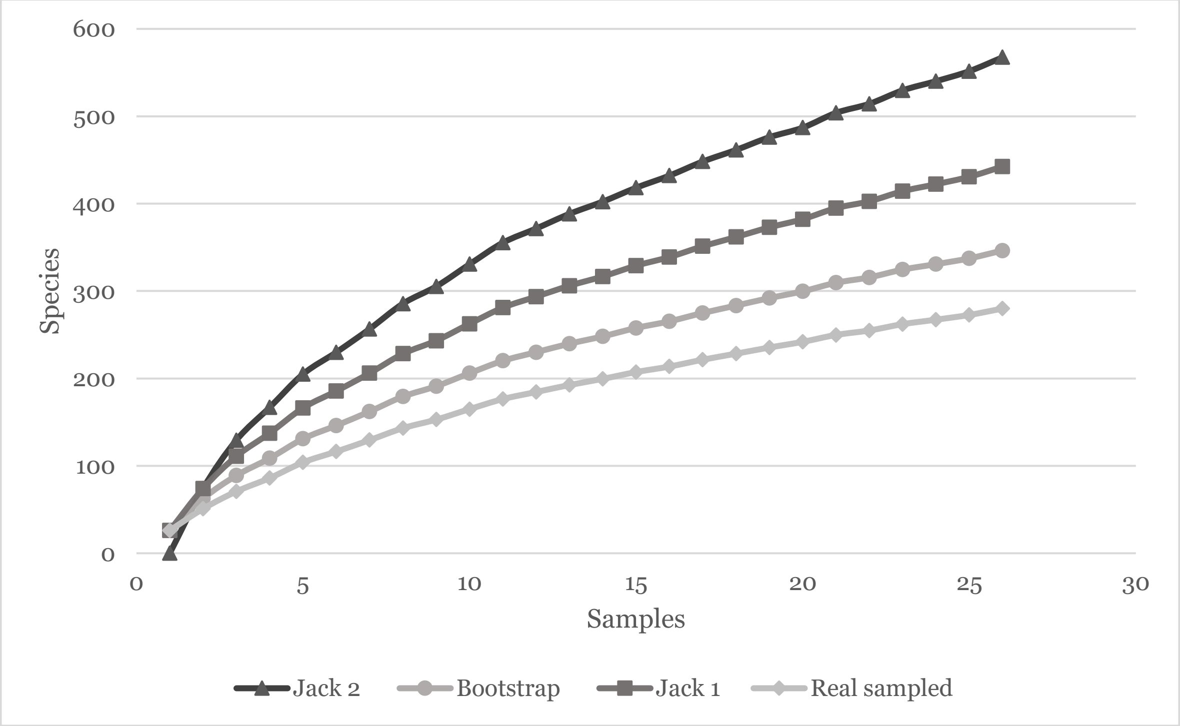


Figure II-2 Total species accumulation curves

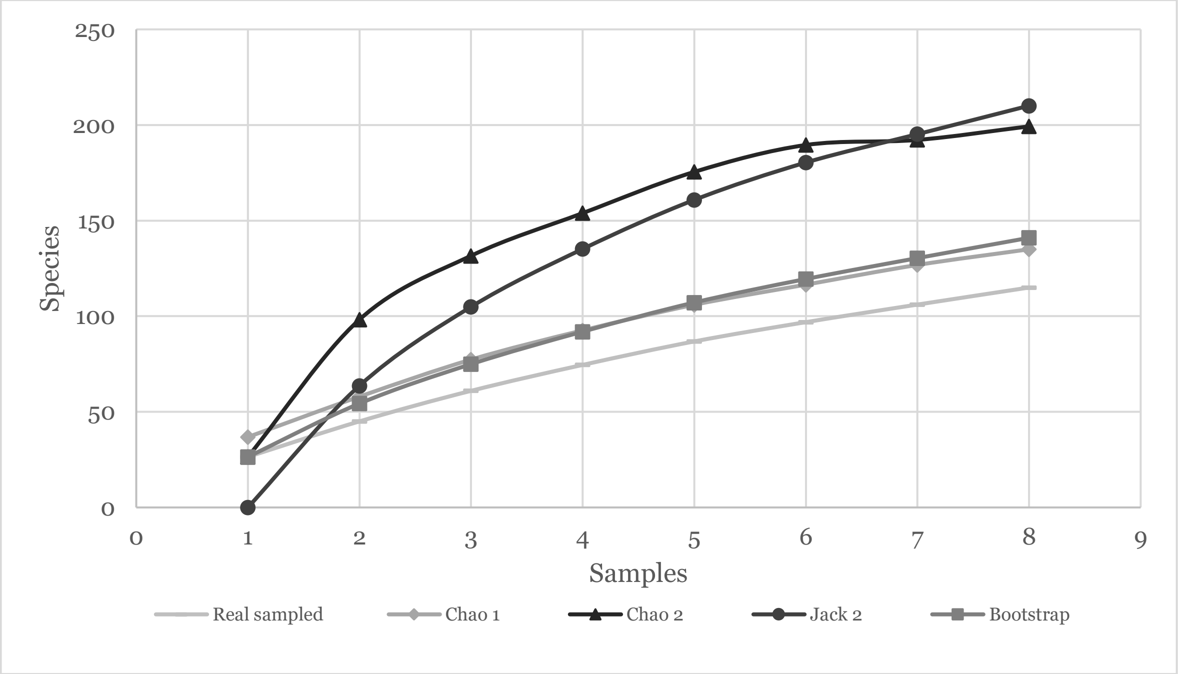


Figure II-3 Discharge sites accumulation curves.

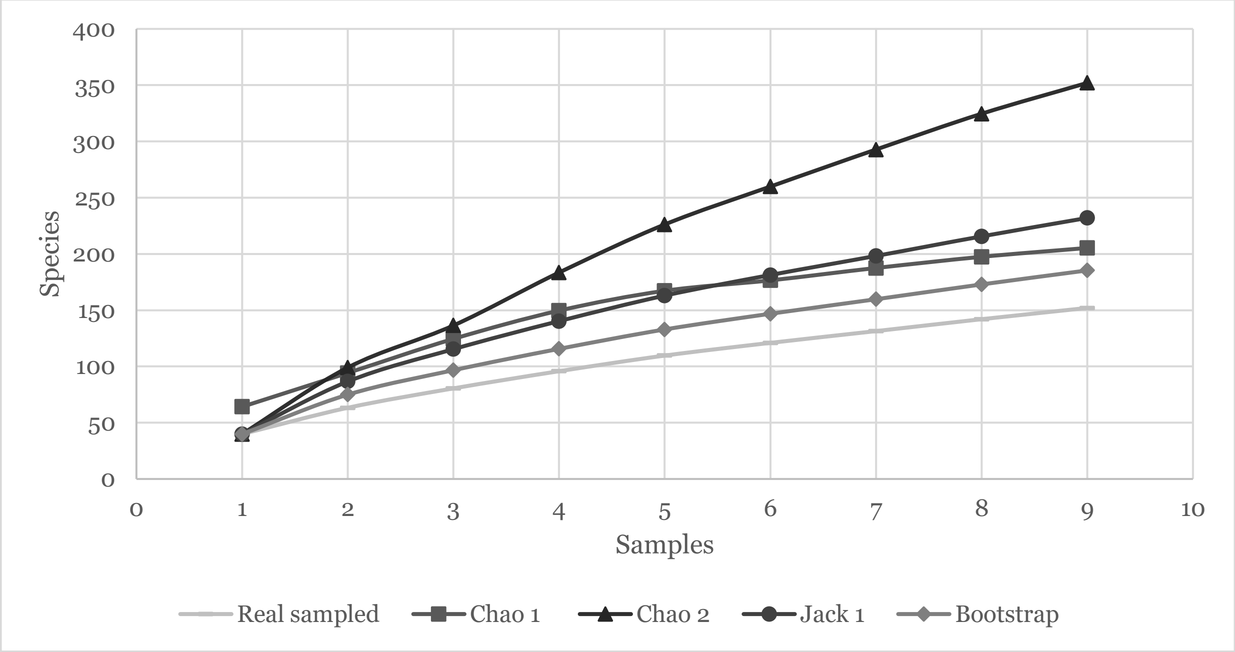


Figure II-4 Recharge sites accumulation curves.

II.3.5. Floristic composition and diversity in recharge and discharge areas

Floristic composition

Although collection took place in both discharge and recharge areas along the Ciénega de Tamasopo microbasin, other species from all types of land uses and vegetation were also collected (Table II.3).

In recharge areas, 130 species (47.1%) from 37 botanic families were registered; the species were associated with the following types of vegetation: tropical sub evergreen forest, *Quercus* forest and humid mountain forest. This last type of vegetation is typically found in regions with higher altitude and humidity than those in the study area. However, the presence of species characteristic of this vegetation may be attributed to the microclimatic factors of the dolines, which create conditions of high humidity and lower temperatures (Quintero *et al.*, 2019). In discharge areas, 78 species (28.3%) from 32 families were documented, representing the gallery forest associated with water discharge.

In addition, there were 23 species (8.3%) present in both recharge and discharge areas, 12 species (4.3%) present mainly in recharge areas, two species (0.7%) mainly in discharge areas, three species (1.1%) in the altitudinally intermediate areas, four species (1.4%) representing the palm grove, 12 species (4.3%) from pasture, five species (1.8%) collected in roadsides and three species (1.1%) associated with sugar cane crops. The remaining four species (1.4%) were collected in more than one habitat (recharge and pasture, pasture and palm grove, etc.) and gardens.

In recharge areas, the genera with the most species (Table II.4) were *Acalypha* (3), *Quercus* (3), *Bauhinia* (2), *Chamaedorea* (2), *Croton* (2) and *Iresine* (2). The species with the highest abundance were *Brosimum alicastrum* (179 individuals), *Casearia laetioides* (114 individuals), *Ardisia escallonioides* (98 individuals), *Hamelia patens* (89 individuals), *Bursera simaruba* (86 individuals), *Solenandra mexicana* (74 individuals), *Ocotea tampicensis* (70 individuals), *Croton niveus* (60 individuals), *Aphananthe monoica* (53 individuals) and *Lysiloma divaricatum* (53 individuals).

In discharge areas the genera with the most species (Table II.5) were *Ruellia* (3), *Citrus* (2), *Euphorbia* (2), *Ficus* (2), *Lippia* (2), *Pithecellobium* (2) and *Solanum* (2). The species with the highest abundance were *Hamelia patens* (192 individuals), *Syngonium podophyllum* (130 individuals), *Brosimum alicastrum* (64 individuals), *Hydrocotyle umbellata* (64 individuals), *Guazuma ulmifolia* (41 individuals), *Inga vera* (40 individuals), *Tabebuia rosea* (32 individuals), *Piper amalago* (31 individuals) and *Esenbeckia berlandieri* (28 individuals).

Table II-3 Botanical richness per habitat collected in Ciénega de Tamasopo

Habitat	**Species**	**Percent**
Recharge areas	130	47.1%
Discharge areas	78	28.3%
Mainly recharge areas	12	4.3%
Mainly discharge areas	2	0.7%
Both recharge and discharge area	23	8.3%
Intermediate	3	1.1%
Palm grove	4	1.4%
Pasture	12	4.3%
Roadside	5	1.8%
Sugarcane crop	3	1.1%
Recharge and pasture	1	0.4%
Pasture and palm grove	1	0.4%
Gardens	2	0.7%
Total	276	100%

Table II-4 Representative families and genera in recharge areas

Families in recharge areas	**Total species**	**Genera in recharge areas**	**Total species**
Euphorbiaceae	7	*Acalypha*	3
Fabaceae	7	*Quercus*	3
Acanthaceae	5	*Bauhinia*	2
Malvaceae	4	*Chamaedorea*	2
Orchidaceae	3	*Croton*	2
Solanaceae	3	*Iresine*	2
Arecaceae	3	*Adiantum*	1
Rubiaceae	3	*Ampelocissus*	1
Amaranthaceae	3	*Annona*	1
Fagaceae	3	*Beaucarnea*	1
Vitaceae	2	*Beloglottis*	1
Lamiaceae	2	*Calliandra*	1
Verbenaceae	2	*Callicarpa*	1
Celastraceae	2	*Capsicum*	1
Poaceae	2	*Centrosema*	1
Zamiaceae	2	*Chiococca*	1
Moraceae	2	*Cissus*	1
Lauraceae	2	*Citharexylum*	1
Pteridaceae	1	*Clematis*	1
Annonaceae	1	*Clinopodium*	1
Asparagaceae	1	*Colubrina*	1
Bromeliaceae	1	*Crossopetalum*	1
Ranunculaceae	1	*Cynodon*	1
Rhamnaceae	1	*Dendropanax*	1
Araliaceae	1	*Dioon*	1

Table II.4 Cont. Representative families and genera in recharge areas.

Families in recharge areas	**Total species**	**Genera in recharge areas**	**Total species**
Bignoniaceae	1	*Dolichandra*	1
Sapindaceae	1	*Dorstenia*	1
Commelinaceae	1	*Euphorbia*	1
Asteraceae	1	*Exostema*	1
Lygodiaceae	1	*Exothea*	1
Malpighiaceae	1	*Garcia*	1
Sabiaceae	1	*Heliocarpus*	1
Urticaceae	1	*Henrya*	1
Myrtaceae	1	*Isocarpha*	1
Tectariaceae	1	*Justicia*	1
Cannabaceae	1	*Lasiacis*	1
Meliaceae	1	*Lygodium*	1
		Lysiloma	1
		Maclura	1
		Malpighia	1
		Meliosma	1
		Mimosa	1
		Myriocarpa	1
		Ocotea	1
		Pelexia	1
		Persea	1
		Petrea	1
		Physalis	1
		Prosthechea	1
		Pseuderanthemum	1
		Pseudobombax	1
		Psidium	1
		Psychotria	1
		Robinsonella	1
		Ruellia	1
		Sabal	1
		Senna	1
		Sida	1
		Solanum	1
		Tectaria	1
		Thunbergia	1
		Trema	1
		Tetramerium	1
		Trichilia	1
		Wimmeria	1
		Zamia	1

Table II-5 Representative families and genera in discharge areas.

Families in discharge areas	Total species	Genera in discharge areas	Total species
Fabaceae	7	*Ruellia*	3
Euphorbiaceae	4	*Citrus*	2
Acanthaceae	3	*Euphorbia*	2
Apocynaceae	3	*Ficus*	2
Asteraceae	3	*Lippia*	2
Rutaceae	3	*Pithecellobium*	2
Salicaceae	3	*Solanum*	2
Solanaceae	3	*Acalypha*	1
Anacardiaceae	2	*Acrocomia*	1
Bignoniaceae	2	*Asclepias*	1
Lauraceae	2	*Bacopa*	1
Malvaceae	2	*Bidens*	1
Moraceae	2	*Carica*	1
Verbenaceae	2	*Cascabela*	1
Araliaceae	1	*Casearia*	1
Arecaceae	1	*Cephalanthus*	1
Caricaceae	1	*Cissampelos*	1
Caryophyllaceae	1	*Cleome*	1
Cleomaceae	1	*Commelina*	1
Commelinaceae	1	*Corchorus*	1
Cupressaceae	1	*Croton*	1
Marantaceae	1	*Cupania*	1
Meliaceae	1	*Desmodium*	1
Menispermaceae	1	*Enterolobium*	1
Myrtaceae	1	*Hydrocotyle*	1
Plantaginaceae	1	*Inga*	1
Poaceae	1	*Leucaena*	1
Polygonaceae	1	*Mangifera*	1
Rubiaceae	1	*Maranta*	1
Sapindaceae	1	*Mimosa*	1
Smilacaceae	1	*Murraya*	1
Thelypteridaceae	1	*Olyra*	1
		Parmentiera	1
		Parthenium	1
		Persea	1
		Physalis	1
		Pleuranthodendron	1
		Psidium	1
		Rauvolfia	1
		Ruprechtia	1
		Salix	1
		Sida	1
		Smilax	1
		Stellaria	1
		Tabebuia	1
		Taxodium	1
		Thelypteris	1
		Toxicodendron	1
		Trichilia	1
		Tridax	1

Diversity

The Shannon diversity index was calculated including the information of every strata for the eight discharge sites and the nine recharge sites, and both groups were graphed for comparison. The discharge sites are labeled with a 'D' prefix, while the recharge sites start with 'R'. The discharge site DNW_46 had the lowest value, with an index of 1.8, while the recharge site RE_SA2 had the highest value, with an index of 3.4 (Figure II.5).

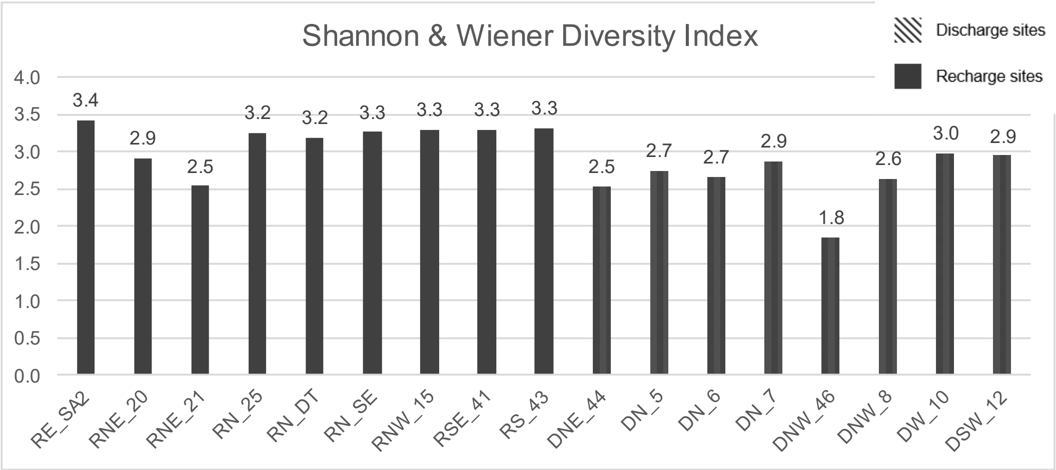


Figure II-5 Shannon and Wiener diversity index graphic for both recharge and discharge areas

An ANOVA test was performed to compare diversity between the recharge and discharge zones. The results indicated significant differences in diversity between the two zones (F (1,15) = 11.20, p = 0.004). The median diversity was higher in the recharge zone (M=3.265) compared to the discharge zone (M=2.702).

The discharge and recharge zones also were separated for individual analysis of diversity and richness. The Margalef richness index and the SHE diversity index were added to gain more information on the differences between sites (Figures II.6 and II.7).

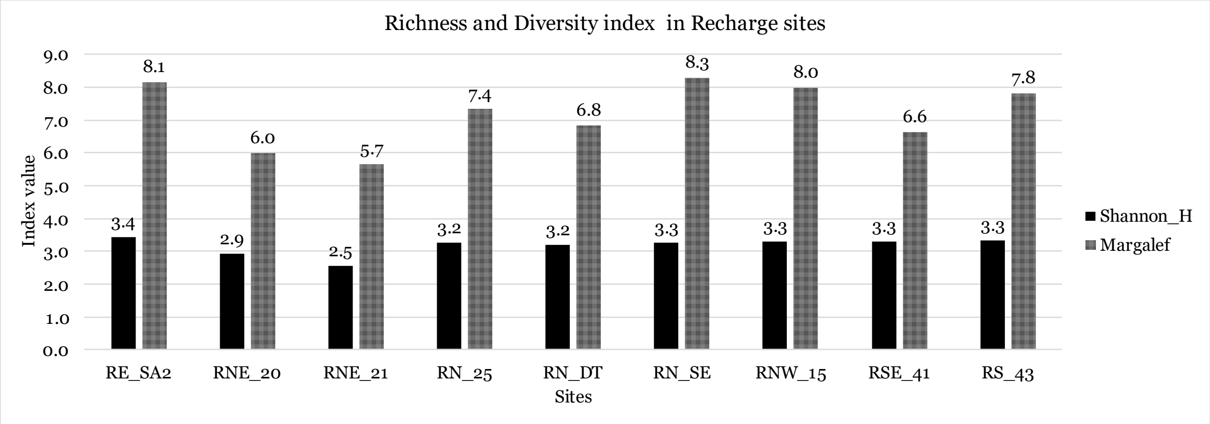


Figure II-6 Graph of richness and diversity indices in recharge zones.

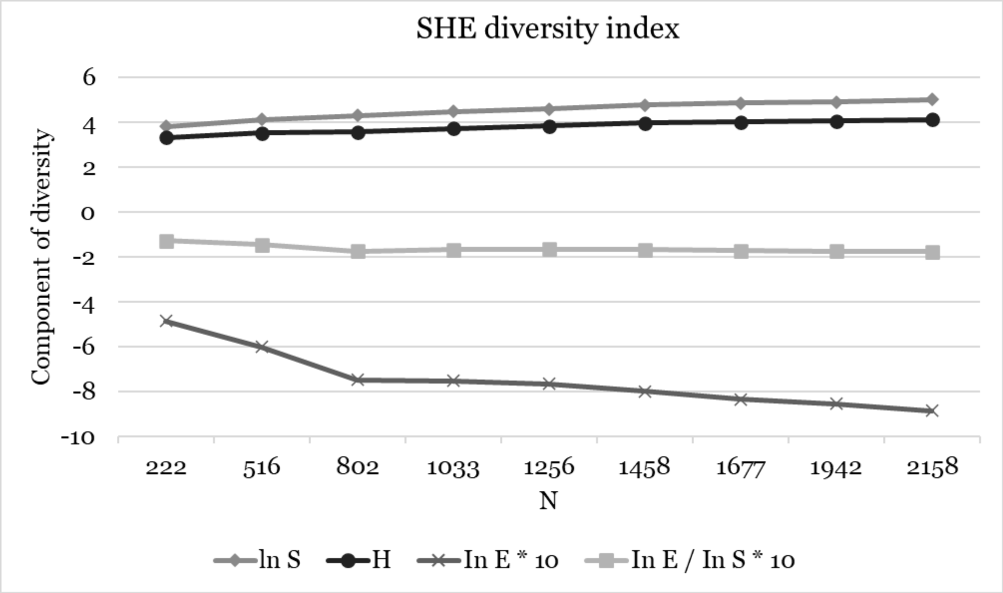


*Figure II-7 SHE diversity index for recharge sites (lnS = Richness component; H = Diversity, InE*10 = Evenness component, InE/InS*10 = Relationship between richness and evenness).*

Among the recharge sites, the site RE_SA2 has the highest diversity index value, however the RN_SE site had the highest richness value. On the other hand, the recharge site RN_21 had the lowest diversity and richness index value. The SHE diversity index breaks down the Shannon index into its richness and evenness components; the graph shows that as richness increases, evenness decreases.

Correspondingly, the same richness and diversity indices were calculated in discharge zones (Figure II.8 & II.9).

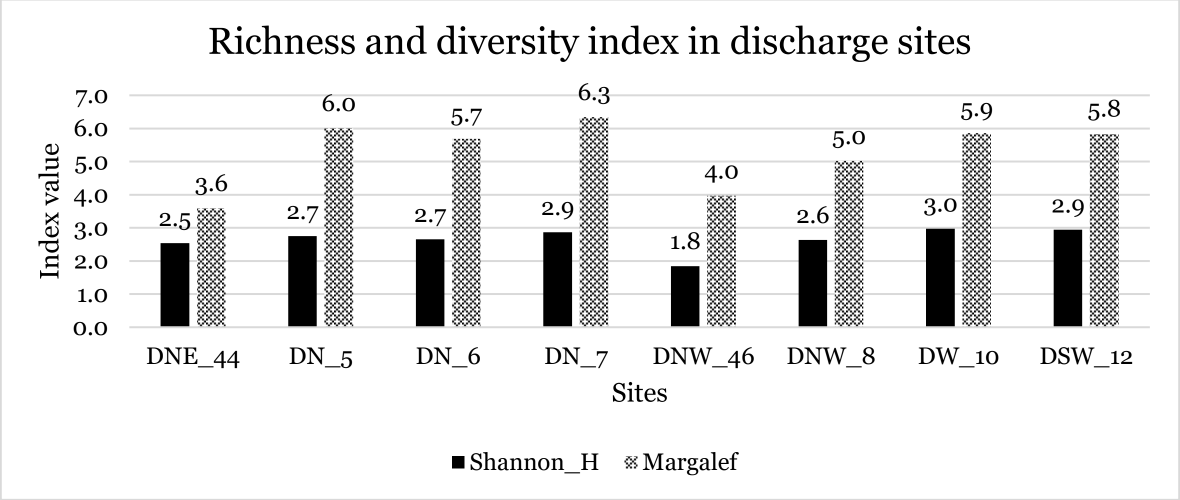


Figure II-8 Richness and diversity indices in discharge zones.

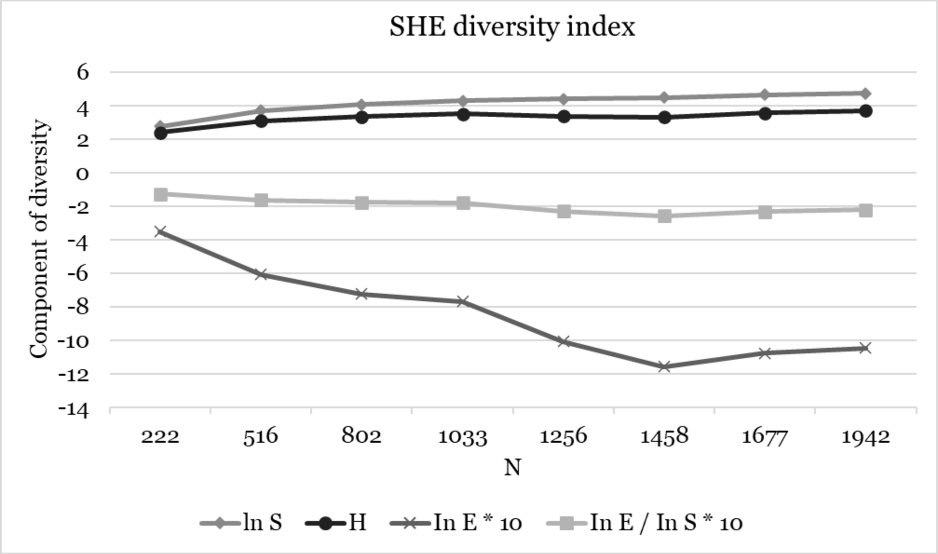


*Figure II-9 SHE diversity index for discharge sites (lnS = Richness component; H = Diversity, InE*10 = Evenness component, InE/InS*10 = Relationship between richness and evenness).*

Among the discharge sites, the DW_10 had the highest diversity index value, nonetheless the DN_7 site had the highest richness index value. On the other hand, the discharge site with the lowest diversity index value was DNW_46; however, site DE_44 showed the lowest richness index value.

For the beta diversity, the Jaccard index was calculated for both the recharge and discharge sites (Table II.6)

Table II-6 Jaccard index for both the recharge and discharge sites. The [1]color scale shows the maximum values in green and the minimum values in red.

Sites	DE_44	DN_5	DN_6	DN_7	DNW_46	DNW_8	DW_10	DW_12	RE_SA2	RN_20	RN_21	RN_25	RN_DT	RN_SE	RNW_15	RSE_41
DN_5	0.122															
DN_6	0.098	0.204														
DN_7	0.167	0.235	0.216													
DNW_46	0.121	0.159	0.220	0.286												
DNW_8	0.100	0.160	0.267	0.220	0.400											
DW_10	0.150	0.132	0.157	0.125	0.085	0.094										
DW_12	0.116	0.148	0.151	0.140	0.152	0.132	0.265									
RE_SA2	0.034	0.136	0.138	0.147	0.138	0.159	0.071	0.069								
RN_20	0.020	0.066	0.164	0.133	0.191	0.212	0.048	0.081	0.290							
RN_21	0.065	0.125	0.240	0.222	0.227	0.220	0.086	0.066	0.219	0.283						
RN_25	0.036	0.092	0.148	0.156	0.192	0.169	0.044	0.074	0.323	0.310	0.298					
RN_DT	0.019	0.063	0.063	0.145	0.135	0.119	0.030	0.045	0.339	0.217	0.183	0.234				
RN_SE	0.089	0.087	0.156	0.147	0.158	0.177	0.071	0.085	0.250	0.290	0.258	0.323	0.203			
RNW_15	0.017	0.057	0.123	0.132	0.121	0.108	0.028	0.056	0.309	0.197	0.185	0.288	0.344	0.171		
RSE_41	0.038	0.133	0.155	0.164	0.113	0.158	0.097	0.077	0.431	0.304	0.224	0.362	0.357	0.297	0.262	
RSW_43	0.054	0.074	0.143	0.188	0.143	0.164	0.058	0.042	0.257	0.219	0.206	0.254	0.227	0.205	0.192	0.246

[1] Color: Red indicates the lowest Jaccard diversity values. As values approach the mean (m=0.165), the color scale transitions to white. As the values increase, the color scale shifts to green, with dark green marking the highest Jaccard diversity values between sites.

The Jaccard index shows the greatest similarity between the recharge zones RSE_41 and RE_SA2 and between discharge zones DNW_8 and DNW_46. On the other hand, there are two areas in the table highlighted in red, containing the comparison between the composition of discharge sites DE_44, DN_5, DW_10, and DW_12 and the sampled recharge sites. These areas represent the high dissimilarity in species sampled between these sites.

Using the values of the Jaccard index, a species turnover diagram was created based on the altitudinal gradient of the sampled sites (Fig. II.10 & Fig. II.11). In the highest and most humid areas, species such as *Quercus xalapensis*, *Aphanante monoica*, *Diospyros conzattii*, and *Brosimum alicastrum* are found, among others. As altitude decreases, individuals of *Quercus* and *Diospyros* are replaced by *Bursera simaruba*, *Maclura tinctoria*, and *Callicarpa acuminata*. As the altitude continues to decrease, species with more drought-tolerant traits, such as *Croton niveus* and *Bauhinia divaricata*, become more prevalent, along with an increased presence of *Bursera*. In the lowest parts of the slopes, *Croton* and *Bauhinia* are more abundant, but species like *Lysiloma divaricatum*, *Ocotea tampicensis*, and *Solenandra mexicana* also appear.

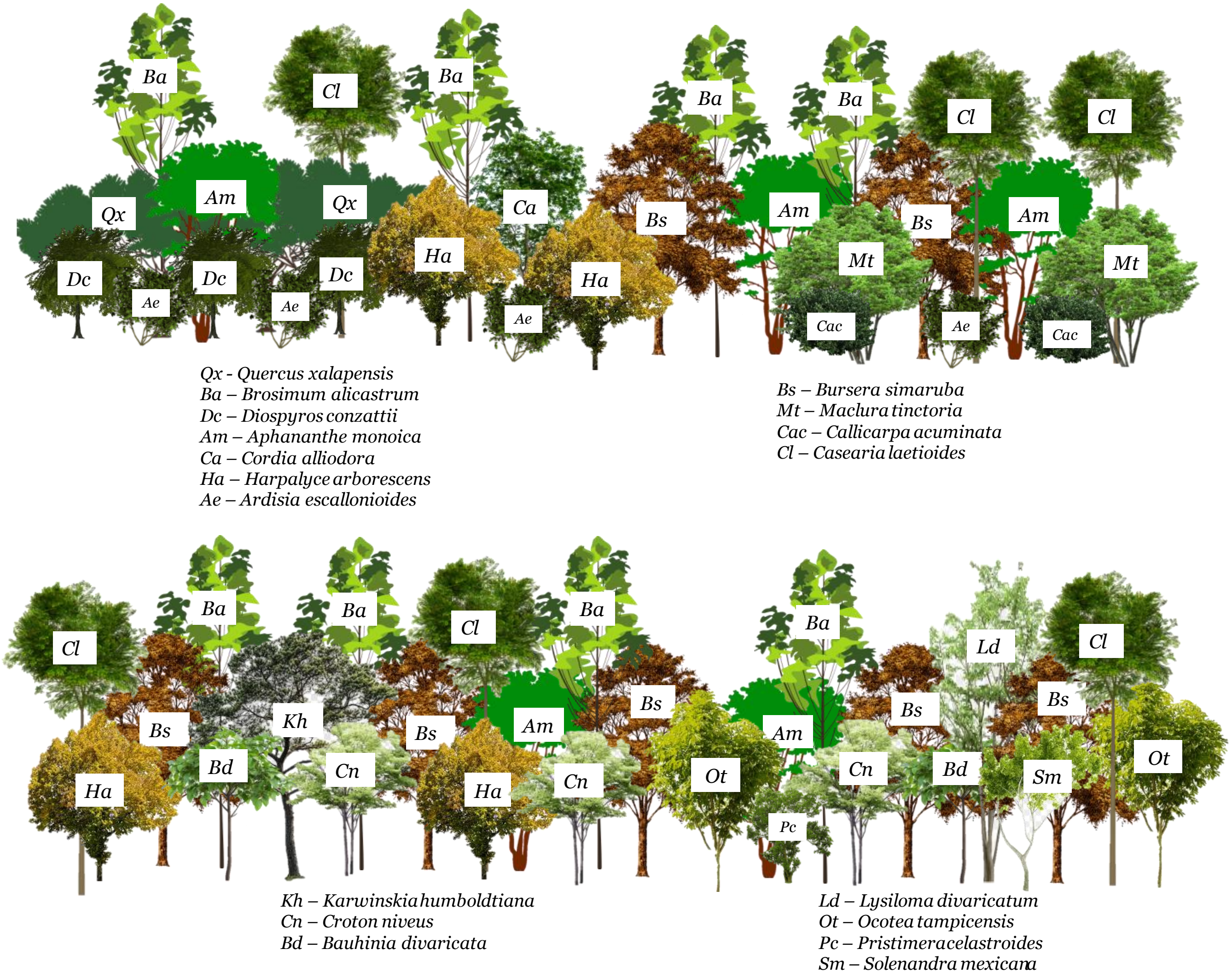
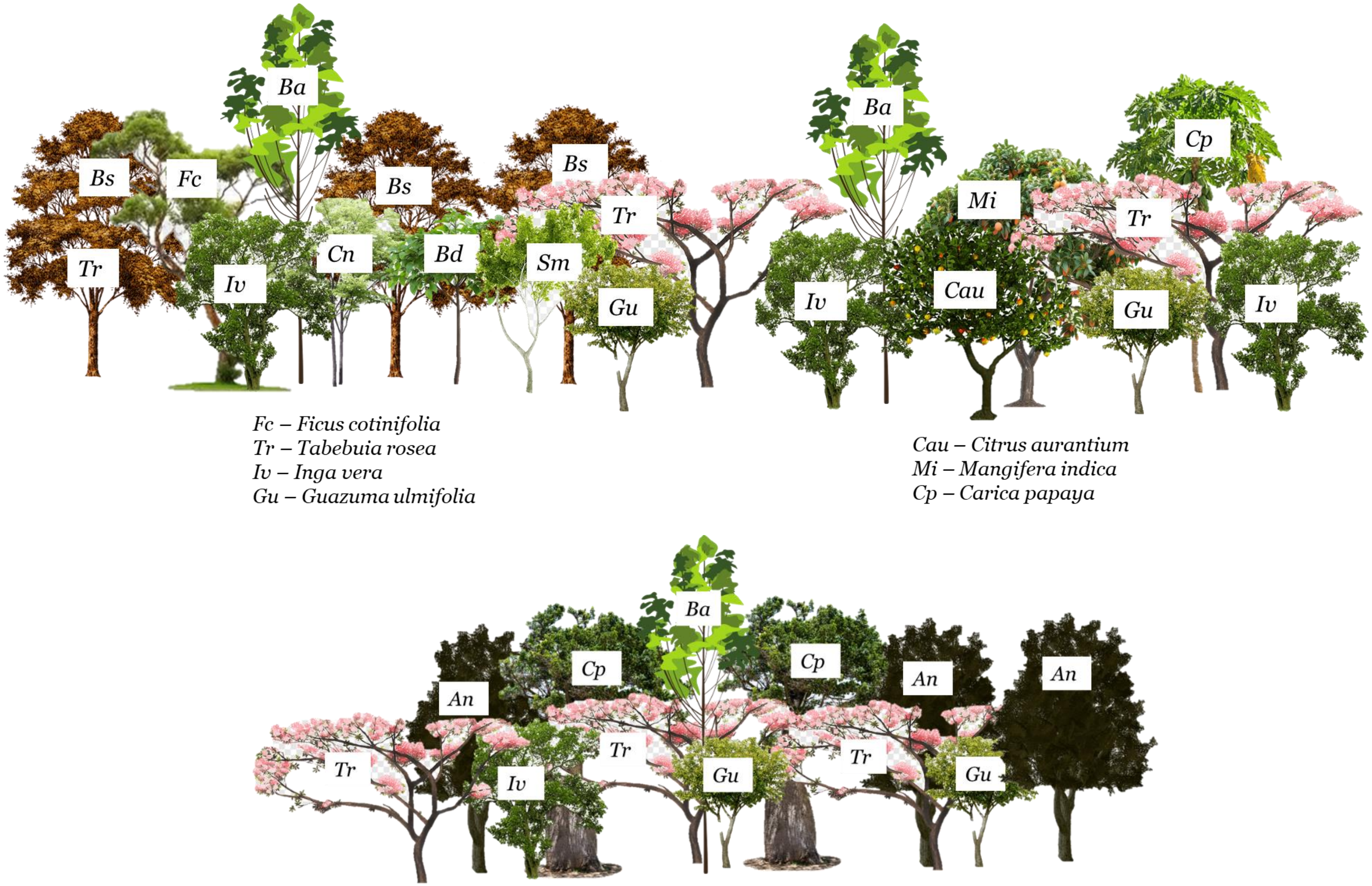


Figure II-10 Species turnover in recharge sites



Fc – Ficus cotinifolia
Tr – Tabebuia rosea
Iv – Inga vera
Gu – Guazuma ulmifolia

Cau – Citrus aurantium
Mi – Mangifera indica
Cp – Carica papaya

Cp – Ceiba pentandra
An – Achatocarpus nigricans

Figure II-11 Species turnover in discharge sites

In the discharge sites, the gradient extends from areas closest to the slopes to those near settlements and water bodies. In sites close to the slopes, species such as *Inga vera*, *Guazuma ulmifolia*, *Ficus cotinifolia*, and *Tabebuia rosea* appear. In sites near settlements, fruit tree species like *Mangifera indica* and *Carica papaya* are present, among others. As the sites approach the wetland and move away from settlements, species such as *Achatocarpus nigricans* and *Ceiba pentandra* begin to appear.
Invasive and disturbance indicator species

Of the total collected, 41 species were documented as indicators of disturbance. The species were collected in different areas, with discharge areas (17) being the ones with the larger number of species followed by recharge areas (11).

In addition, three invasive species (1.1% of the total collected), two introduced (0.7%) and one cultivated (0.4%) were registered both in recharge and discharge areas.

Table II-7 Disturbance indicator species in discharge sites

Disturbance type	**Disturbance indicator species**	**Reference**
General disturbance	*Ruellia blechum* L.	Thomas & Acosta, 2003
Anthropogenic	*Mangifera indica* L.	Parrota, 1993
Associated with crops	*Asclepias curassavica* L.	Villaseñor & Espinosa, 1998
General disturbance	*Bidens pilosa* L.	Rzedowski & Rzedowski, 2008
Associated with crops	*Parthenium hysterophorus* L.	Villaseñor & Espinosa, 1998
Associated with crops	*Tridax procumbens* L.	Villaseñor & Espinosa, 1998
Livestock	*Parmentiera aculeata* (Kunth) Seem.	Rzedowski & Rzedowski, 1993
General disturbance	*Acalypha alopecuroidea* Jacq.	Medicina Tradicional Mexicana, 2009
General disturbance	*Euphorbia hypericifolia* L.	Stalter, 2016
Anthropogenic	*Euphorbia marginata* Pursh	Peirson et al., 1813
Livestock	*Mimosa pigra* L.	Martínez et al. 2008
Anthropogenic	*Persea americana* Mill.	Van der Werff & Lorea, 1997
Associated with crops	*Sida rhombifolia* L.	Fryxell, 1993
Anthropogenic	*Maranta arundinacea* L.	Calderón de Rzedowski, 2001
Secondary vegetation	*Trichilia hirta* L.	Calderón de Rzedowski & Germán, 1993
Associated with crops	*Physalis aff. coztomatl* Dunal	Martínez et al. 2020
General disturbance	*Lippia dulcis* Trevir.	Nash & Nee, 1984

Table II-8 Disturbance indicator species in recharge sites.

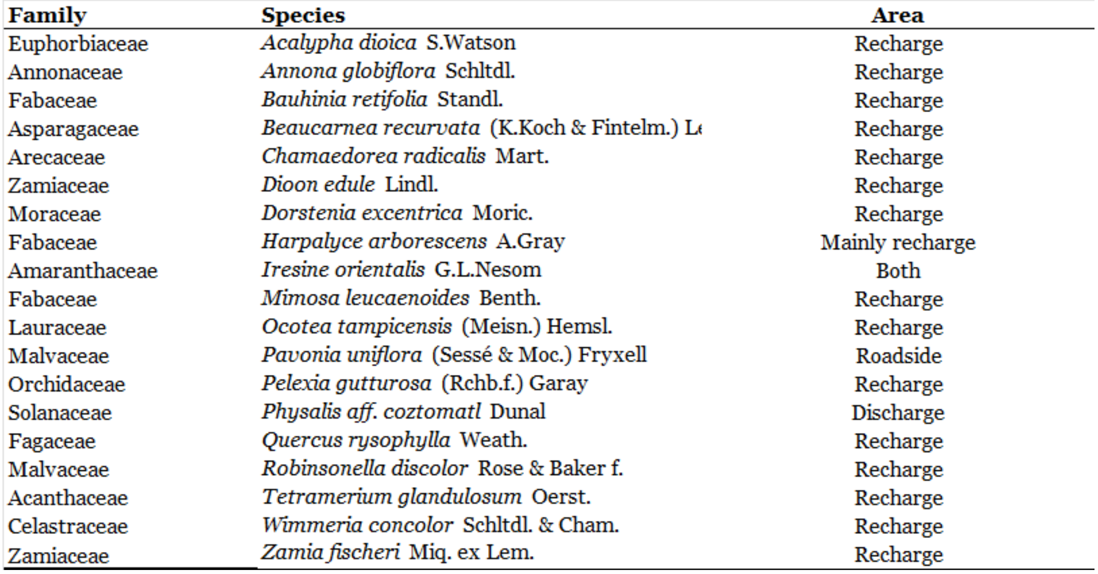
Disturbance type	**Disturbance indicator species**	**Reference**
Roads	*Cissus aff. microcarpa* Vahl	Rzedowski & Rzedowski, 2005
Secondary vegetation	*Dolichandra unguis-cati* (L.) L.G.Lohmann	Hokche *et al*. 2008
General disturbance	*Euphorbia heterophylla* var. *cyathophora* (Murray) Griseb.	Villaseñor & Espinosa, 1998
Livestock	*Gibasis pellucida* (M.Martens & Galeotti) D.R.Hunt	Espejo *et al.* 2009
Associated with roads and crops	*Iresine diffusa* Humb. & Bonpl. ex Willd.	Martínez & Díaz de Salas *et al.* 2017
General disturbance	*Isocarpha oppositifolia* (L.) Cass.	Villaseñor & Espinosa, 1998
Roads	*Ruellia lactea* Cav.	Thomas & Acosta, 2003
Secondary vegetation	*Sabal mexicana* Mart.	Martínez Ponce, 2016
Secondary vegetation	*Senna atomaria* (L.) H.S.Irwin & Barneby	Rzedowski & Rzedowski, 1997
Associated with crops	*Sida acuta* Burm.f.	Villaseñor & Espinosa, 1998
General disturbance	*Trema micranthum* (L.) Blume	Vázquez *et al.* 1999

II.3.6. Endemism

Of the entire collection, 18 species were reported endemic to México and one species was reported endemic to San Luis Potosí. The species endemic to México were: *Acalypha dioica, Annona globiflora, Bauhinia retifolia, Beaucarnea recurvata, Chamaedorea radicalis, Dioon edule, Dorstenia excentrica, Harpalyce arborescens, Iresine orientalis, Mimosa leucaenoides, Ocotea tampicensis, Pavonia uniflora, Pelexia gutturosa, Physalis* aff. *coztomatl, Quercus rysophylla, Robinsonella discolor, Tetramerium glandulosum* and *Wimmeria concolor*. The endemic species of San Luis Potosí was *Zamia fischeri* and was located in the recharge site RSW_43.

Most of the endemic species were found in recharge areas (Table II.9), except for *Physalis aff. coztomatl* which was found in the discharge site DN_5.

Table II-9 Endemic species per area of collection

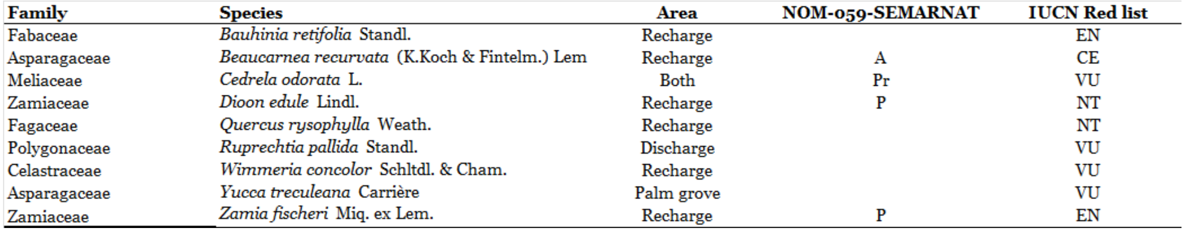


Family	Species	Area
Euphorbiaceae	*Acalypha dioica* S.Watson	Recharge
Annonaceae	*Annona globiflora* Schltdl.	Recharge
Fabaceae	*Bauhinia retifolia* Standl.	Recharge
Asparagaceae	*Beaucarnea recurvata* (K.Koch & Fintelm.) L	Recharge
Arecaceae	*Chamaedorea radicalis* Mart.	Recharge
Zamiaceae	*Dioon edule* Lindl.	Recharge
Moraceae	*Dorstenia excentrica* Moric.	Recharge
Fabaceae	*Harpalyce arborescens* A.Gray	Mainly recharge
Amaranthaceae	*Iresine orientalis* G.L.Nesom	Both
Fabaceae	*Mimosa leucaenoides* Benth.	Recharge
Lauraceae	*Ocotea tampicensis* (Meisn.) Hemsl.	Recharge
Malvaceae	*Pavonia uniflora* (Sessé & Moc.) Fryxell	Roadside
Orchidaceae	*Pelexia gutturosa* (Rchb.f.) Garay	Recharge
Solanaceae	*Physalis aff. coztomatl* Dunal	Discharge
Fagaceae	*Quercus rysophylla* Weath.	Recharge
Malvaceae	*Robinsonella discolor* Rose & Baker f.	Recharge
Acanthaceae	*Tetramerium glandulosum* Oerst.	Recharge
Celastraceae	*Wimmeria concolor* Schltdl. & Cham.	Recharge
Zamiaceae	*Zamia fischeri* Miq. ex Lem.	Recharge

II.3.7. Species at risk

Nine species with some category of risk were registered (Table II.10). Just four species were found in the NOM-059-SEMARNAT-2010, *Beaucarnea recurvata, Cedrela odorata, Dioon edule* and *Zamia fischeri*.

Table II-10 Species with a category of risk in the IUCN Red list and NOM-059-SEMARNAT-2010.



Family	Species	Area	NOM-059-SEMARNAT	IUCN Red list
Fabaceae	*Bauhinia retifolia* Standl.	Recharge		EN
Asparagaceae	*Beaucarnea recurvata* (K.Koch & Fintelm.) Lem	Recharge	A	CE
Meliaceae	*Cedrela odorata* L.	Both	Pr	VU
Zamiaceae	*Dioon edule* Lindl.	Recharge	P	NT
Fagaceae	*Quercus rysophylla* Weath.	Recharge		NT
Polygonaceae	*Ruprechtia pallida* Standl.	Discharge		VU
Celastraceae	*Wimmeria concolor* Schltdl. & Cham.	Recharge		VU
Asparagaceae	*Yucca treculeana* Carrière	Palm grove		VU
Zamiaceae	*Zamia fischeri* Miq. ex Lem.	Recharge	P	EN

A *= Threatened,* ***Pr*** *= Subject to special protection,* ***P*** *= In danger of extinction,* ***EN*** *= Endangered,* ***CE*** *= Critically endangered,* ***VU*** *= Vulnerable,* ***NT*** *= Near threatened.*

Most species in a category of risk were registered in recharge areas with the exception of *Yucca treculeana* (Palm grove) and *Ruprechtia pallida* (Discharge).

II.4. Discussion

In general, the flora of the Ciénega de Tamasopo micro-basin, like all of the Huasteca region, is influenced by the orographic, geological, hydrological, and climatic conditions of the area (Puig, 1991). There is an influence from the trade winds coming from the Gulf of Mexico, mainly during summer, which provide the necessary humidity to support vegetation types such as medium sub-evergreen forests, oak forests, and some species characteristic of humid forests (Rzedowski, 1965). In the area, also there are drier areas that feature species representative of low deciduous forests and palm groves. Additionally, human activity appears to have favored secondary vegetation and induced palm groves in some places. All these conditions bring a vast diversity of flora to the micro-basin.

The 276 species registered in the Ciénega de Tamasopo micro-basin represent the 1.3% of the national flora documented by Villaseñor & Ortiz (2014). At state level the species found in the micro-basin represent the 5.1% of the total in San Luis Potosí (Villaseñor, 2016).

Regarding sampling efficiency according to the different richness estimators, the species accumulation curves did not reach an asymptote, suggesting that there are still species to be identified at the site. It is important to mention that this study did not aim to conduct a comprehensive botanical inventory of the Ciénega but rather focused on the recharge and discharge sites. The discharge sites showed a higher sampling efficiency value, mainly due to the lower species diversity observed in these areas.

The Ciénega de Tamasopo stands out for its ecological importance, which is why various studies have been conducted in the area focusing on water, soil, pollutants, and potential land use change (Tapia *et al.,* 2010; Zapata, 2011; Zubieta, 2012; Krienen *et al.*, 2017, and Cruz, 2023, among others). However, the present study is the first to more comprehensively document the flora present in the micro-basin. Previous general studies in the Ciénega de Tamasopo (Puig, 1991; Torres, 2008; Galindo, 2012; Zubieta, 2012; Carranza, 2016; Pérez, 2017; Rocha 2019) reported 89 species of plants, which represent only the 32.2% of the actual species found in the present study and an enrichment of the knowledge of the diversity at this site. Additionally, a significant number of species were sampled but could not be identified due to the absence of reproductive structures. This could potentially increase the recorded species richness in the area.

Near the area of study there are two floristic studies which can be, at some extent, compared with the flora of the Ciénega de Tamasopo: the floristic inventory of the Biosphere reserve Sierra del Abra Tanchipa (De Nova *et al.*, 2019) and the vascular flora of the Espinazo del Diablo canyon (Castillo, 2015). The Sierra del Abra Tanchipa is formed by calcareous rocks that construct a karstic landscape, and is located in the same hydrologic region as the Ciénega de Tamasopo; in its floristic inventory 89 families, 305 genera and 427 species of vascular plants were recorded (De Nova *et al.*, 2014). In addition, the Espinazo del Diablo canyon is also part of the Sierra Madre Oriental and shares some of the karstic formations and climatic conditions with the Ciénega de Tamasopo; in its flora, Castillo (2015) reports 573 species and 400 genera. Both floras surpass what was reported in the Ciénega de Tamasopo by nearly twice the number of species; however, the present research was conducted not only with the aim of documenting the existing species but also their structure and the plant associations related to the recharge and discharge zones (Alviso *et al.*, in progress). Therefore, the species reported are considered a significant contribution to the knowledge of the area and for the future conservation and recovery of the ecosystems.

Table II-11 Comparison of the floristic diversity of the present study site and similar studies.

Study site	Area (km^2)	Number of families/genera/ species	Vegetation type	Representative families	Altitude (m)	Reference
Biosphere reserve Sierra del Abra Tanchipa	214.7	89/305/427	Tropical deciduous forest, tropical semi deciduous forest, tropical semi evergreen forest.	Fabaceae, Orchidaceae, Poaceae, Asteraceae, Euphorbiaceae	100-700	De Nova *et al*., 2014
Espinazo del Diablo canyon	18	120/400/573	Low deciduous forest, medium evergreen and sub-deciduous forest, oak forest, humid oak forest, cloud forest, gallery forest, and submontane scrubland.	Fabaceae, Asteraceae, Orchidaceae, Euphorbiaceae, Solanaceae, Rubiaceae	550-1500	Castillo, 2015
Bethania, Campeche, Mexico	2	23/33/34	Semi evergreen tropical forest	Fabaceae, Euphorbiaceae, Sapotaceae	ND	Zamora, 2017
Actopan river, Veracruz	39.76	104/394/666	Low deciduous tropical forest	Fabaceae, Asteraceae, Poaceae, Euphorbiaceae	400-900	Castillo-Campos, 2007
Ciénega de Tamasopo micro-basin	266.6	65/156/276	Low deciduous tropical forest, medium semi evergreen tropical forest, oak forest, palm grove, gallery forest	Fabaceae, Euphorbiaceae, Malvaceae, Rubiaceae	266-826	Present study

All the studies consulted (Table II.11) show Fabaceae and Euphorbiaceae as two of the families with the greatest species diversity, which is consistent with the flora present in the Ciénega de Tamasopo micro-basin. Additionally, eight of the 24 most diverse families (representing 55% of the total flora registered) in this study are among the 15 families with the highest number of native species recorded by Villaseñor (2003).

There are few studies on floristic composition in recharge and discharge zones; Caranqui *et al.* (2021) conducted a floristic characterization of areas with high hydric recharge potential in the Ichubamba-Yasepan páramo in Ecuador, while Monteron and Tampus (2016) documented riparian vegetation in groundwater discharge zones in the Philippines. However, the geographical conditions of these sites differ from those of the Ciénega de Tamasopo, making this research a precedent for flora in groundwater recharge and discharge zones in a warm sub-humid climate.

The flora documented in the Ciénega de Tamasopo micro-basin shows a differentiation between the representative families of recharge zones and discharge zones. Some of the representative families of discharge zones, such as Asteraceae and Solanaceae, have a high percentage of species recognized as weeds or disturbance indicators (Jimenez *et al.*, 2020; Sierra *et al.*, 2014), nonetheless, Monteron & Tampus (2016) acknowledge Asteraceae as one of the families characteristic of riparian vegetation so it could be a combination of both a sign of disturbance and a natural composition of the ecosystem. Additionally, the *Rutaceae* family (listed as one of the most diverse in discharge zones) is characteristic of introduced and cultivated species of great value to human communities. This composition of families in the discharge area appears to indicate some level of disturbance, which can be attributed to the accessibility of these zones and its closeness to crops and pasture sites.

For the recharge areas, the diversity of families is comparable to the ones registered in low semideciduous tropical forest, medium semievergreen tropical forest and oak forest (Table II.11) and is similar to the species documented by Puig (1991) for the Huasteca region in the same vegetation types. This diversity is caused by environmental conditions (which will be further discussed in Chapter 3) that differentiate a humid and a dry region in the Ciénega de Tamasopo micro-basin.

The Shannon index showed that, in addition to having greater taxonomic diversity, the recharge zones also exhibit higher biological diversity. Unlike the discharge zones, most recharge sites yielded Shannon index values around 3, which are considered indicative of high diversity. In contrast, the majority of discharge sites fall within expected normal diversity ranges, with the exception of site DNW_46, which has values below 2, considered indicative of low diversity (Krebs, 1999; Magurran, 2004; Castillo, 2015). However, high diversity does not necessarily indicate a better ecosystem condition, as multiple studies have linked high diversity to the level of disturbance in a site (Attiwill, 1994; Hobbs & Huenneke, 1992; Biswas

& Mallik, 2010; Yeboah & Chen, 2016). This relationship has been widely studied and debated, making it essential to complement the information with other environmental parameters to accurately assess the ecosystem's condition.

The recharge sites RE_SA2 and RN_SE (located to the east and north of the wetland, respectively) showed the highest richness and diversity indices. Further investigation into the environmental parameters that may have favored these conditions will be further discussed in Chapter 3, using multivariate analysis. The SHE index diagrams indicate that diversity values are influenced by changes in evenness between samples. In both recharge and discharge sites, greater evenness is observed in smaller sample sizes, as sample size increases, evenness decreases. In discharge zones, this decrease is more abrupt, indicating greater dominance by certain species in these sites (Magurran, 2004; Moreno, 2001; Hayek & Buzas, 2010).

The lowest values for diversity and richness were found at discharge sites DE_44 and DNW_46 (to the east and northwest of the wetland, respectively). This may indicate a level of disturbance that favors the dominance of certain species in these areas.

Beta diversity is a measure of the extent to which the diversity of two or more spatial units differs (Whittaker, 1960). The Jaccard index calculated in Table II.6 shows two blocks of low similarity between communities, corresponding to discharge sites DE_44, DN_5, DW_10, and DW_12. These discharge sites show very low values relative to all recharge sites, indicating that the species composing the communities in these discharge sites are characteristic exclusively of these areas. No recharge site showed this exclusivity of species; although similarity values with the discharge zones were not high, they did not fall below the average.

The number of endemic species is low in comparison to the national total, with just 18 endemic species registered in the study site, approximately 0.1% of the endemism in México (Villaseñor, 2016). In regard of the endemic species of San Luis Potosí, only one was registered in the Ciénega de Tamasopo, approximately 0.3% of the endemism in the state (De Nova, 2018b).

The highest concentration of endemic species was found in the recharge zones, favored by the type of vegetation, altitude, and limited access to these sites. These zones feature oak forest and tropical sub-deciduous forest vegetation, which, according to Rzedowski (1991), show the greatest amount of endemism for the subhumid region. Additionally, their location within the Sierra Madre Oriental promotes endemism in these areas (Aragón *et al.* 2021).

Of the nine species classified under a risk category according to the IUCN Red list (IUCN, 2024), only four are included in the NOM-059-SEMARNAT-2010 (SEMARNAT, 2010), highlighting the need for evaluation and protection of the remaining species. Most of these at-risk species were collected in recharge zones, which are more susceptible to land-use change due to agricultural and anthropic pression in the area. Therefore, these sites should be considered a priority for conservation.

II.5. Conclusion

The Ciénega de Tamasopo micro-basin features a wide variety of vegetation formations, ranging from gallery forests located along the edges of water bodies to palm groves, low deciduous forests, medium sub-evergreen forests, and oak forests, following an altitudinal gradient. In some areas, the climatic conditions even allow for the presence of an ecotone towards cloud forest. This variety of habitats gives the flora of the Ciénega great diversity, reflected in the number of species, genera, and families collected.

With this research, it was possible to compile a floristic inventory of the recharge and discharge zones of the Ciénega de Tamasopo, in addition to including species found throughout the microbasin. This fulfilled the specific objective of identifying the vegetal composition in these priority areas for groundwater flow.

However, much remains to be done. The 276 species collected in this study represent only a portion of the richness of the micro-basin, to which aquatic species must be added, as their collection was not within the objectives of this research. The data provided by this study offers information on the diversity related to groundwater recharge and discharge zones, allowing us to create a picture of the optimal conditions for this type of ecosystem and thereby generate efforts for its conservation.

The Ciénega de Tamasopo hosts a variety of endemic species and species in risk categories; however, it is constantly subjected to anthropogenic pressures that threaten the diversity of the ecosystems present. It is essential to continue research and conservation efforts, as well as to consider the social factor, which has been scarcely studied in the area.

II.6. References

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Appendix A.

*Floristic composition of the Ciénega de Tamasopo microbasin. Area of collection: **R** = Recharge, **D** = Discharge, **SCc** = Sugarcane crop, **RD** = Both recharge and discharge, **Pa** = Pasture, **Pg** = Palm grove, **Ga** = Garden, **I** = Intermediate, **Ro** = Roadside; Endemism: **Na** = Native, EMx = Endemic to México, ESLP = Endemic to San Luis Potosí; Status: **A** = Threatened, **Pr** = Subject to special protection, **P** = In danger of extinction, **EN** = Endangered, **CE** = Critically endangered, **VU** = Vulnerable, **NT** = Near threatened; Life form: **H** = Herb, **S** = Shrub, **T** = Tree, **V** = Vine; Disturbance type: **Gen** = General, **Ro** = Roadside, **Cr** = Crops, **SV** = Secondary vegetation, **Ls** = Livestock, **He** = Heliophytes; Vegetation: **Tdf** = Tropical deciduous forest, **Tsdf** = Tropical semi deciduous forest, **Gf** = Gallery Forest, **Mcf** = Montane cloud forest, **Xs** = Xerophytic shrubland, **Of** = Oak forest, **Opf** = Oak-Pine Forest, **Pf** = Pinus forest, **SV** = Secondary Vegetation, **Ri** = Riparian, **D** = Desert, **Sl** = Shrubland, **F** = Forest, **Tf** = Tropical forest, **Mtsef** = Medium Tropical semi evergreen forest, **LTdf** = Low Tropical deciduous forest, **Gl** = Grassland, **DTf** = Disturbed Tropical forest, **Sms** = Sub montane scrub, **Ma** = Mangrove.*

Family/Species	**Area of collection**	**Endemism**	**Status**	**Life form**	**Disturbance**	**Vegetation**
Acanthaceae						
Henrya insularis Nees	R	Na		H		Tdf, Tsdf, Gf, Mcf
Justicia brandegeeana Wassh. & L.B.Sm.	R	Na		H		Tdf
Justicia pilosella (Nees) Hilsenb.	SCc	Na		H		Xs, Gl, Of, Tdf
Ruellia blechum L.	D	Na		H	Gen	SV
Ruellia lactea Cav.	D	Na		H	Ro	SV, Xs, Tdf, Gl, Of, OPf
Ruellia sp.	D					
Ruellia tuberosa L.	D	Na		H	Ro	Ri
Tetramerium glandulosum Oerst.	R	EMx		S		D, Sl
Thunbergia alata Bojer ex Sims	R	In		V		
Achatocarpaceae						
Achatocarpus nigricans Triana	RD	Na		T		Sl, Ri, F
Amaranthaceae						
Iresine arbuscula Uline & W.L.Bray	R	Na		T		Tf
Iresine diffusa Humb. & Bonpl. ex Willd.	R	Na		H	Ro, Cr	F, Sl
Iresine orientalis G.L.Nesom	RD	Na		S		
Pseuderanthemum alatum (Nees) Radlk.	R	Na		H		Mtsef

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Anacardiaceae						
Mangifera indica L.	D	Cu		T	An	OPf, Ri
Spondias mombin L.	RD	Na		T		Tsdf
Toxicodendron radicans (L.) Kuntze	D	Na		S		Ri, Mcf, OPf
Annonaceae						
Annona globiflora Schltdl.	R	EMx		S		Tdf, Of, Mcf
Apocynaceae						
Asclepias curassavica L.	D	Na		H		Tf
Cascabela thevetia (L.) Lippold	D	Na		S		Tf, SV
Metastelma schlechtendalii Decne.	Pa	Na		V		Tdf, Xs
Rauvolfia sp.	D					
Tabernaemontana alba Mill.	MD	Na		S		Tsdf, Tdf, Of
Araceae						
Syngonium podophyllum Schott	RD	Na		H		Tf, Of, Ri
Araliaceae						
Dendropanax arboreus (L.) Decne. & Planch.	R	Na		T		Tsdf, SVTsdf, Mcf
Hydrocotyle umbellata L.	D	Na		H		Ri
Arecaceae						
Acrocomia aculeata (Jacq.) Lodd. ex R.Keith	D	Na		T		SVTsdf
Chamaedorea elegans Mart.	R	Na		S		Tf
Chamaedorea radicalis Mart.	R	EMx		S		MTsef, OPf, LTf
Sabal mexicana Mart.	R	Na		T		Tf, Ri

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Asparagaceae						
Beaucarnea recurvata (K.Koch & Fintelm.) Lem.	R	EMx	A, CE	T		LTdf
Yucca treculeana Carrière	Pg	Na	VU	T		Sl
Asteraceae						
Bidens pilosa L.	D	Na		H	Gen	Gl
Chromolaena odorata (L.) R.M.King & H.Rob.	Pa	Na		H	Ro, Cr	Tf, F, Ri
Isocarpha oppositifolia (L.) Cass.	R	Na		H	Ro	Sl
Lepidaploa tortuosa (L.) H.Rob.	Pa	Na		S		OPf, Mcf
Parthenium hysterophorus L.	D	Na		H	Gen	Tdf, Tsdf
Pseudogynoxys chenopodioides (Kunth) Cabrera	Pa	Na		V		Gl, F
Tridax procumbens L.	D	Na		H	Gen	Gl
Trixis inula Crantz	Pa	Na		H		SVLdf, Sl, Of
Bignoniaceae						
Dolichandra unguis-cati (L.) L.G.Lohmann	R	Na		V	SV	Tf
Parmentiera aculeata (Kunth) Seem.	D	Na		T	Ls	SVTf
Tabebuia rosea (Bertol.) DC.	D	Na		T		Tf
Boraginaceae						
Cordia alliodora (Ruiz & Pav.) Oken	RD	Na		T	Ls	Tf, SVTf
Bromeliaceae						
Bromelia sp.	R			S		
Burseraceae						
Bursera simaruba (L.) Sarg.	RD	Na		T		Tf
Campanulaceae						
Lobelia sartorii Vatke	Pg	Na		H		Pf, OPf, Of, MTsdf, Gl, Mcf
Cannabaceae						
Aphananthe monoica (Hemsl.) J.-F.Leroy	RD	Na		T		Tsdf, Mcf
Trema micranthum (L.) Blume	R			T	SV	SV
Caricaceae						
Carica papaya L.	D	Na		T		SVTsdf
Caryophyllaceae						
Stellaria ovata Willd. ex D.F.K.Schltdl.	D	Na		H		Mcf
Celastraceae						
Crossopetalum uragoga (Jacq.) Kuntze	R	Na		S		Tdf
Wimmeria concolor Schltdl. & Cham.	R	EMx	VU	S		Tdf, Of, OPf, Mcf, Xs
Cleomaceae						
Cleome aculeata L.	D	Na		H		Tdf
Commelinaceae						
Commelina erecta L.	D	Na		H		Gl, Tdf, Of, OPf, SV
Gibasis pellucida (M.Martens & Galeotti) D.R.Hunt	R	Na		H	Ls	Tdf, Mcf, Of

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Convolvulaceae						
Ipomoea cholulensis Kunth	Pa	Na		H	SV	Of, Mcf
Merremia umbellata Hallier f.	Pa	Na		V		MTsef, LTdf, SV
Cupressaceae						
Taxodium mucronatum Ten.	D	Na		T		Gf
Euphorbiaceae						
Acalypha alopecuroidea Jacq.	D	Na		H	Gen	DTf
Acalypha dioica S.Watson	R	EMx		H		
Acalypha flavescens S.Watson	R	Na		H		
Acalypha schlechtendaliana Müll.Arg.	R	Na		H		
Cnidoscolus multilobus (Pax) I.M.Johnst.	I	Na		S	He	Mcf, Tf
Adelia barbinervis Cham. & Schltdl.	RD	Na		T		Tf, Xs
Croton ciliatoglandulifer Ortega	D	Na		S		Ri, Tdf, Xs, Of
Croton cortesianus Kunth	R	Na		S		LTdf, MTsdf
Croton draco Schltdl.	Pa	Na		T		Gf, Tef
Croton niveus Jacq.	R	Na		T		Xs, Of, Tf
Euphorbia heterophylla var. *cyathophora* (Murray) Griseb.	R	Na		H	Gen	
Euphorbia hypericifolia L.	D	Na		H	Ro	
Euphorbia marginata Pursh	D	Na		H	Gen	Gl
Garcia nutans Rohr	R	Na		S		Tef, Tsef
Fabaceae						
Bauhinia divaricata L.	R	Na		S		Tf
Bauhinia retifolia Standl.	R	EMx	EN	T		Sms, Of
Calliandra houstoniana (Mill.) Standl.	R	Na		S		Of, Mcf
Centrosema plumieri (Turpin ex Pers.) Benth.	RD	Na		V	Ro	Gl
Centrosema sp.	R					
Centrosema virginianum (L.) Benth.	Pa	Na		V		Of, Tdf, Sms
Desmodium sp.	D					
Enterolobium cyclocarpum (Jacq.) Griseb.	D	Na		T		Tsdf
Harpalyce arborescens A.Gray	R	EMx		T		Mcf, Tdf
Indigofera miniata Ortega	Pg	Na		H		SV, LTdf
Inga vera Willd.	D	Na		T		Tsdf, Ri, SV
Leucaena leucocephala (Lam.) de Wit	D	Na		T		Tf, Ma
Lysiloma acapulcense (Kunth) Benth.	R	Na		T		Tf
Lysiloma divaricatum (Jacq.) J.F.Macbr.	R	Na		T		Tf
Machaerium salvadorense (Donn.Sm.) Rudd	SCc	Na		S		Df, Gf
Mimosa leucaenoides Benth.	R	EMx		T		Sms, Tdf, Of
Mimosa pigra L.	D	Na		S	Gen	Tf
Piscidia piscipula (L.) Sarg.	R	Na		T		Tf

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Fabaceae						
Pithecellobium dulce (Roxb.) Benth.	D	Na		T	Cr	Tf, Ri
Pithecellobium lanceolatum (Humb. & Bonpl. ex Willd.) Benth.	D	Na		T		Gf
Rhynchosia minima (L.) DC.	Pg	Na		H	Ro	Sl
Senna atomaria (L.) H.S.Irwin & Barneby	R	Na		T		Xs, Of, Opf
Tamarindus indica L.	Ga	In		T		Tsdf
Vachellia cornigera (L.) Seigler & Ebinger	RD	Na		S	SV	Tf
Fagaceae						
Quercus polymorpha Schltdl. & Cham.	R	Na		T		Of, Mcf
Quercus rysophylla Weath.	R	EMx	NT	T		Of, OPf
Quercus sp.	R			T		
Lamiaceae						
Callicarpa acuminata Kunth	R	Na		S		Tf
Clinopodium brownei (Sw.) Kuntze	R	Na		H		Tef
Ocimum campechianum Mill.	Ro	Na		H	Ro	Ri
Teucrium cubense Jacq.	Pa	Na		H	Gen	Xs, Gl
Lauraceae						
Ocotea tampicensis (Meisn.) Hemsl.	R	Na		T		Tdf, Of
Persea liebmannii Mez	R	Na		T		Mcf, Tsdf, Of
Persea americana Mill.	D	Na		T		Mcf, Of
Loganiaceae						
Spigelia humboldtiana Cham. & Schltdl.	I	Na		H		Tf, Of
Lygodiaceae						
Lygodium venustum Sw.	R	Na		S		Of, Mcf, Tf
Malpighiaceae						
Malpighia glabra L.	R	Na		S		Gf, Tf
Malvaceae						
Anoda cristata (L.) Schltdl.	Pa	Na		H	Cr	
Ceiba pentandra (L.) Gaertn.	D	Na		T		Ri, Tsdf
Corchorus siliquosus L.	D	Na		S		Of, Tdf
Guazuma ulmifolia Lam.	RD	Na		T		Tdf, Xf, Opf
Heliocarpus donellsmithii Rose	R	Na		T		Tf
Melochia pyramidata L.	SCc	Na		H		Tf
Pavonia uniflora (Sessé & Moc.) Fryxell	Ro	EMx		S		Mcf, Opf
Pseudobombax ellipticum (Kunth) Dugand	R	Na		T		Tf, Of, Opf
Robinsonella discolor Rose & Baker f.	R	EMx		T		Tf, Of, Mcf
Sida acuta Burm.f.	R	Na		H	Ro	Sl
Sida rhombifolia L.	D	Na		H	Ro	Gl

Appendix A. Continuation

Family/Species	**Area of collection**	**Endemism**	**Status**	**Life form**	**Disturbance**	**Vegetation**
Marantaceae						
Maranta arundinacea L.	D	Na		H	He	Of, Opf, Mcf
Meliaceae						
Cedrela odorata L.	RD	Na	Pr, VU	T		Tsdf
Trichilia havanensis Jacq.	R	Na		S		SVMcf, SVTdf
Trichilia hirta L.	D	Na		S	Gen	Ri, Tf
Menispermaceae						
Cissampelos pareira L.	D	Na		V		Tf
Moraceae						
Brosimum alicastrum Sw.	RD	Na		T		Tsdf, Ri
Dorstenia excentrica Moric.	R	EMx		H		Tsdf, Of
Ficus cotinifolia Kunth	RD	Na		T		Ma, Tf, Gl
Ficus maxima Mill.	D	Na		T		Tsdf, Gf
Ficus obtusifolia Kunth	D	Na		T		Tf
Ficus pertusa L.f.	Ga	Na		T		Tf
Maclura tinctoria (L.) D.Don ex Steud.	R	Na		T		Tf
Myrtaceae						
Eugenia capuli (Schltdl. & Cham.) Hook. & Arn.	RD	Na		S		Mcf, Tf, Gf
Psidium guajava L.	D	Na		S	Gen	
Psidium oligospermum Mart. ex DC.	R	Na		T		Tf, Smf
Nyctaginaceae						
Pisonia aculeata L.	R	Na		V		SVTsdf, SVMcf
Orchidaceae						
Beloglottis costaricensis (Rchb.f.) Schltr.	R	Na		H		Tf, Mcf
Pelexia gutturosa (Rchb.f.) Garay	R	EMx		H		Tdf
Prosthechea livida (Lindl.) W.E.Higgins	R	Na		H		Of, Tdf
Petiveriaceae						
Rivina humilis L.	Ro	Na		H		LTdf, OPf, Xf
Piperaceae						
Piper amalago L.	RD	Na		S		Tf, Mcf, Ri
Plantaginaceae						
Bacopa monnieri (L.) Wettst.	D	Na		H		Ri
Plumbaginaceae						
Plumbago zeylanica L.	Ro	Na		H		Tf
Poaceae						
Cynodon dactylon (L.) Pers.	R	In		H	Ro	
Lasiacis divaricata (L.) Hitchc.	R	Na		H		Tdf
Olyra latifolia L.	D	Na		H		SV

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Polygonaceae						
Ruprechtia pallida Standl.	D	Na	VU	T		Gf, Tf
Primulaceae						
Ardisia escallonioides Schltdl. & Cham.	RD	Na		S		Tf, Mcf, Of
Parathesis serrulata (Sw.) Mez	I	Na		S		Mcf
Pteridaceae						
Adiantum tricholepis Fée	R	Na		H		Ri, Tf, Gf
Ranunculaceae						
Clematis grossa Benth.	R	Na		V		OPf
Rhamnaceae						
Colubrina elliptica (Sw.) Briz. & W.L.Stern	R	Na		T		Tf
Karwinskia humboldtiana (Schult.) Zucc.	RD	Na		S		Of, Xs, Tdf
Rubiaceae						
Cephalanthus occidentalis L.	D	Na		S		Ri
Chiococca alba (L.) Hitchc.	R	Na		S		Gf
Exostema caribeum (Jacq.) Schult.	R	Na		S		Gf
Hamelia patens Jacq.	RD	Na		S		
Psychotria costivenia Griseb.	R	Na		S		Tsdf
Psychotria erythrocarpa Schltdl.	RD	Na		S		Tf
Psychotria sp.	RD					
Randia aculeata L.	RD	Na		S		Tf, Mcf
Randia laetevirens Standl.	RD	Na		S		OPf, Tsdf
Solenandra mexicana (A.Gray) Borhidi	RD	Na		T		Tf
Rutaceae						
Citrus sp.	D			T		
Citrus aurantiifolia (Christm.) Swingle	D	Cu		T		Tf, Mcf, Xs
Esenbeckia berlandieri Baill.	RD	Na		T		Tdf, Tsdf
Murraya paniculata (L.) Jack	D	In		T		Tf, Mcf
Sabiaceae						
Meliosma alba (Schltdl.) Walp.	R	Na		T		OPf, Mcf
Salicaceae						
Casearia aculeata Jacq.	D	Na		S		Of, Tf
Casearia laetioides (A.Rich.) Warb.	RD	Na		T		Tf
Pleuranthodendron lindenii (Turcz.) Sleumer	D	Na		T		Gf, Ri
Salix humboldtiana Willd.	D	Na		T		Ri, Gf, Tf

Appendix A. Continuation

Family/Species	**Area of collection**	**Endemism**	**Status**	**Life form**	**Disturbance**	**Vegetation**
Sapindaceae						
Cardiospermum halicacabum L.	RD	Na		H		SVTdf, Of, Xs
Cupania dentata Moc. & Sessé	D	Na		S		Tsdf
Exothea paniculata Radlk.	R	Na		S		Tdf, Tsdf, Of
Sapindus saponaria L.	RD	Na		T		Tdf, Tsdf, Mcf, OPf
Serjania cardiospermoides Schltdl. & Cham.	Pa	Na		V		Tsdf
Schoepfiaceae						
Schoepfia schreberi J.F.Gmel.	Pg			T		Of, Tdf, Mcf
Smilacaceae						
Smilax moranensis M.Martens & Galeotti	D	Na		V		Mcf, Of, OPf
Solanaceae						
Capsicum rhomboideum (Dunal) Kuntze	R	Na		S		Of, Gf, Mcf
Physalis aff. coztomatl Dunal	D	EMx		H	Gen	OPf, Mcf
Physalis gracilis Miers	R	Na		H		Mcf, Gf, Sms
Solanum diphyllum L.	D	Na		S		Tf
Solanum hirtum Vahl	D	Na		S		Tf
Solanum lanceifolium Jacq.	R	Na		V		Tdf
Tectariaceae						
Tectaria heracleifolia (Willd.) Underw.	R	Na		S		
Thelypteridaceae						
Thelypteris puberula (Baker) C.V.Morton	D	Na		S		Gf, Mcf
Urticaceae						
Myriocarpa longipes Liebm.	R	Na		S		Tsdf, Mcf
Verbenaceae						
Citharexylum berlandieri B.L.Rob.	R	Na		S		Tdf, Of, Xs
Lippia alba (Mill.) N.E.Br. ex Britton & P.Wilson	D	Na		S	Gen	Tf
Lippia dulcis Trevir.	D	Na		H		Tsef
Petrea volubilis L.	R	Na		V		Tf, Ri
Violaceae						
Pombalia oppositifolia (L.) Paula-Souza	Ro	Na		H		Tdf, Of
Vitaceae						
Ampelocissus aff. erdvendbergianus Planch.	R	Na		V		Tsdf
Cissus aff. microcarpa Vahl	R	Na		V	Ro	Tdf, Tsdf, Of
Zamiaceae						
Dioon edule Lindl.	R	EMx	P, NT	S		Of, Tf, Xs
Zamia fischeri Miq. ex Lem.	R	ESLP	P, EN	H		Of, Tdf, Mcf

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Unknown						
A	R					
Aguacate de olor	D					
Almedro	R					
B	R					
Cuachalala	R					
Desc, B	D					
Desc. A	R					
Desc. A 12-07-2023	D					
Desc. B 12-07-2023	D					
Desc. B 14-08	R					
Desc. C	R					
Desc. Parecido al piñoncillo	R					
Desconocida 36	R					
Desconocido 1	R					
Desconocido 100	R					
Desconocido 102	R					
Desconocido 103	R					
Desconocido 109	R					
Desconocido 114	D					
Desconocido 12	R					
Desconocido 121	D					
Desconocido 127	D					
Desconocido 132	D					
Desconocido 135	D					
Desconocido 136	D					
Desconocido 144	D					
Desconocido 146	D					
Desconocido 148	D					
Desconocido 150	D					
Desconocido 2	R					
Desconocido 34	RD					
Desconocido 35	R					
Desconocido 36	R					
Desconocido 37	R					
Desconocido 39	R					
Desconocido 42	R					
Desconocido 43	R					
Desconocido 44	R					
Desconocido 45	R					
Desconocido 46	R					
Desconocido 47	R					
Desconocido 49	R					
Desconocido 50	R					

Appendix A. Continuation

Family/Species	Area of collection	Endemism	Status	Life form	Disturbance	Vegetation
Desconocido 51	R					
Desconocido 52	R					
Desconocido 53	R					
Desconocido 54	R					
Desconocido 57	R					
Desconocido 58	R					
Desconocido 59	R					
Desconocido 61	R					
Desconocido 64	R					
Desconocido 66	R					
Desconocido 67	R					
Desconocido 68	R					
Desconocido 69	R					
Desconocido 73	R					
Desconocido 79	D					
Desconocido 87	D					
Desconocido 88	RD					
Desconocido 96	R					
Desconocido chica	R					
F	RD					
G	R					
Granjena blanca	R					
Granjena morada	R					
H	R					
K	R					
Lima	D					
Manzanilla	RD					
Oconote	D					
Pahua	D					
Recolecta 121	R					
Recolecta 134	R					
Recolecta 177	R					
Recolecta 252	R					
Recolecta 253	R					
San Enrique	D					

III. Chapter III Vegetation structure at Ciénega de Tamasopo, San Luis Potosí, México

Abstract

The Ciénega de Tamasopo wetland is a Ramsar site declared in 2008 for its ecological importance. Although it has been acknowledged as a wetland of international importance there is almost no information about the flora in the area. Through this study, the structure of the vegetation associated with water recharge and discharge zones was evaluated. Ecological sampling was conducted between 2022 and 2024, recording vegetation and environmental parameters at 9 recharge sites and 8 discharge sites. Abundance was analyzed by site type and stratum, along with the diameter and height distribution of the arboreal stratum. Importance value indices were calculated for each site and stratum to identify characteristic species. Additionally, multivariate ordination and classification analyses were performed to relate species abundance at each site to environmental parameters.

The TWINSPAN multivariate analysis defined seven different groups: Oak Forest (OF), Tropical Deciduous Forest with *Bursera* Assemblages (TdFB), Secondary Vegetation of Low Dry Deciduous Forest (SVLddF), Medium Tropical Sub-Evergreen Forest (MTseF), Ecotone of Low Tropical Deciduous Forest (ELTdF), Low Tropical Deciduous Forest with Disturbance (LTdFD), and Gallery Forest (GF). Each of these groups was characterized, including their associated species.

Highlighted species for the first four groups, corresponding to recharge zones, include *Brosimum alicastrum*, *Bursera simaruba*, *Ocotea tampicensis*, *Harpalyce arborescens*, and *Esenbeckia berlandieri*. For discharge zones, the notable species include *Inga vera*, *Hydrocotyle umbellata*, *Ceiba pentandra*, *Tabebuia rosea*, *Hamelia patens*, and *Syngonium podophyllum*, among others.

Key words: Vegetation structure, groundwater recharge, groundwater discharge, TWINSPAN, multivariate analysis.

III.1. Introduction

Vegetation is described as the composition and structure of plant species that occupy a region, forming communities that vary based on factors such as altitude, latitude, and water availability among others. This vegetation reflects both the climatic and edaphic conditions as well as the biological interactions of the area (Mueller & Ellenberg, 1974; Whittaker, 1975; Velázquez *et al.* 2016).

Vegetation science has a tradition of almost three centuries. Earlier work was primarily concerned with the description of unusual landscapes and their vegetation (Mueller & Ellenberg, 1974). But systematic descriptions of recurring vegetation patterns began only with Alexander Von Humboldt (1806) who classified repeatedly recurring growth forms into types.

Significant advances have been made since the time of Humboldt in the study of vegetation, utilizing methods and tools that facilitate data collection, interpretation, and analysis, which have evolved into what we now consider vegetation ecology and vegetation structure studies (Matteucci & Colma, 1982; Kent & Coker, 1992; Magurran, 2004; Bonham, 2013).

Studies on vegetation structure aim to identify plant communities and their relationship with the environmental parameters of specific areas (Matteucci & Colma, 1982). These studies are conducted with the intent of addressing environmental issues that require precise information on the communities and their dynamics to conserve priority habitats.

The Ciénega de Tamasopo wetland is located in the municipality of Tamasopo and is one of the last marshes in the Neotropical region of Mexico (Torres, 2008). In recent years, it has experienced accelerated land-use change driven by agrarian policies implemented in the 1970's (Moreno Unda, 2011), which promoted sugarcane cultivation as the main economic activity in the area. In 1998, the State Government's Secretariat of Ecology and Environmental Management (SEGAM, for its acronym in Spanish) and the Limnology Institute of the University of Guadalajara conducted an assessment indicating signs of eutrophication in the wetland, partly due to impacts from land-use change, pollutant discharges, and resource exploitation (Pérez, 2017).

The Ciénega de Tamasopo microbasin has a groundwater flow facilitated by the karstic formations that constitute it; this groundwater flow feeds this wetland, designated a Ramsar site in 2008 for its international importance (Torres, 2008). Toth (1963) describes two priority zones for supporting flow systems: recharge zones and discharge zones. The vegetation in these areas is distinctive and can serve as a surface indicator of their location (Peñuela & Carrillo, 2012), as well as playing an important role in interacting with surface water to facilitate infiltration (Le Maitre, 1999; Kurc & Small, 2007).

Various studies have been conducted on vegetation in groundwater recharge and discharge zones (Finch, 1998; Keese *et al.*, 2005; Döll & Fiedler, 2005; Antalia, 2011; Yulistyarini, 2011; Kim & Jackson, 2012; Gardea, 2019; Orozco *et al.*, 2023). However, in Mexico, the available information focuses on arid zones and their vegetation (Antalia, 2011; Gardea, 2019; Orozco *et al.*, 2023), thus creating models that describe groundwater flow in these respective areas.

For this reason, the objective of this study is to analyze the structure of vegetation associated with recharge and discharge zones in a karst landscape with a warm subhumid climate, thereby generating information for the subsequent conservation of this ecosystem and the development of a model of the groundwater flow system.

III.2. Materials and methods

III.2.1. Study area

The microbasin of the Ciénega de Tamasopo wetland is located southeast of the municipality of Tamasopo, San Luis Potosí, within the Pánuco hydrological region (Pérez, 2017). The climate classification in the area shows two types: semi-warm subhumid (A)C(m)(w) and warm subhumid $Aw_2(w)$ (INEGI, 2008). The study site is in the physiographic province of the Sierra Madre Oriental, in the Huasteco Karst subprovince, and within the paleogeographic unit of the Valles-San Luis Potosí

Platform. The elevation ranges from 200 to 1000 m above sea level. The rocks present are mostly sedimentary, predominantly limestone (Pérez, 2017).

III.2.2. Methods

III.2.2.1. Data Collection

Data collection was conducted from March 2023 to July 2024, over a total of 37 days with 12-hour work shifts. At each site, vegetation strata were identified, and plot sizes were assessed following Padilla (2013). Nine recharge areas and eight discharge areas were sampled (Figure III.1). In recharge areas, for the tree stratum, two rectangular plots of 200 m² each were established, three plots of 10 m² each for the shrub stratum, and three plots of 1 m² for the herbaceous stratum.

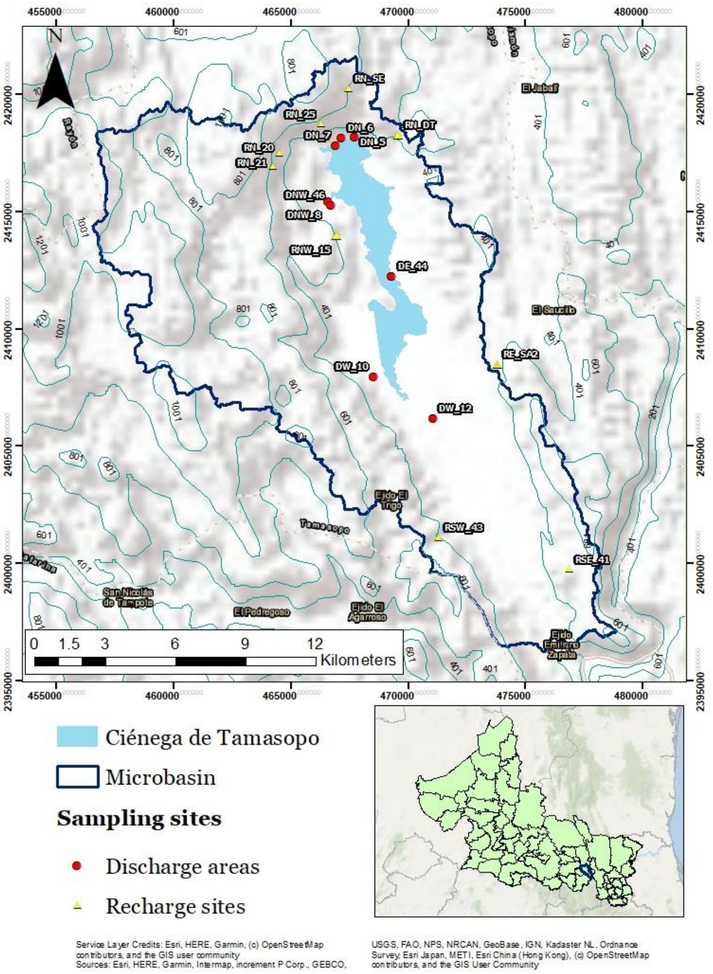

Figure III-1 Sampling sites on Ciénega de Tamasopo microbasin

Each individual sampled within the plots was identified by scientific name, and its stratum was recorded, as well as diameter at breast height (DBH, measured only for trees), coverage, height, and basal area (Alanís *et al.* 2020, Matteucci & Colma, 1982). Environmental variables such as exposure, litter, slope, altitude, geological formation, and visible impacts were also recorded.

For sampling the tree stratum, all individuals with a DBH > 2.5 cm were included, following the methodology of Gentry (1988). Height was measured using a Forestry Pro-ll laser rangefinder for trees and 5 m measuring tapes for shrubs and herbaceous plants. Crown diameter was measured with 50 m measuring tapes, while DBH and basal diameter were measured using a forestry caliper.

In discharge areas, due to less dense vegetation in the tree stratum, the nearest neighbor method was used, based on Matteucci and Colma (1982), while the shrub and herbaceous strata continued to be sampled using plot methods. Data recording followed the same procedure as in recharge areas. A species accumulation curve was created using the program EstimateS to assess the sampling quality.

III.2.2.2. Statistical analysis

Abundance, frequency and dominance

Abundance is defined as the number of individuals per species found in a locality (Lamprecht, 1990). Mackenzie *et al.* (1998) defines it as the number of individuals per unit area or habitat unit.

$$A_i = \frac{Number\ of\ individuals\ from\ species\ i}{Area}$$

Harold and Hocker (1984) define frequency as the number of times a species is represented, and Lamprecht (1990) as the presence or absence of a species in a given community. Frequency can be defined as the percentage of times a species occurs in sampling sites.

$$F_i = \frac{Individuals\ from\ species\ i}{Total\ of\ individuals}$$

Granados and Tapia (1990) mention that dominance refers to the extent of area covered, space occupied, or degree of control in a community by one or more species. The absolute dominance of a species is defined as the sum of individual crown diameter, expressed in m², divided by the sampled area.

$$D_i = \frac{Crown\ diameter\ of\ species\ i}{Area}$$

Importance value index (IVI)

For the horizontal characterization of the plant community, the Importance Value Index (IVI) was used. This index, developed by Curtis and McIntosh (1951), is calculated as the sum of the percentage values of abundance, dominance, and frequency, providing a metric for the presence of each species within the community. According to Curtis and McIntosh (1951) and Lamprecht (1990), this index is straightforward to interpret, as the three variables are expressed in percentage values, with the final result presented on a scale from 0 to 300.

The Importance Value Index was calculated for each sampling site and for each stratum.

$$IVI = AR_i + DR_i + FR_i$$

Parameters for assessing Forest site quality

The analysis of diameter class distribution for different tree species within a forest stand allows for the evaluation of its ecological and conservation status, and has been used as a measure of forest site quality assessment (Ajbilou *et al.* 2003).

The tree stratum serves as a natural archive, containing valuable information about the history of the forest. Diameter class distribution has been utilized to study the dynamics of forest populations, their relationship with environmental factors, and their response to various management types (Bernadzki *et al.*, 1998; Solomon and Gove, 1999).

To analyze diameter distribution, DBH (Diameter at Breast Height) parameters of the tree stratum were used and plotted in a histogram. Additionally, the height distribution of the tree stratum at each site was plotted.

Multivariable analysis

Multivariable analysis is the branch of statistics that addresses the simultaneous examination of numerous variables. This type of analysis is widely used in community ecology for two main reasons: it helps uncover structure within the data, and it provides a relatively objective synthesis that facilitates the understanding and effective communication of results (Gauch, 1982).

Principal Component Analysis (PCA) was used for ordination. An abundance matrix of species from each sampled site was constructed, with data normalized by log transformation Log(X+1). This matrix was then processed using Past4 software for analysis. The same procedure was applied to analyze the matrix of environmental parameters.

Biological data was correlated with environmental parameters through Canonical Correspondence Analysis (CCA), conducted using CANOCO 4.56 software.

For site classification, the TWINSPAN program in PC-Ord 6 was used with the recorded species samples to identify vegetation groups or associations. This program is based on correspondence analysis and is one of the most widely used numerical methods for divisive hierarchical classification of communities, distinguishing them by the presence or relative abundance of indicator species (Southwood and Henderson, 2000; Lozada, 2010; López, 2013).

III.3. Results

Abundance by site and strata

Abundance was recorded based on the number of individuals sampled at each site. The recharge sites (See Fig. III.2) RNE_20, RNE_21, and RSE_41 registered the highest number of individuals sampled, while discharge sites DN_6, DN_5, and DNE_44 showed the lowest numbers.

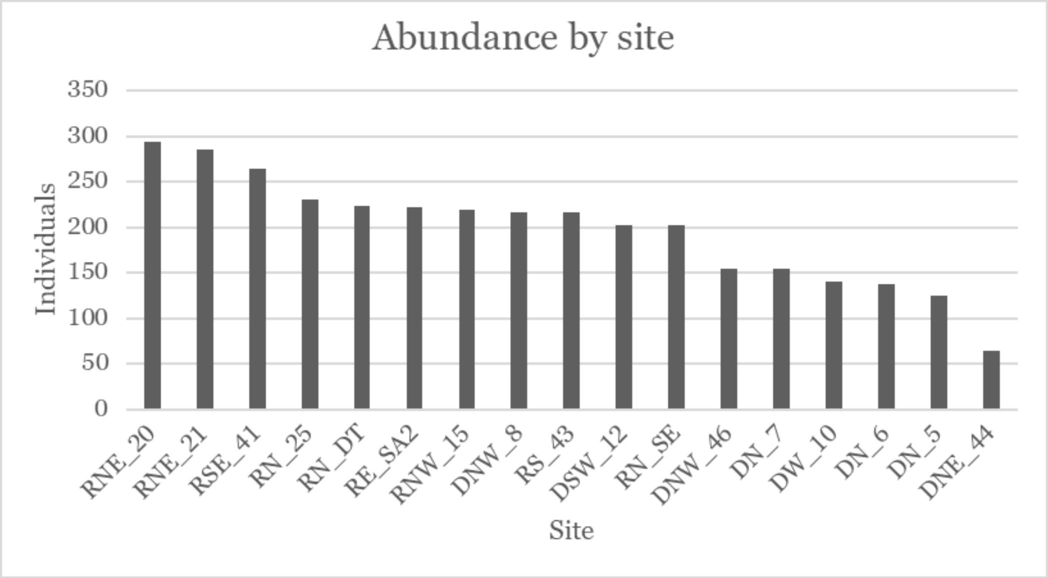

Figure III-2 Abundance by site.

Subsequently, abundance was broken down by strata for each sampled site (Figure III.3). In general, the tree stratum was the most abundant in all recharge sites (marked with an initial "R"), while in most discharge sites (marked with an initial "D"), the herbaceous stratum was the most abundant.

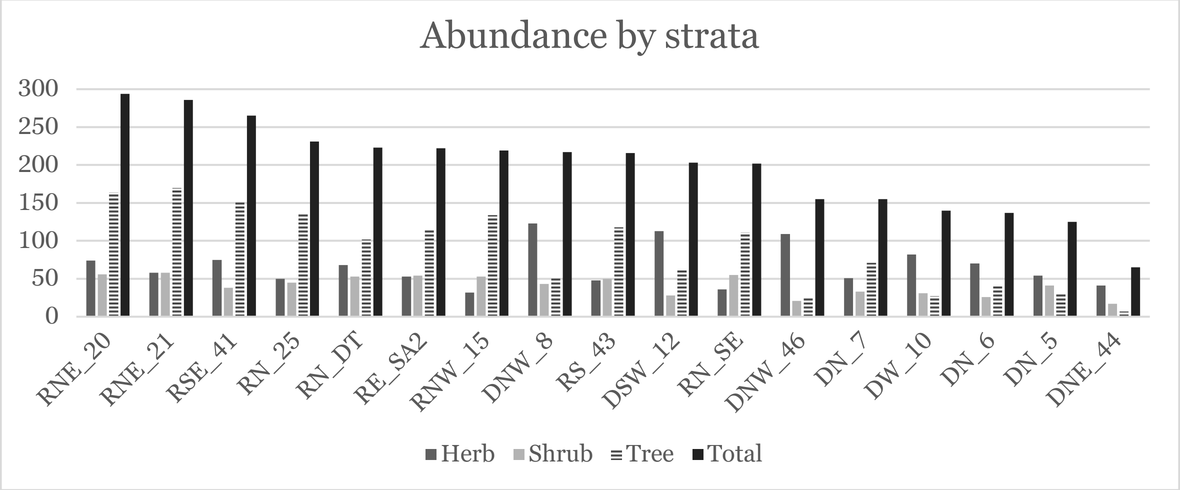

Figure III-3 Abundance broken down by strata.

Importance value index (IVI)

The importance value index was calculated for each site and each stratum, separating the recharge sites (Tables III.1 through III.9) from the discharge sites (Table III.10 through III.17). For each sampling site, the top three species in each stratum with the highest importance values were highlighted, and the Shannon diversity index obtained in Chapter 2 of this thesis was also included. The IVI can reach a maximum value of 300, as it is the sum of three relative values.

Table III-1 IVI and environmental parameters for recharge site RE_SA2

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RE_SA2	East	West	329	35	Herb	*Ocotea tampicensis*	65.6	3.4
						Justicia brandegeeana	62.6	
						Dolichandra quadrivalvis	35.5	
					Shrub	*Randia laetevirens*	87.9	
						Justicia brandegeeana	41.1	
						Ardisia escallonioides	36.7	
					Tree	*Ocotea tampicensis*	43.1	
						Lysiloma divaricatum	37.3	
						Sabal mexicana	22.7	

Table III-2 IVI and environmental parameters for recharge site RNW_15.

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RNW_15	Northwest	Northeast	376	35	Herb	*Mimosa leucaenoides*	47.3	3.3
						Pristimera celastroides	39.2	
						Cardiospermum halicacabum	33.5	
					Shrub	*Pristimera celastroides*	55.0	
						Celtis pallida	24.9	
						Randia laetevirens	21.1	
					Tree	*Brosimum alicastrum*	94.5	
						Bursera simaruba	30.4	
						Collect 134	27.5	

Table III-3 IVI and environmental parameters for recharge site RN_DT

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RN_DT	North	North	388	53	Herb	*Dolichandra unguis-cati*	75.8	3.2
						Dolichandra quadrivalvis	51.5	
						Cardiospermum halicacabum	26.9	
					Shrub	*Celtis pallida*	57.4	
						Ardisia escallonioides	39.8	
						Annona globiflora	36.3	
					Tree	*Croton niveus*	50.8	
						Solenandra mexicana	43.0	
						Bursera simaruba	33.1	

Table III-4 IVI and environmental parameters for recharge site RN_SE

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RN_SE	North	South-Southeast	826	40	Herb	*Ardisia escallonioides*	47.2	3.3
						Cynodon dactylon	41.2	
						Guazuma ulmifolia	36.5	
					Shrub	*Ardisia escallonioides*	86.1	
						Wimmeria concolor	43.9	
						Celtis pallida	40.9	
					Tree	*Quercus xalapensis*	74.6	
						Guazuma ulmifolia	25.3	
						Aphananthe monoica	24.6	

Table III-5 IVI and environmental parameters for recharge site RN_25

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RN_25	North	Southwest	550	30	Herb	*Lasiacis divaricata*	66.5	3.2
						Psychotria erythrocarpa	53.4	
						Celtis pallida	45.1	
					Shrub	*Harpalyce arborecens*	45.6	
						Psidium oligospermum	37.4	
						Crossopetalum uragoga	36.2	
					Tree	*Casearia laetioides*	40.5	
						Bursera simaruba	38.8	
						Piscidia piscipula	30.5	

Table III-6 IVI and environmental parameters for recharge site RNE_20

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RNE_20	Northeast	Northeast	532	35	Herb	*Hamelia patens*	164.8	2.9
						Unknown 73	44.4	
						Lasiacis divaricata	31.7	
					Shrub	*Unknown 73*	63.0	
						Annona globiflora	43.3	
						Acalypha schlechtendaliana	35.3	
					Tree	*Quercus polymorpha*	48.4	
						Casearia laetioides	48.3	
						Esenbeckia berlandieri	38.2	

Table III-7 IVI and environmental parameters for recharge site RNE_21

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RNE_21	Northeast	Northeast-east	442	40	Herb	*Hamelia patens*	113.8	2.5
						Syngonium podophyllum	91.8	
						Unknown 88	39.4	
					Shrub	*Brosimum alicastrum*	95.9	
						Hamelia patens	37.2	
						Piper amalago	18.0	
					Tree	*Brosimum alicastrum*	70.5	
						Diospyros conzattii	43.6	
						Quercus polymorpha	28.3	

Table III-8 IVI and environmental parameters for recharge site RSE_41

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RSE_41	Southeast	Southwest-west	344	40	Herb	*Dolichandra unguis-cati*	57.0	3.3
						Centrosema plumieri	56.9	
						Justicia brandegeeana	36.8	
					Shrub	*Psychotria erythrocarpa*	79.2	
						Ardisia escallonioides	38.0	
						Ocotea tampicensis	29.5	
					Tree	*Casearia laetioides*	44.3	
						Piscidia piscipula	35.3	
						Lysiloma divaricatum	26.9	

Table III-9 IVI and environmental parameters for recharge site RS_43

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
RS_43	South	North	349	47	Herb	*Unknown 100*	60.9	3.3
						Unknown 96	54.0	
						Pseuderanthemum alatum	25.8	
					Shrub	*Ardisia escallonioides*	94.8	
						Acalypha flavescens	42.5	
						Bauhinia sp.	29.2	
					Tree	*Brosimum alicastrum*	48.4	
						Aphananthe monoica	39.5	
						Unknown 96	35.3	

Table III-10 IVI and environmental parameters for discharge site DNW_8

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DNW_8	Northwest	NA	281	5	Herb	*Hamelia patens*	128.0	2.6
						Syngonium podophyllum	62.7	
						Acrocomia aculeata	26.0	
					Shrub	*Brosimum alicastrum*	46.3	
						Piper amalago	45.6	
						Psychotria erythrocarpa	38.8	
					Tree	*Bursera simaruba*	55.4	
						Guazuma ulmifolia	52.1	
						Tabebuia rosea	44.2	

Table III-11 IVI and environmental parameters for discharge site DNW_46

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DNW_46	Northwest	NA	286	5	Herb	*Hamelia patens*	211.7	1.8
						Thelypteris puberula	50.1	
						Syngonium podophyllum	22.9	
					Shrub	*Ardisia escallonioides*	47.5	
						Desconocido 87	41.0	
						Randia laetevirens	37.6	
					Tree	*Brosimum alicastrum*	68.8	
						Piper amalago	52.8	
						Guazuma ulmifolia	42.6	

Table III-12 IVI and environmental parameters for discharge site DN_6

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DN_6	North	NA	283	5	Herb	*Hamelia patens*	108.2	2.7
						Brosimum alicastrum	75.7	
						Olyra latifolia	36.5	
					Shrub	*Casearia lactioides*	66.1	
						Citrus x aurantifolia	41.8	
						Cupania dentata	41.4	
					Tree	*Brosimum alicastrum*	61.9	
						Tabebuia rosea	37.5	
						Guazima ulmifolia	28.0	

Table III-13 IVI and environmental parameters for discharge site DSW_12

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DSW_12	Southwest	NA	266	0	Herb	*Syngonium podophyllum*	49.3	2.9
						Lippia dulcis	47.1	
						Hydrocotyle umbellata	46.0	
					Shrub	*Casearia aculeata*	110.5	
						Karwinskia humboldtiana	52.1	
						Tabernaemontana alba	35.2	
					Tree	*Inga vera*	131.9	
						Guazuma ulmifolia	41.8	
						Parmentiera aculeata	27.4	

Table III-14 IVI and environmental parameters for discharge site DW_10

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DW_10	West	NA	272	0	Herb	*Hydrocotyle umbellata*	59.4	3
						Stellaria ovata	47.7	
						Hamelia patens	41.5	
					Shrub	*Tabernaemontana alba*	78.6	
						Bidens pilosa	39.6	
						Vachellia cornigera	33.6	
					Tree	*Ceiba pentandra*	82.7	
						Parmentiera aculeata	79.4	
						Lysiloma divaricatum	44.1	

Table III-15 IVI and environmental parameters for discharge site DN_5

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DN_5	North	NA	276	10	Herb	*Syngonium podophyllum*	173.1	2.7
						Unknown 136	70.9	
						Trichilia hirta	15.7	
					Shrub	*Esenbeckia berlandieri*	89.9	
						Tabernaemontana alba	34.5	
						Carica papaya	31.0	
					Tree	*Tabebuia rosea*	138.1	
						Mangifera indica	44.4	
						Parmentiera aculeata	32.6	

Table III-16 IVI and environmental parameters for discharge site DN_7

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DN_7	North	NA	291	0	Herb	*Syngonium podophyllum*	184.5	2.9
						Cardiospermum halicacabum	22.9	
						Centrosema plumieri	22.3	
					Shrub	*Pleurathodendron lindenii*	40.9	
						Unknown 146	35.7	
						Unknown 144	32.5	
					Tree	*Unknown B*	80.1	
						Guazuma ulmifolia	53.5	
						Ficus cotinifolia	50.8	

Table III-17 IVI and environmental parameters for discharge site DNE_44

Site	Microbasin region	Exposition	Altitude	Slope	Strata	Species	IVI	Shannon Diversity Index
DNE_44	Northeast	NA	278	0	Herb	*Olyra latifolia*	95.9	2.5
						Piper amalago	70.0	
						Cissampelos pareira	54.8	
					Shrub	*Malpighia glabra*	63.2	
						Pithecellobium lanceolatum	60.5	
						Inga vera	46.4	
					Tree	*Inga vera*	135.1	
						Achatocarpus nigricans	103.6	
						Tabebuia rosea	42.6	

Sites characterization

The species with the highest importance value in each site provide valuable information about the composition and type of vegetation present in the area. Below, the main vegetation characteristics of each site are detailed:

Recharge Zones

Site: RE_SA2

Locality: Saucillo

Notable species include *Ocotea tampicensis*, *Ardisia escallonioides*, and *Sabal mexicana*, typical of low deciduous forests and palm groves with relatively low humidity conditions. Additionally, *Randia laetevirens* and *Dolichandra quadrivalvis*, which are characteristic of secondary vegetation and disturbed conditions, primarily due to livestock presence, are also observed. The average height of the arboreal stratum is 8.3 m, and this stratum is the most abundant on the site. Additionally, the height class distribution in this site shows the highest frequency in intermediate classes and a low number of juvenile individuals, which reflects the disturbed state of the site. Based on these characteristics, site RE_SA2 can be classified as secondary vegetation of low deciduous forest with signs of disturbance.

Site: RNW_15

Locality: Presa Mocha

Dominant species include *Brosimum alicastrum* and *Bursera simaruba*, which are associated with medium semi-deciduous forests. However, the presence of species like *Mimosa leucaenoides*, *Pristimera celastroides*, *Cardiospermum halicacabum*, and *Celtis pallida*, which are adapted to dry environmental conditions, indicates that this site can be considered a low deciduous forest in dry conditions.

Site: RN_DT

Locality: Cabezas

Species such as *Croton niveus*, *Annona globiflora*, and *Dolichandra unguis-cati* are characteristic of secondary vegetation associated with tropical forests. Therefore, this site can be classified as secondary vegetation of low deciduous forest.

Site: RN_SE

Locality: Serranillo

Serranillo is the highest-altitude site sampled. This site features *Quercus xalapensis*, *Wimmeria concolor*, and *Aphananthe monoica*, which are characteristic of oak forests and cloud forests. Additionally, species like *Guazuma ulmifolia*, which occasionally extends into oak forests, are present. Based on these characteristics, the vegetation in this site is classified as oak forest.

Site: RN_25

Locality: San Isidro

Species such as *Casearia laetioides* and *Bursera simaruba* are typical of medium, low semi-deciduous and low deciduous forests, while *Harpalyce arborescens*, *Psychotria erythrocarpa*, *Piscidia piscipula*, and *Psidium oligospermun* are associated with deciduous forests. The average height of the arboreal stratum is 7.27 m, and this stratum is the most abundant in the site. This site is characterized by vegetation classified as low semi-deciduous forest.

Site: RNE_21

Locality: Joya de los novillos

This site is characterized by the presence of *Quercus polymorpha*, associated with *Diospyros conzattii*, which are typical of oak forests. Additionally, the presence of humid conditions is indicated by species such as *Hamelia patens* and *Syngonium podophyllum*. The vegetation on this site is defined as oak forest.

Site: RNE_20

Location: Joya de los Novillos

Similar to RNE_21, this site includes *Quercus polymorpha* in its composition. However, it also features species such as *Lasiacis divaricata*, *Annona globiflora*, and *Esenbeckia berlandieri*, which are associated with drier conditions. Therefore, the vegetation in this site may represent an ecotone between oak forest and deciduous tropical forest.

Site: RSE_41

Location: San José el Viejo

Species such as *Justicia brandegeeana*, *Psychotria erythrocarpa*, *Casearia laetioides*, and *Piscidia piscipula* characterize this site as tropical forest vegetation, often associated with *Bursera simaruba* groupings (Puig, 1991). The average height of the arboreal stratum is 6.51 m, leading to the classification of this site's vegetation as low deciduous tropical forest.

Site: RS_43

Location: La Ceiba

This site includes species like *Acalypha flavescens*, *Pseuderanthemum alatum*, *Brosimum alicastrum*, *Aphananthe monoica*, and *Ardisia escallonioides*, which are characteristic of sub-evergreen tropical forest vegetation. With an average arboreal stratum height of 6.82 m, the vegetation here is classified as low sub-evergreen tropical forest.

Discharge sites

Site: DNW_8

Location: La Joya de los Novillos

This site features tropical forest species such as *Brosimum alicastrum*, *Bursera simaruba*, *Guazuma ulmifolia*, *Psychotria erythrocarpa*, and *Piper amalago*. However, the presence of species like *Acrocomia aculeata*, characteristic of secondary vegetation, indicates that the vegetation here corresponds to secondary low deciduous tropical forest. In this case, the height and diameter class distribution indicates that most individuals in this site are young, further supporting the idea that it corresponds to secondary vegetation.

Site: DNW_46

Location: La Joya de los Novillos

The conditions at this site closely resemble those of DNW_8, as they are located only 210 m apart. Species like *Brosimum alicastrum*, *Guazuma ulmifolia*, and *Piper amalago* are also present here. However, the presence of *Thelypteris puberula* in the herbaceous stratum, as indicated by its importance value index, suggests the humid conditions typical of gallery forests. These characteristics suggest that the vegetation in this site represents an ecotone between low deciduous tropical forest and gallery forest.

Site: DN_6

Location: Cabezas

This site features tropical forest species such as *Brosimum alicastrum*, *Casearia laetioides*, and *Guazuma ulmifolia*. Additionally, the presence of *Olyra latifolia* and *Citrus aurantifolia* indicates human influence and anthropogenic impact. As such, the vegetation at this site corresponds to secondary low deciduous tropical forest or low deciduous tropical forest with disturbance.

Site: DSW_12

Location: 20 de Noviembre

Species on this site are characteristic of riparian vegetation and gallery forest, including *Hydrocotyle umbellata*, *Casearia aculeata*, *Karwinskia humboldtiana*, *Inga vera*, and *Lippia dulcis*. The presence of *Parmentiera aculeata* suggests some degree of disturbance due to cattle activity. Therefore, the vegetation in this area corresponds to gallery forest.

Site: DW_10

Location: Capuchinas

This site features species associated with riparian vegetation and gallery forest, such as *Hydrocotyle umbellata*, *Bidens pilosa*, and *Ceiba pentandra*. However, the presence of species indicative of cattle disturbance, such as *Vachellia cornígera* and *Parmentiera aculeata*, suggests that the vegetation in this area corresponds to a gallery forest with disturbance.

Site: DN_5

Location: Cabezas

This site includes species typical of low deciduous tropical forest, such as *Esenbeckia berlandieri* and *Syngonium podophyllum*. Additionally, the presence of species like *Carica papaya*, *Mangifera indica*, and *Parmentiera aculeata* indicates secondary vegetation and disturbance in the area. Therefore, the vegetation in this zone corresponds to a low deciduous tropical forest with disturbance.

Site: DN_7

Location: Cabezas

The species at this site are associated with humid forests and low tropical forests, such as *Pleuranthodendron lindenii*, *Syngonium podophyllum*, *Ficus cotinifolia*, and *Guazuma ulmifolia*. However, it also includes riparian vegetation species, although they are not among the highest IVI values, such as *Inga vera* and *Pithecellobium lanceolatum*. Therefore, the vegetation in this site is classified as an ecotone between low deciduous tropical forest and gallery forest.

Site: DN_44

Location: La Esperanza

This site is the closest to the wetland and includes species such as *Achatocarpus nigricans*, *Inga vera*, *Pithecellobium lanceolatum*, and *Malpighia glabra*, which are typical of gallery forests. Visually, this site showed significant impacts due to its proximity to sugarcane plantations. Some species collected at this site, such as *Toxicodendron radicans* and *Vachellia cornigera*, further confirm the presence of disturbance in the area.

Parameters for assessing forest site quality

The total coverage per stratum was recorded in recharge and discharge zones for each of the sampled species. The 20 species with the highest total coverage in m² were highlighted.

Hamelia patens showed the highest total coverage in herb stratum for both recharge and discharge zones; however, in discharge zones, the coverage of this species is twice that in recharge zones (Figure III.4).

For the shrub stratum (Figure III.5), *Randia aculeata* had the highest total coverage in recharge zones, while *Tabernaemontana alba* showed the highest value in discharge zones.

For the tree stratum (Figure III.6), *Brosimum alicastrum* had the highest total coverage in recharge zones, while *Tabebuia rosea* showed the highest value in discharge zones.

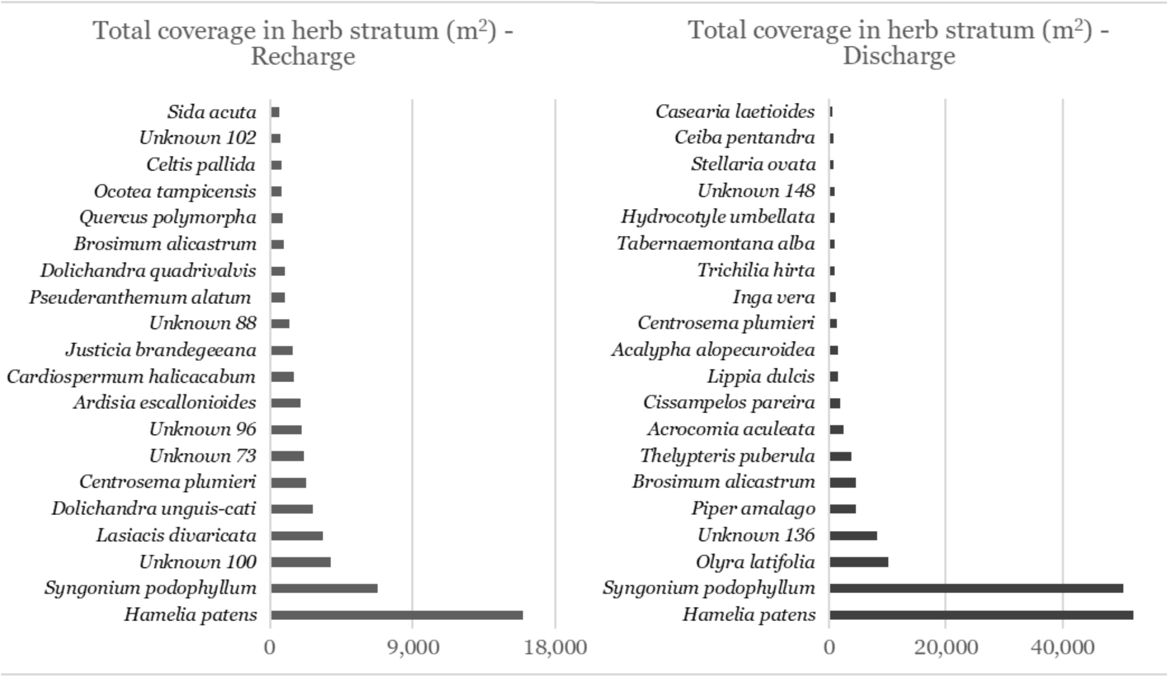

Figure III-4 Total coverage in m2 of the herb stratum in recharge (left) and discharge (right) zones.

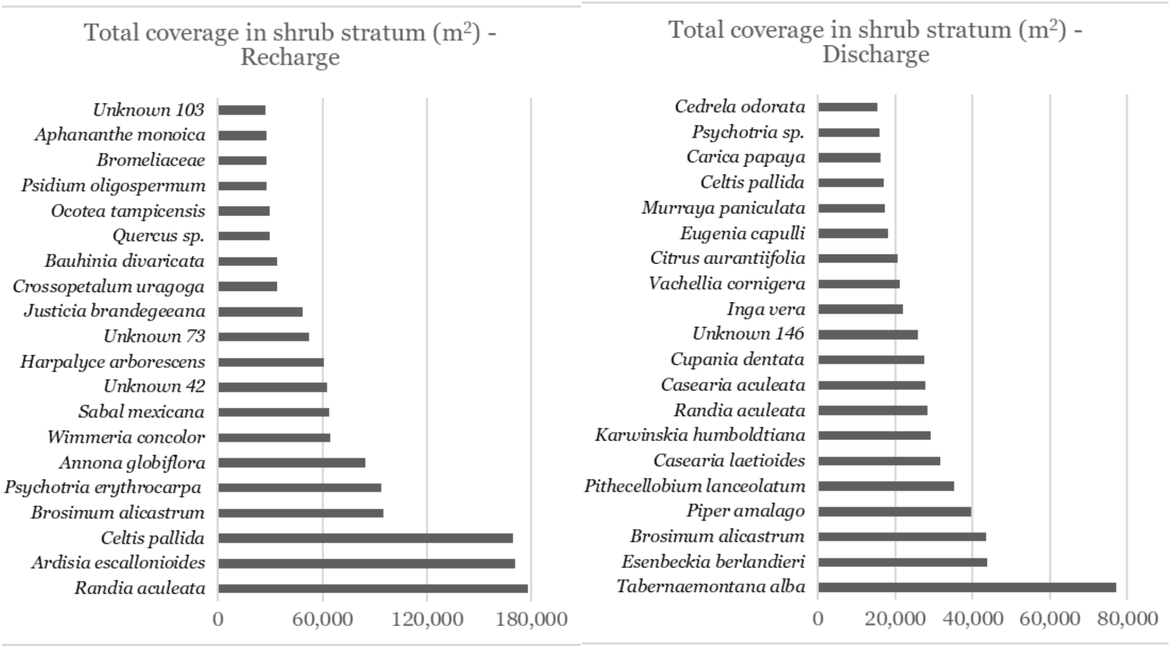

Figure III-5 Total coverage in m2 of the shrub stratum in recharge (left) and discharge (right) zones

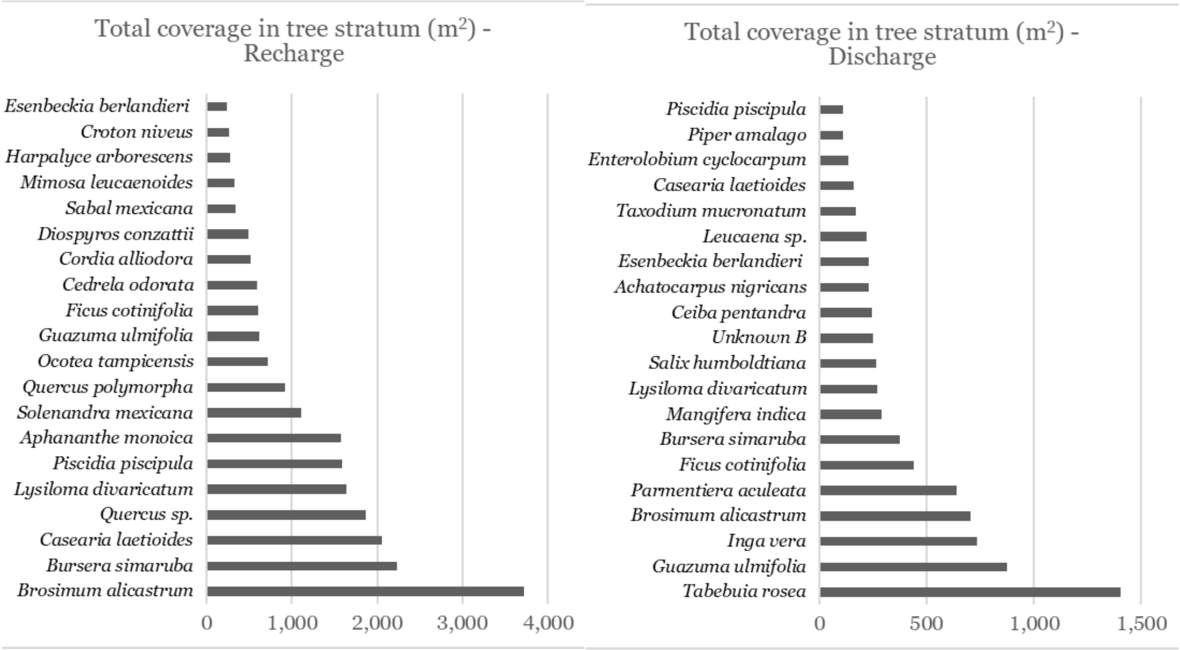

Figure III-6 Total coverage in m2 of the arboreal stratum in recharge (left) and discharge (right) zones.

The analysis of diameter and height distribution is used in forestry sciences to characterize arboreal communities. These studies provide information on the structure and stability of these communities to achieve sustainable use of timber resources. Distribution by height class was carried out for the individuals in the tree stratum within the recharge zones (Figure III.7).

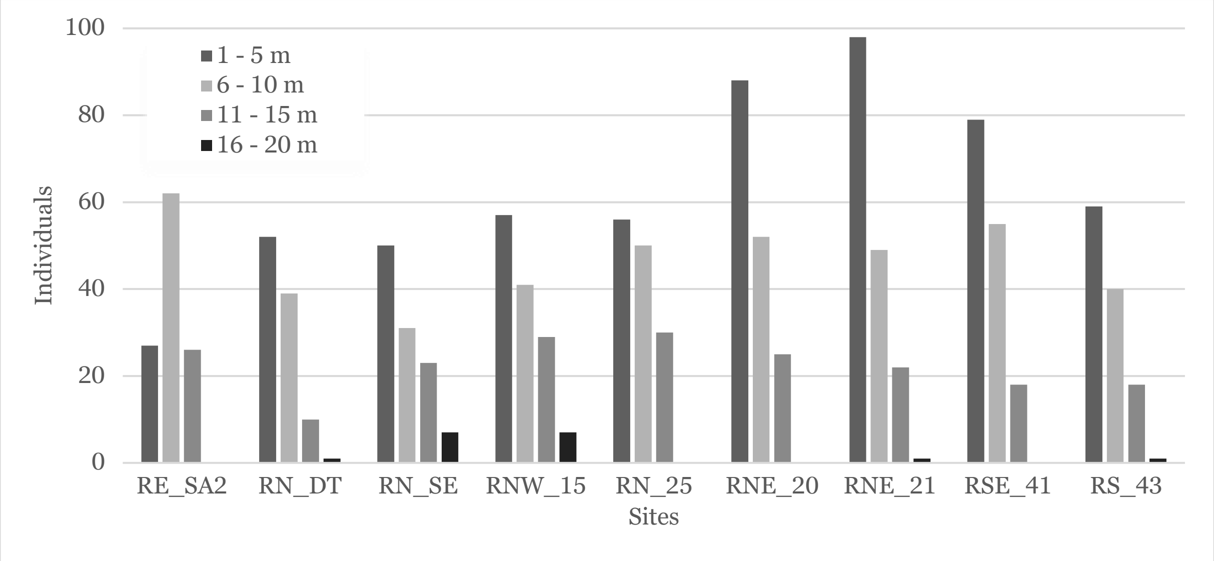

Figure III-7 Height distribution of tree stratum in recharge zones

In recharge zones, sites RNE_20 and RNE_21 stand out, as most of their individuals are between 1 and 5 meters tall. The tallest individuals, in the 16 to 20-meter class, are found only at some sites, with RN_SE and RNW_15 showing the highest frequency; however, they do not exceed 10 individuals per site.

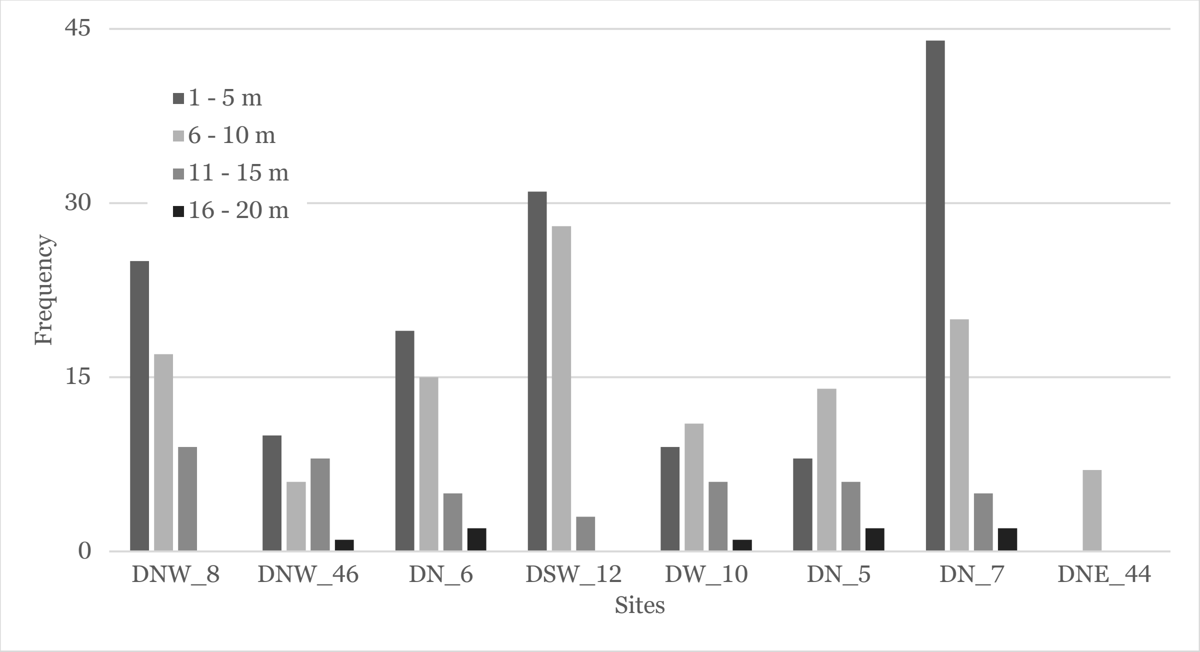

Figure III-8 Height distribution of tree layer in groundwater discharge zones

The discharge site DN_7 had the most individuals in the 1 to 5 meters class, followed by DSW_12 (Figure III.8). At sites DNW_46, DW_10, and DN_5, individuals are more evenly distributed across the height classes, whereas at site DNE_44, all individuals fall within the 6 to 10-meter height class.

The DBH distribution in recharge sites (Figure III.9) is concentrated within the first class, ranging from 1 to 25 cm in diameter. In contrast, discharge zones (Figure III.10) feature larger diameter classes, extending up to 251–300 cm, whereas the highest class in recharge zones is 76–100 cm. The distribution in discharge zones is primarily concentrated in the first class, spanning 1–50 cm in diameter. Additionally, site DE_44 is the only one with individuals in the largest diameter class.

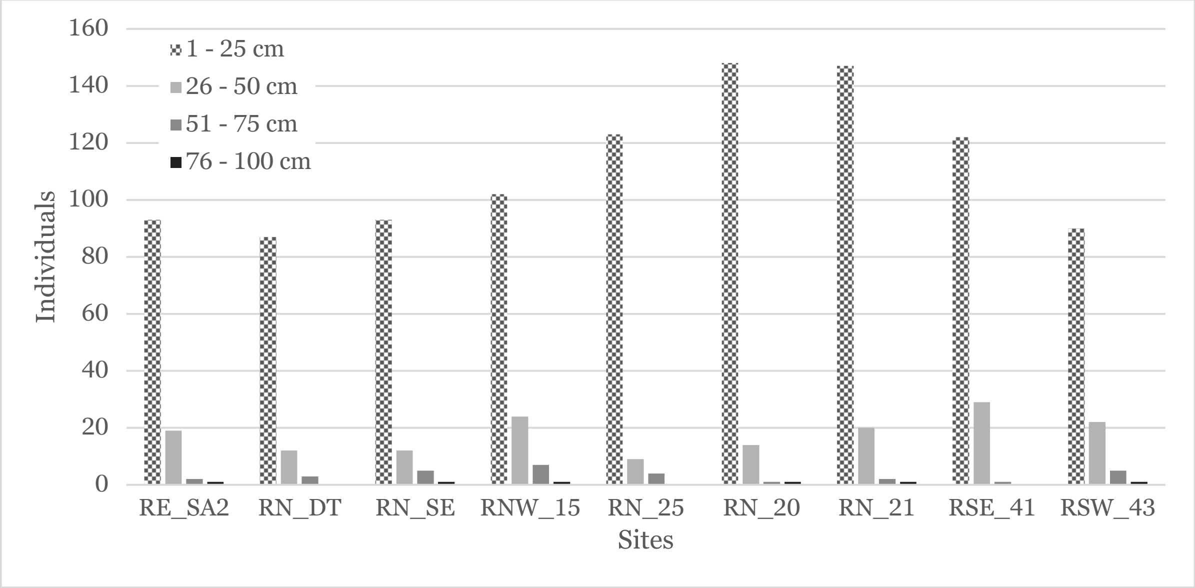

Figure III-9 Diameter at Breast Height (DBH) Distribution of the tree stratum in recharge zones

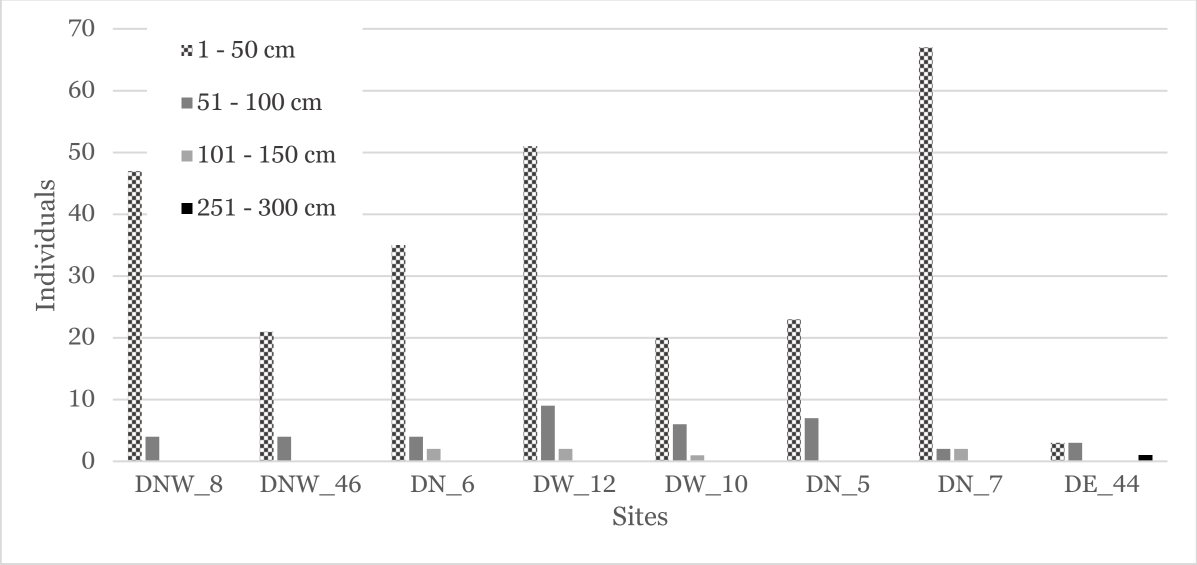

Figure III-10 Diameter at Breast Height (DBH) Distribution of the tree stratum in discharge zones

Multivariable analysis

The abundance matrix of the species recorded at the sampling sites was entered into the PAST software, and a biplot was constructed (Figure III.11) based on the principal component analysis data. Axes 1 and 2 represent 42.4% and 24.6% of the data variance, respectively.

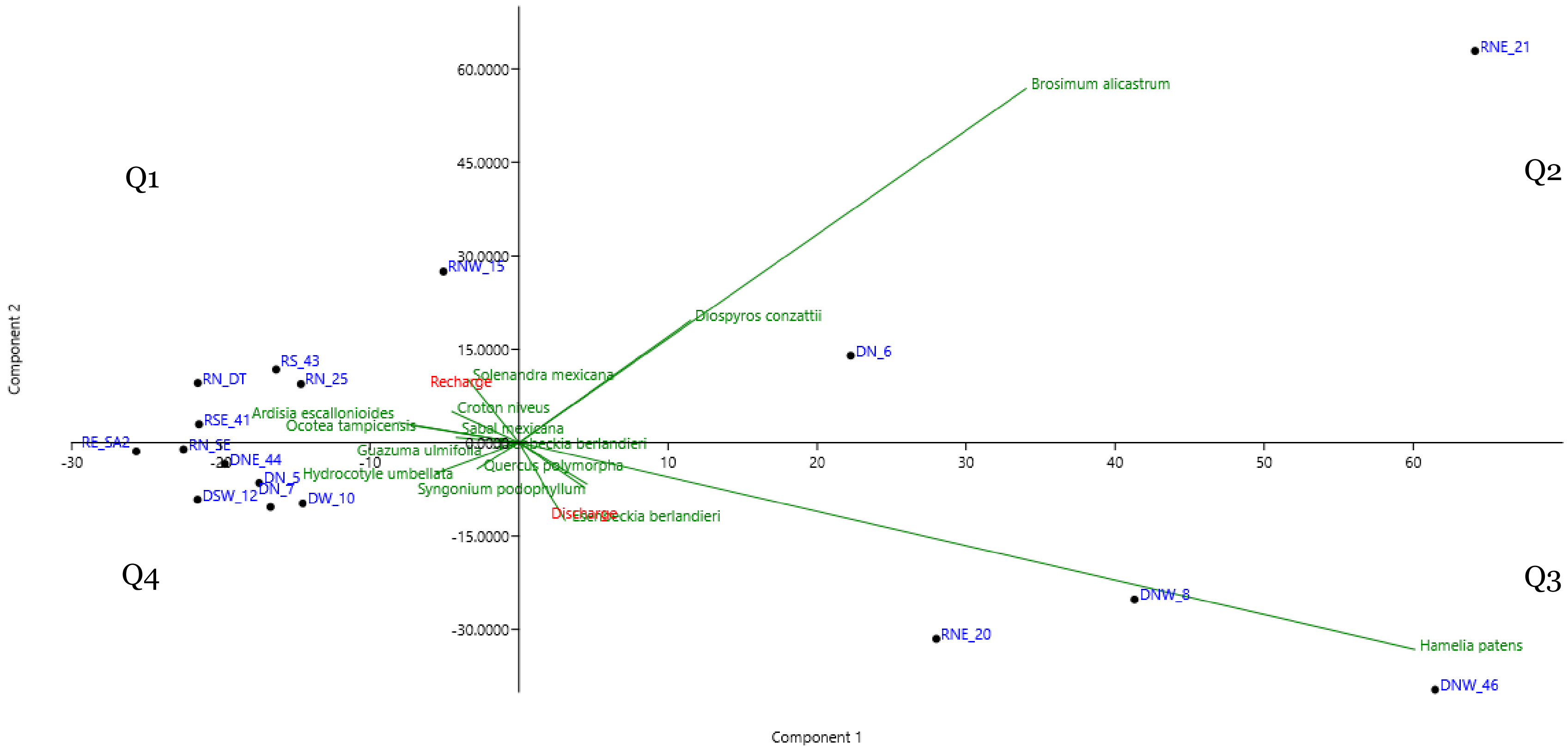

Figure III-11 Biplot of the species and the sampling sites. The species with the highest weight in each component were selected for improved visualization.

Figure III.11 displays four quadrants (labeled Q1 to Q4) defined by the axes of principal components 1 and 2. Quadrant 1 includes the recharge sites RNW_15, RS_43, RN_25, RN_DT, and RSE_41. Associated with the arrangement of these sites are the species *Solenandra mexicana*, *Croton niveus*, *Sabal mexicana*, *Ardisia escallonioides*, and *Ocotea tampicensis*.

Quadrant 2 contains the discharge site DN_6 and the recharge site RNE_21, both related to the species *Brosimum alicastrum* and *Diospyros conzattii*.

Quadrant 3 includes the discharge sites DNW_8 and DNW_46, as well as the recharge site RNE_20. The species associated with these sites are *Esenbeckia berlandieri*, *Syngonium podophyllum, Quercus polymorpha* and *Hamelia patens*.

Finally, Quadrant 4 comprises the discharge sites DW_10, DSW_12, DN_5, DN_7, and DNE_44, in addition to the recharge sites RE_SA2 and RN_SE. These sites are related to the species *Guazuma ulmifolia* and *Hydrocotyle umbellata*.

It can also be observed that the axis 1 seemingly divides species associated with humid environments or riparian vegetation (Q3 and Q4), such as *Hydrocotyle umbellata* and *Syngonium podophyllum*, from species typical of relatively drier environments (Q1 and Q2), such as *Solenandra mexicana* and *Ardisia escallonioides*; therefore, component 1 could be related to a humidity gradient.

Additionally, the matrix of environmental variables was entered into PAST to generate the biplot from the principal component analysis. The data were standardized to ensure comparability. Axes 1 and 2 represent 43% and 14% of the data variance, respectively.

In Figure III.12, a clear separation between recharge and discharge zones can be observed, divided by the axis of Component 2. The discharge zones are located in quadrants 1 and 4, while the recharge zones are found in quadrants 2 and 3.

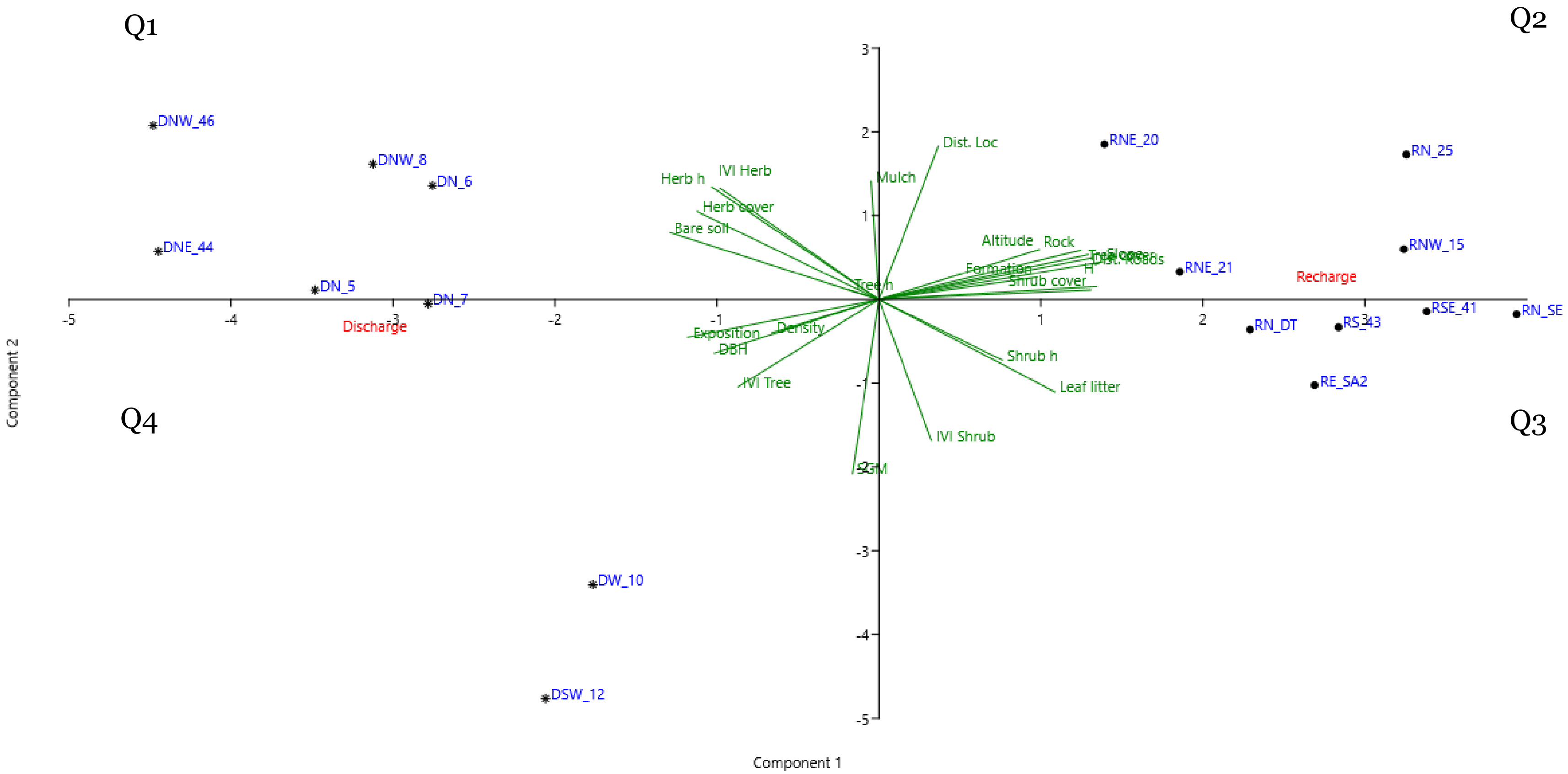

Figure III-12 Biplot of the environmental parameters and sampling sites.

Additionally, in Figure III.11 it can be observed that Axis 1 appears to represent an altitudinal gradient, with the recharge sites located on the far right at higher altitudes and the discharge sites on the far left at lower altitudes.

The environmental parameters associated with the ordination of discharge zones are primarily influenced by the dominance of the herbaceous and arboreal strata, characterized by larger diameter at breast height values in these areas. In contrast, the ordination of recharge zones is driven by the presence of exposed rock formations, slopes, shrub layer cover, and the percentage of leaf litter.

Biological data were correlated with environmental parameters through Canonical Correspondence Analysis (CCA), using a species and an environmental matrix. Two biplots were created: one incorporating all environmental variables (Figure III.13) and another focusing exclusively on the statistically significant variables (Figure III.14).

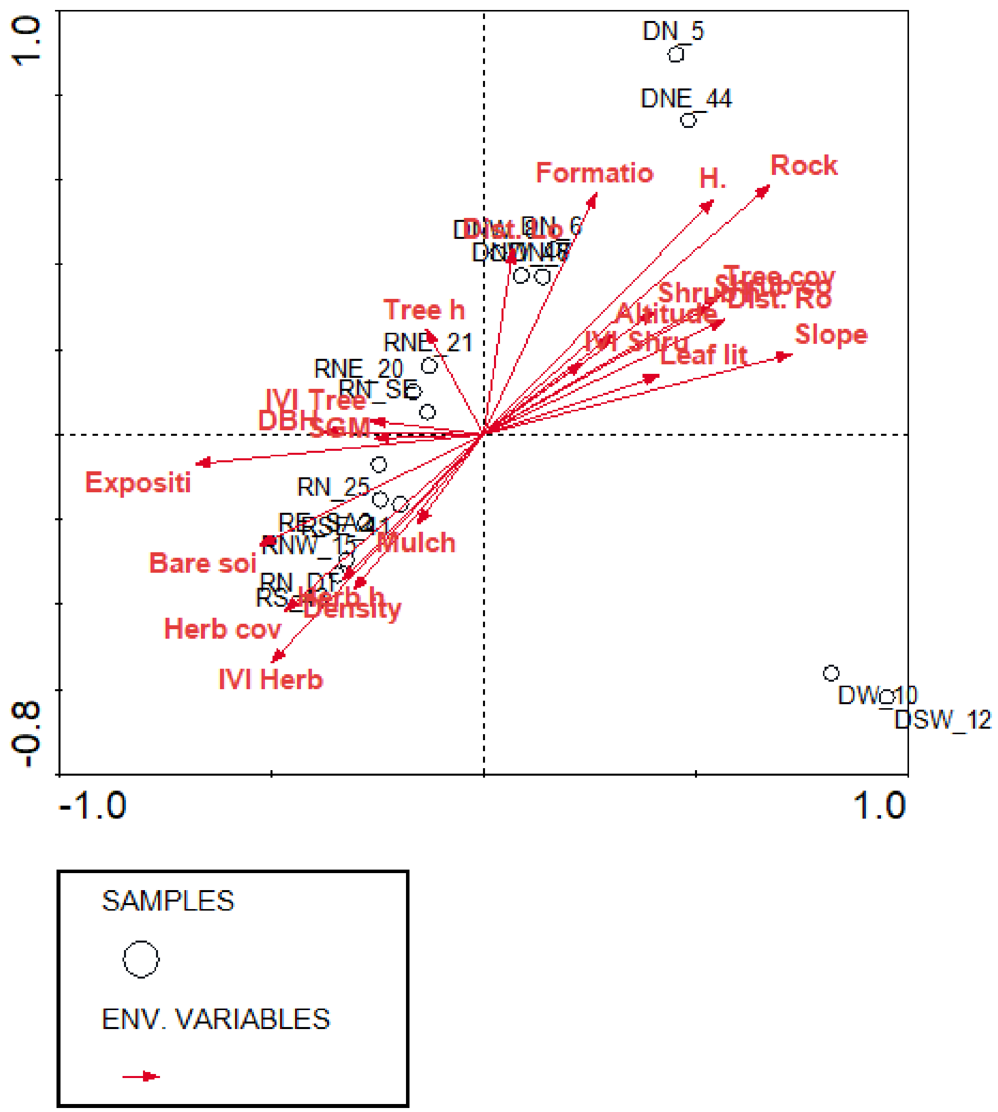

Figure III-13 Samples correlation to environmental parameters

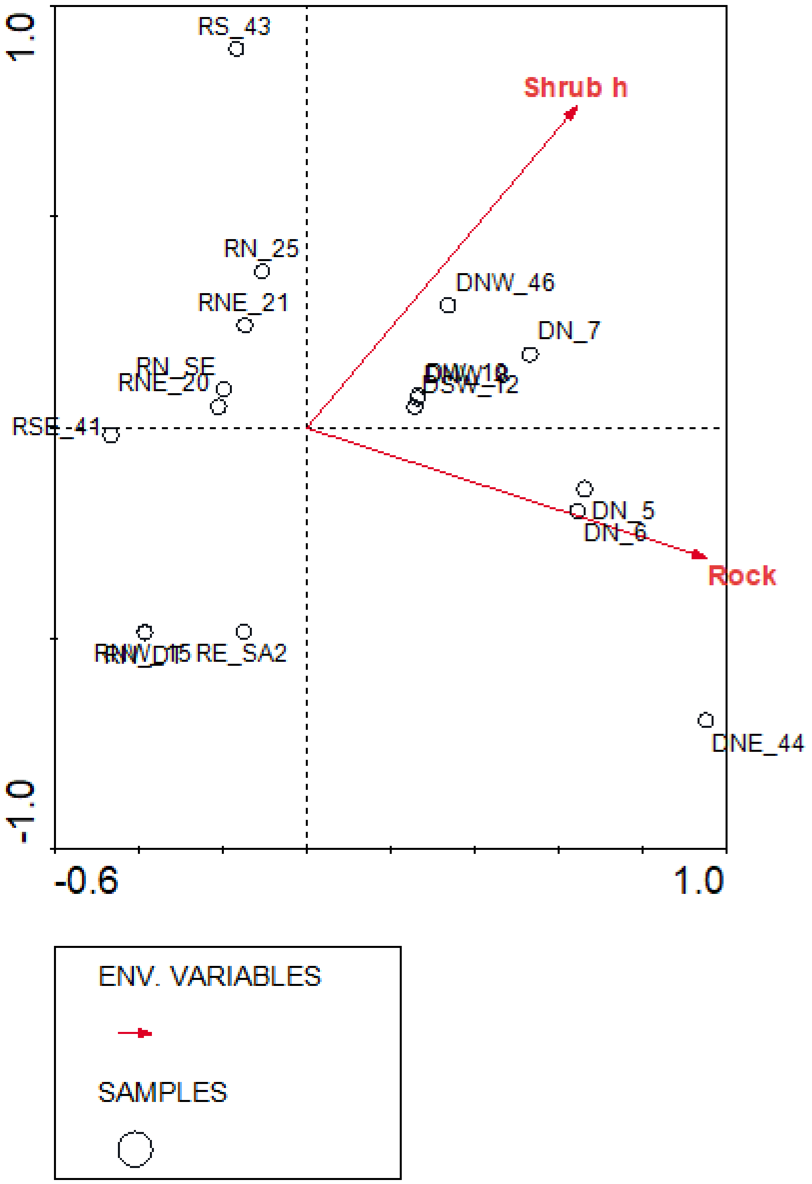

Figure III-14 Samples correlation to statistically significant variables.

Figure III.13 shows that the recharge sites are grouped in quadrants 1 and 4, while the discharge sites are located in quadrants 2 and 3.

In Figure III.14, this arrangement persists; however, the discharge sites DNW_46, DN_7, DNW_8, DW_10, and DSW_12 are shown to correlate with the height of the shrub layer. Additionally, the discharge sites DN_5, DN_6, and DNE_44 are associated with the percentage of rock present at the sampling sites.

To perform the hierarchical classification of the sites and identify indicator species for the different groups, the TWINSPAN tool in the PCORD software was used. A diagram was created with the obtained data, including the indicator species and the eigenvalues of each division. The groupings were recorded to analyze their characteristics.

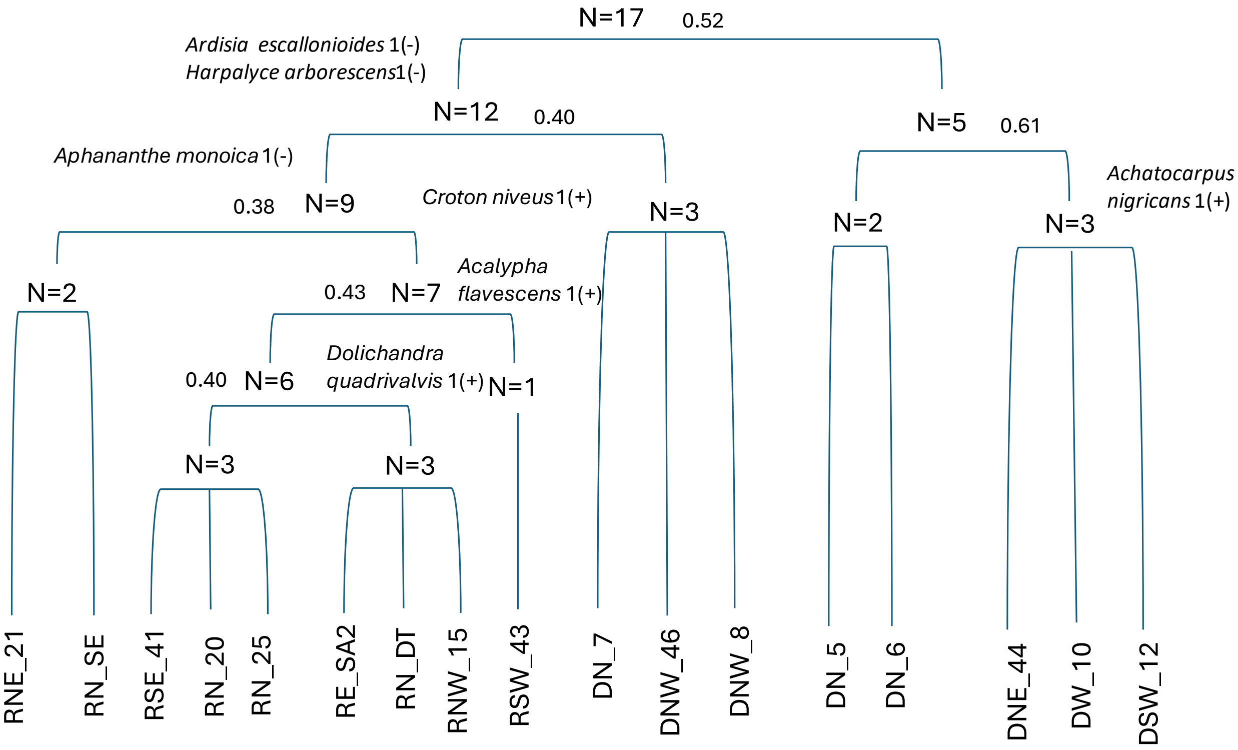

Figure III-15 TWINSPAN of the study site. The diagram shows the indicator species for each division and its eigenvalue.

Seven groups were created based on TWINSPAN divisions. The first four groups, from left to right, comprise the recharge sites, while the remaining three groups include the discharge sites.

III.4. Discussion

The descriptive analysis showed that the average abundance of individuals was higher in the recharge zones (M=239.8) compared to the discharge zones (M=149.8). These differences were statistically significant according to the analysis of variance (F(1,15)=21.23, $p<0.001$). This suggests that environmental conditions in the recharge zones favor greater individual abundance due to the presence of medium and low tropical forests with denser vegetation. In contrast, discharge zones include ecotones of low tropical forests, riparian vegetation, and gallery forests, which typically have less dense vegetation (Miranda & Hernández, 1963; Rzedowski, 1965; Puig, 1991).

Abundance also varies by stratum. In discharge zones, the herbaceous stratum tends to be more abundant due to the presence of clearings and the availability of water from springs and streams. In recharge zones, the canopy is denser, as there is greater coverage of the arboreal stratum, which is reflected in a lower abundance of individuals in the herbaceous stratum.

Parameters for assessing Forest site quality

In discharge zones, individuals exhibit greater heights and diameters, favored by the constant water flow from springs and streams. Water is a critical environmental factor for plant growth, as its availability directly influences photosynthesis through its necessity in the biochemical photosynthetic processes and indirectly through its impact on the opening and closing of leaf stomata (Mooney, 1986).

The primary factor influencing tree growth is water stress (Barnes *et al.*, 1997). Thus, soil water availability plays a key role in the productivity of many species.

In recharge zones, most sites exhibit an inverted J-shaped distribution, where the highest frequency of individuals is found in the lower diameter and height classes. This distribution is common in tropical forests and can also be interpreted as a successional stage of vegetation, with most individuals in a juvenile state (Gómez & Vázquez, 1981; Gentry, 1982; Vázquez & Orozco, 1993). Since diameter information alone cannot determine whether these are natural tropical forest formations or successional states, additional information on species composition and environmental parameters at the site will be considered.

The only site that deviated from this pattern was RE_SA2, where the height distribution follows a bell-shaped curve, with the highest frequency of individuals in the intermediate height classes. This distribution indicates a deficient regeneration rate, which is characteristic of heliophilous species in the early stages of secondary succession (Rollet, 1974). During the succession process, pioneer species develop and form a dense canopy that limits the amount of light reaching the ground, preventing the regeneration of heliophilous species (Levy, 2000; Temgoua *et al.*, 2020). Therefore, this site may be one of the most recently impacted among the recharge sites.

In discharge zones, all sites show an inverted J-shaped distribution for diameter at breast height (DBH). Regarding height distribution:

Sites DNW_8, DN_6, DSW_12, and DN_7 show the highest frequency of individuals in the lowest height class, indicating a prevalence of juvenile individuals.

Sites DNW_46, DW_10, and DN_5 display the highest frequency in the intermediate classes, suggesting more established vegetation with less renewal.

Site DNE_44 contains all individuals in the intermediate class, potentially indicating unique conditions: vegetation regeneration from a single event (e.g., mass logging, fire, or pest outbreak), intraspecific competition homogenizing forest composition, or anthropogenic disturbance favoring certain species (Oliver & Larson, 1996; Smith *et al.*, 1997; Kimmins, 2004; FAO, 2010).

Group classification and distribution

Using the classification data provided by TWINSPAN, seven vegetation groupings were identified in the Ciénega de Tamasopo (Figure III.16):

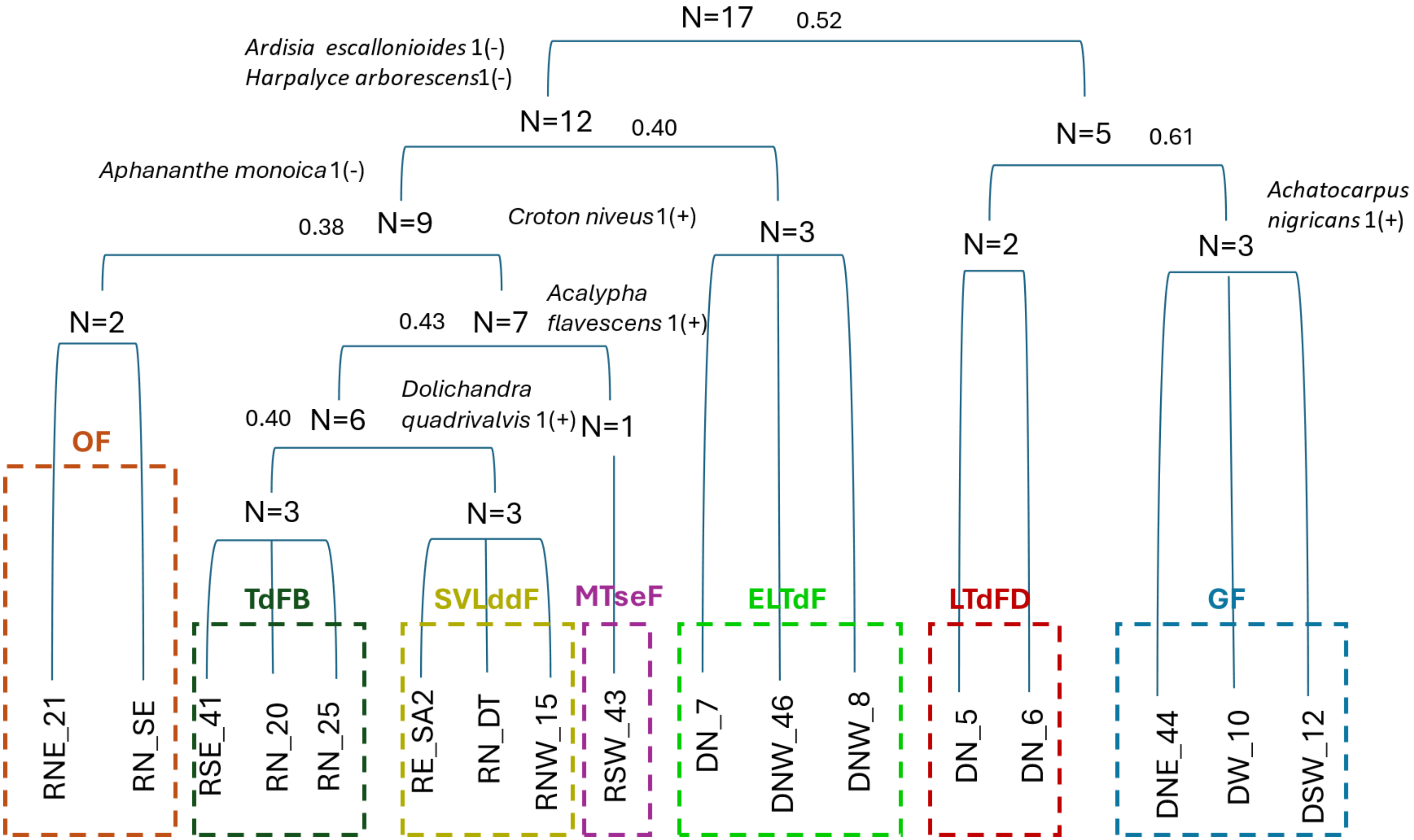

Figure III-16 TWINSPAN Groups

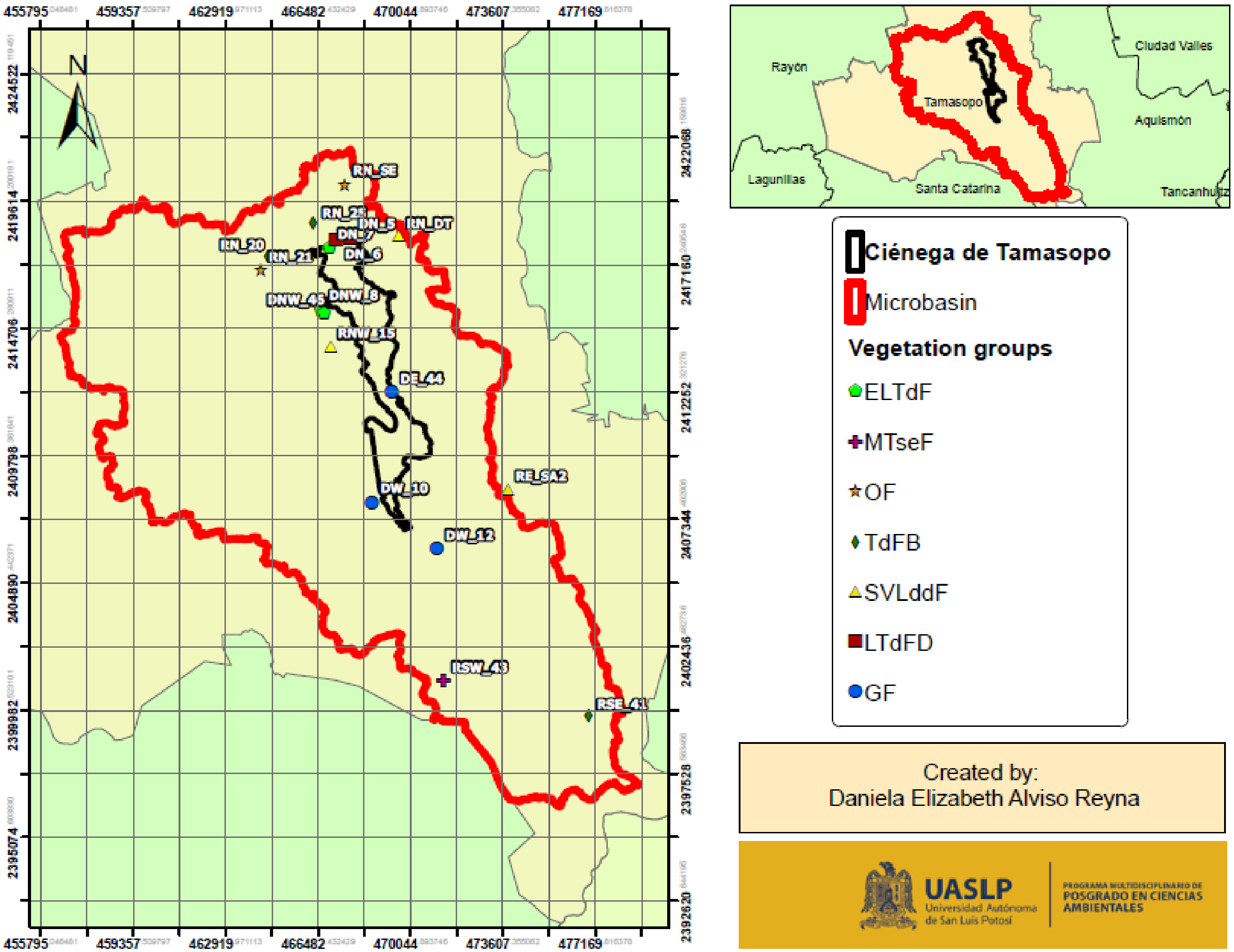

Figure III-17 Ubication of each vegetation group in Ciénega de Tamasopo microbasin.

Oak Forest (OF): This grouping includes sites RNE_21 and RN_SE, located in the northern and northeastern parts of the Ciénega. Characteristic species in these sites include associations of *Quercus polymorpha* and *Diospyros conzattii* (RNE_21) as well as *Quercus xalapensis* and *Aphananthe monoica* (RN_SE). The herbaceous layer features *Hamelia patens*, *Syngonium podophyllum*, and *Ardisia escallonioides*. These species are associated with humid environments, facilitated by the altitude (820 m) at RN_SE and the doline formation at RNE_21.

Tropical Deciduous Forest with *Bursera* Assemblages (TdFB): This group includes sites RN_25, RSE_41, and RNE_20, located at altitudes between 340 and 550 m. These sites feature *Bursera simaruba* stands. According to Puig (1991), species such as *Ocotea tampicensis*, *Casearia laetioides*, *Annona globiflora*, and *Lysiloma divaricatum* are prominent in this group, which is characterized by warm and humid conditions.

Secondary Vegetation of Low Dry Deciduous Forest (SVLddF): This group comprises sites RE_SA2, RN_DT, and RNW_15, which are among the closest to roads and populated areas (average distance to settlements: 1.9 km; to roads: 0.63 km). The indicator species is *Dolichandra quadrivalvis*, a liana typical of tropical forests. Other notable species include *Ocotea tampicensis*, *Lysiloma divaricatum*, *Cardiospermum halicacabum*, *Celtis pallida*, *Pristimera celastroides*, and *Randia laetevirens*, associated with drier conditions. Additionally, species such as *Sabal mexicana*, *Annona globiflora*, and *Croton niveus* indicate secondary vegetation.

Medium Tropical Sub evergreen Forest (MTseF): This grouping includes only site RS_43. The indicator species for this group is *Acalypha flavescens*. Although limited information is available for this species, the *Acalypha* genus is typical of tropical areas. Other notable species in this site include *Pseuderanthemum alatum* in the herbaceous layer, *Ardisia escallonioides* in the shrub layer, and *Brosimum alicastrum* and *Aphananthe monoica* in the tree layer. These species are characteristic of subperennial medium forests (Puig, 1991).

Recharge zones are concentrated in these four groupings, associated with tropical forests and their derivatives. Discharge zones fall into the following three groups:

Ecotone of Low Tropical Deciduous Forest (ELTdF): This group includes sites DN_7, DNW_46, and DNW_8, located in the northern and northwestern parts of the Ciénega de Tamasopo. Characteristic species include tropical forest representatives such as *Bursera simaruba*, *Brosimum alicastrum*, *Piper amalago*, and *Guazuma ulmifolia*. However, species such as *Thelypteris puberula* and *Pleuranthodendron lindenii*, indicative of gallery forests, also appear.

Low Tropical Deciduous Forest with Disturbance (LTdFD): This group includes sites DN_5 and DN_6, located near the settlement of Cabezas. While species typical of tropical forests are present, notable additions include *Carica papaya*, *Citrus x aurantiifolia*, *Mangifera indica*, and *Parmentiera aculeata*. These species, either cultivated for human consumption or accessible to livestock, indicate anthropogenic pressure.

Gallery Forest (GF): This group includes sites DNE_44, DW_10, and DSW_12, situated on vertisol soils. The indicator species is *Achatocarpus nigricans*, characteristic of riparian vegetation. Other species, such as *Hydrocotyle umbellata*, *Casearia aculeata*, *Inga vera*, *Bidens pilosa*, *Ceiba pentandra*, and *Phitecellobium dulce*, are typical of riparian and gallery forest vegetation. Evidence of disturbance is suggested by the presence of *Parmentiera aculeata* and *Vachellia cornigera*.

Once the groups were established, a principal component analysis (PCA) was performed (Figure III.18 & III.19). Each vegetation group was highlighted, and a biplot was generated using the environmental parameter matrix.

The principal component analysis (PCA) provided insights into the environmental parameters influencing the differentiation of vegetation groups in the Ciénega de Tamasopo. Axes 1 and 2 explained 64.26% and 13.49% of the total variance, respectively.

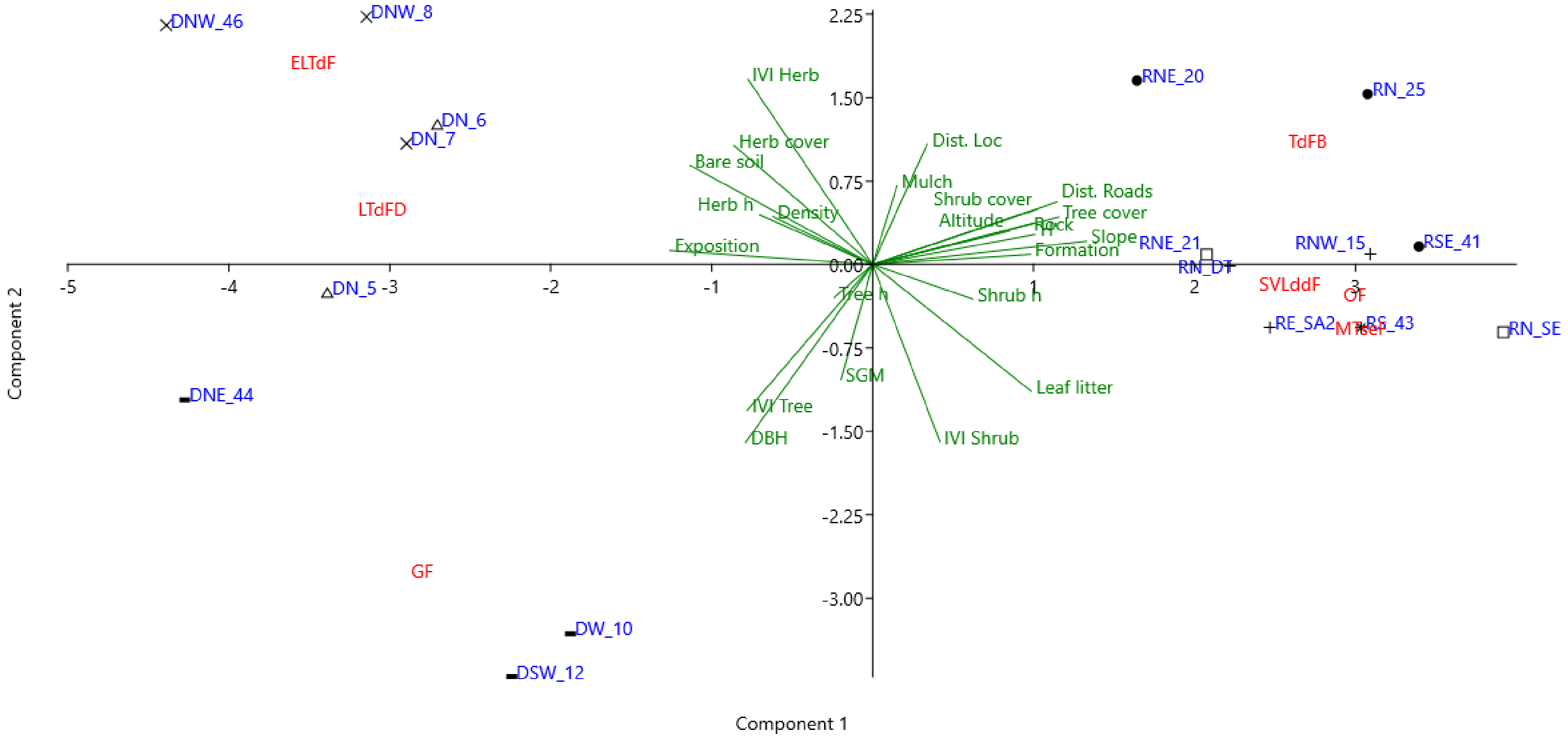

Figure III-18 Principal component analysis representing components 1 and 2.

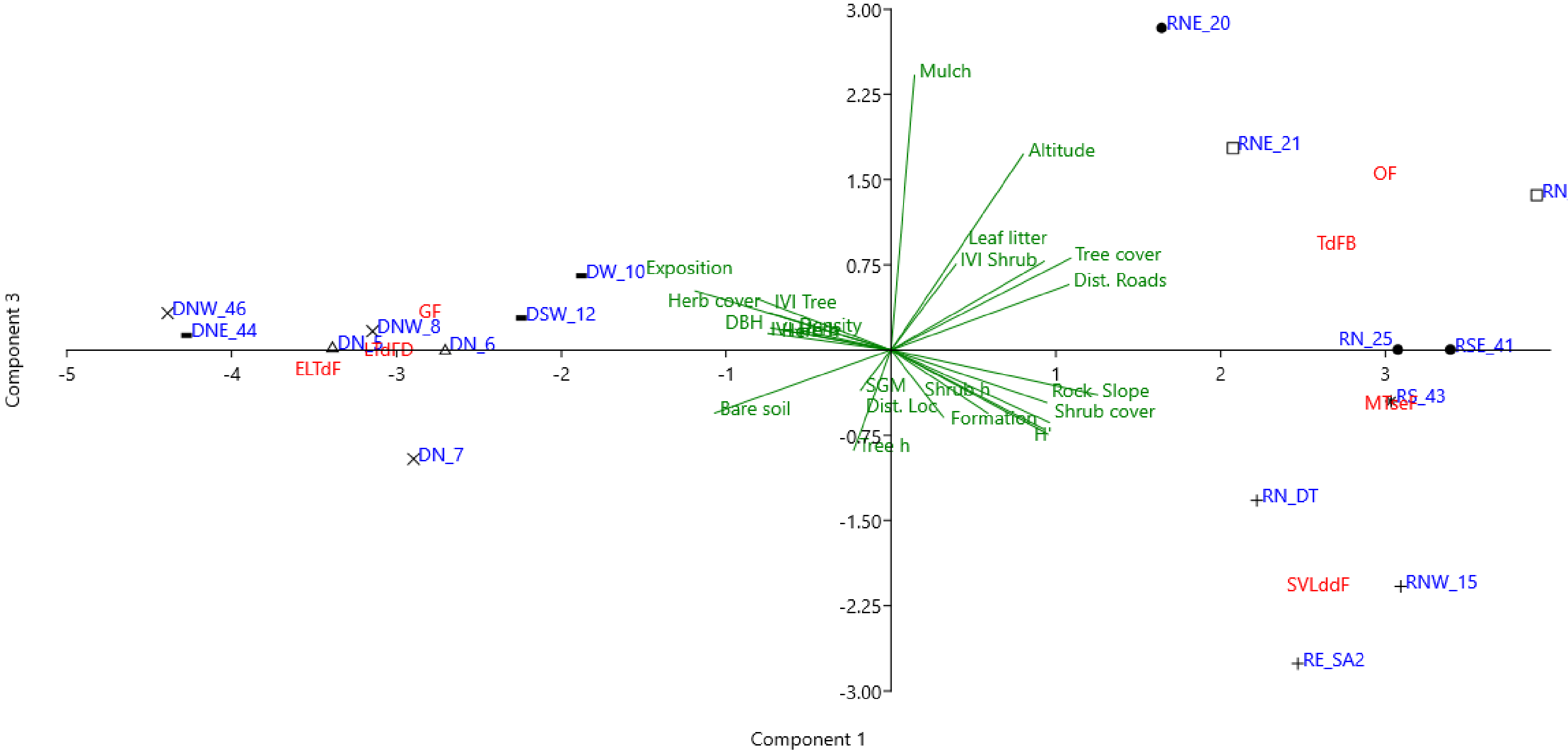

Figure III-19 Principal components analysis representing components 1 and 3.

Axis 1 was primarily correlated with slope, tree cover, distance to roads, shrub cover, and Shannon diversity index (H'), reflecting a gradient associated with structural vegetation attributes and diversity, typical of water recharge zones. In contrast, Axis 2 was associated with herbaceous importance value index (IVI Herb), distance to localities, herbaceous cover, bare soil, and mulch, indicating a gradient influenced by herbaceous dominance and anthropogenic disturbance, characteristic of discharge zones. These axes highlight the contrasting ecological dynamics between recharge and discharge areas, with recharge zones showing higher diversity and arboreal dominance, and discharge zones exhibiting greater herbaceous prevalence and human impact.

There is also an altitudinal gradient in which discharge zones are located at lower elevations than recharge zones. This creates a temperature gradient, where lower areas are warmer and support tropical vegetation, while higher elevations are cooler and favor the presence of oak forests or cloud forest ecotones. Additionally, exposure plays an important role, as north-facing slopes tend to be more humid than south-facing ones, allowing some recharge sites to exhibit a vegetation composition similar to that of discharge zones.

III.5. Conclusion

The vegetation of the Ciénega de Tamasopo is a relatively unexplored but highly significant topic due to the land-use changes caused by agricultural and livestock activities in the area. Through this research, it was possible to determine the composition of recharge and discharge sites in the region, as well as their main characteristics. Seven groupings were classified: four associated with recharge sites and three with discharge sites, with their indicator species identified.

Using the distributions of diameter and height classes, the state of each site was evaluated and complemented with floristic composition to determine whether the vegetation was primary, secondary, or showed signs of disturbance.

Multivariate methods allowed for the management of large amounts of data, including species abundance and environmental parameters, enabling the identification of similarities among sites and their classification and grouping based on these characteristics.

Overall, it was determined that recharge zones have greater species abundance and higher floristic diversity. The tree layer contains the largest number of individuals in these sites. Vegetation in these zones primarily corresponds to oak forests, medium and low tropical forests, and their derivative vegetation types.

In discharge zones, species abundance is lower, but the distribution of individuals is concentrated in larger diameter and height classes, a pattern facilitated by water availability. The herbaceous layer contains the most abundant individuals, characteristic of riparian vegetation. Vegetation in these zones includes secondary lowland deciduous forest, ecotonal vegetation, and gallery forests.

The information obtained will be complemented with other studies within the project "Evaluation of the process of eutrophication and environmental alteration that affects the RAMSAR site Ciénega de Tamasopo (SLP)" with the aim of developing a groundwater flow system model in a karstic landscape.

III.6. References

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IV. Chapter IV. General conclusions

This research was based on three specific objectives, from which the general conclusions will be derived.

To elaborate a floristic list of the water recharge and discharge zones of the Ciénega de Tamasopo wetland.

In accordance with this objective, it was possible not only to identify the floristic composition of the recharge and discharge zones but also to complement this with information on other species present in the microbasin of the Ciénega de Tamasopo.

The floristic composition of the Ciénega microbasin matches that reported in sites with similar climatic and geological conditions, as well as the composition associated with the vegetation types present in the area: tropical forest (low subdeciduous forest, medium subevergreen forest), oak forest, and gallery forest.

Recharge zones exhibited greater species richness compared to discharge zones, as well as better conservation status, given that they hosted fewer disturbance indicator species. In contrast, discharge zones showed a stronger association with human impact, as evidenced by the presence of ornamental, cultivated, or invasive species. On the other hand, disturbance in recharge zones was more related to secondary succession processes and livestock presence, favoring the existence of heliophilous species and those adapted to herbivory.

Nineteen endemic species were found, mostly in recharge zones, mainly due to the variety of ecosystems generated by the terrain, the altitudinal gradient, and the microclimatic factors associated with the dolines. Likewise, most of the species with some risk status were found in recharge zones, reaffirming the importance of conservation in these areas.

To analyze the community diversity of the vegetation in the water recharge and discharge zones of the Ciénega de Tamasopo wetland.

A significant difference in diversity was observed among the sampled sites, with higher values in recharge zones compared to discharge zones. The Margalef and SHE indices revealed the influence of species richness and evenness on overall diversity. In discharge zones, abundance was concentrated in a few herbaceous species, leading to a higher dominance of these taxa.

The Jaccard beta diversity index indicated similarity between the sites RSE_41 and RE_SA2, which, although not grouped together by TWINSPAN, share common species such as *Ocotea tampicensis* and *Justicia brandegeeana*. Both TWINSPAN and the Jaccard index assess site similarity based on presence-absence data; however, each provides specific insights into community dynamics. The Jaccard index helps identify species turnover patterns and shared species, while TWINSPAN focuses on indicator species that distinguish each community. Both analyses revealed a low similarity between discharge and recharge sites. This information is consistent with the findings in Chapter 3, where moisture, altitude, and temperature gradients distinguish recharge zones from discharge zones, and vegetation in discharge zones is predominantly riparian and associated with gallery forests, while vegetation in recharge zones is characteristic of tropical forests.

To characterize and analyze the vegetation structure based on the water recharge and discharge zones of the Ciénega de Tamasopo wetland.

The use of statistical analyses and multivariate methods enabled the characterization of recharge and discharge zones, while parameters such as height and diameter distribution, along with knowledge of the composition of disturbance-indicator species, allowed for the assessment of site conditions.

In general, factors such as exposure, altitude, humidity, distance to settlements, and specific conditions associated with dolines and water bodies determine the composition and structure of the recharge and discharge zones in the microbasin.

In conclusion, summarizing the findings from each chapter, the vegetation structure in the recharge and discharge zones of the Ciénega de Tamasopo microbasin is as follows:

- <u>Recharge Zones</u>: Recharge areas exhibited higher species richness, greater floristic diversity, and a higher number of endemic species as well as those in a risk category. The arboreal stratum had the highest frequency of individuals, with diameter at breast height (DBH) and height distributions showing an inverted J pattern typical of tropical forests. Vegetation in these zones is represented by oak forests, tropical deciduous forests, and associated vegetation. Representative species include *Brosimum alicastrum*, *Bursera simaruba*, *Ocotea tampicensis*, *Harpalyce arborescens*, and *Esenbeckia berlandieri*. The difference in altitude between these zones, along with the exposure gradient, promotes a greater variety of vegetation types compared to the discharge zones. Additionally, the difficulty of human access in some areas contributes to better ecosystem conservation. However, the presence of disturbance-indicator species highlights the impact of livestock in certain areas.

- <u>Discharge Zones:</u> Discharge areas exhibited lower species richness, reduced floristic diversity, and fewer endemic species or those in a risk category compared to recharge zones. The herbaceous stratum had the highest frequency of individuals. In the arboreal stratum, DBH and height distributions were skewed towards intermediate classes, indicating more robust trees than those in recharge zones. This reflects the role of water availability in tree development in these areas. Vegetation in these zones corresponds to gallery forests and ecotonal areas with tropical deciduous forests. Representative species include *Inga vera*, *Hydrocotyle umbellata*, *Ceiba pentandra*, *Tabebuia rosea*, *Hamelia patens*, and *Syngonium podophyllum*, among others. In these zones, the parameters that differentiate plant communities are primarily related to the degree of disturbance. However, hydrogeochemical conditions could provide valuable insights into the groupings.

Finally, based on the information obtained in this study, the following research areas are proposed:

- What is the floristic composition of aquatic plants in the Ciénega, and how do they relate to the anthropogenic impacts present in the site?
- What is the structure and composition of secondary vegetation associated with forest fires, and how can this information contribute to ecosystem conservation?
- Is there a disturbance gradient of vegetation communities in relation to the distance from population centers in the Ciénega?