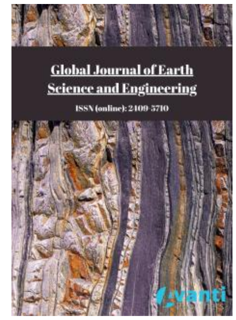
Global Journal of Earth Science and Engineering, 2025, 66-90

Published by Avanti Publishers

Global Journal of Earth Science and Engineering

ISSN (online): 2409-5710



Hydrogeochemical Characterization and Therapeutic Zoning of Low-Enthalpy Geothermal Hot Springs in Mexico: Implications for Wellness Tourism and Sustainable Resource Management

María J. Puy-Alquiza[1,*], Miren Y.M. Puy[2,*], Ma. D.C. Salazar-Hernández[3], Rosa Maria Prol-Ledesma[4] and Velia Y.O. Zubia[5]

[1]Department of Mining, Metallurgy and Geology, Division of Engineering, University of Guanajuato, Guanajuato 36000, Mexico; [2]Department of Agro-Genomics, National School of Higher Studies, León Unit, National Autonomous University of Mexico, Guanajuato 36969, Mexico; [3]UPIGG-IPN, Av. Mineral de Valenciana 200, Industrial Puerto Interior, Silao de la Victoria 36275, Mexico; [4]Institute of Geophysics, National Autonomous University of Mexico, Circuito de la Investigación Científica s/n, Ciudad Universitaria, Coyoacán, Ciudad de México 04150, Mexico; [5]Department of Architecture, Division of Architecture, Art and Design, University of Guanajuato, Guanajuato 36000, Mexico

ARTICLE INFO

Article Type: Research Article
Academic Editor: Sid Ali Ouadfeul
Keywords:
Wellness tourism
Therapeutic zoning
Geothermal heritage
Thermal mineral waters
Hydrogeochemical analysis
Low-enthalpy geothermal systems
Timeline:
Received: October 31, 2025
Accepted: December 05, 2025
Published: December 10, 2025

Citation: Puy-Alquiza MJ, Puy MYM, Salazar-Hernández MDC, Prol-Ledesma RM, Zubia VYO. Hydrogeochemical characterization and therapeutic zoning of low-enthalpy geothermal hot springs in Mexico: Implications for wellness tourism and sustainable resource management. Glob J Earth Sci Eng. 2025; 12: 66-90.

DOI: https://doi.org/10.15377/2409-5710.2025.12.5

*Corresponding Author
Email: mj.puy@ugto.mx

ABSTRACT

This study aims to characterize the geochemical composition of low-enthalpy thermal waters in Mexico and to evaluate their therapeutic potential and sustainable applications, establishing a scientific and territorial framework for integrated resource management. Data were compiled from hot springs distributed across 21 Mexican states, covering the period from 1975 to 2024. The analysis integrates hydrogeochemical databases from academic and governmental sources, complemented by technical reports, satellite imagery, and cartographic tools (Google Maps and Canvas X GIS 11). A total of 21 thematic maps were developed to illustrate the spatial distribution of thermal mineral water types (sulfurous, ferruginous, bicarbonate, calcium, and magnesium), temperature ranges, functional classifications, and levels of tourism development.

The results indicate that minerals such as sulfur, iron, calcium, and bicarbonate contribute to well-documented therapeutic effects related to dermatological, musculoskeletal, digestive, and respiratory treatments. Comparative analysis with previous hydrothermal studies confirms Mexico's exceptional geothermal diversity and rich cultural heritage, while also highlighting persistent challenges related to conservation, regulation, and sustainable resource management. Overall, this research highlights Mexican thermal waters as a valuable natural and cultural geothermal heritage and advocates their sustainable use through thermal routes, therapeutic centers, and territorial planning strategies that integrate human health, environmental conservation, and community participation. The findings provide a solid scientific foundation for future geothermal policy development and wellness-oriented georesource management.

1. Introduction

Low-enthalpy geothermal systems represent one of the most accessible and sustainable expressions of Earth's internal energy [1-3]. Across Mexico, numerous low-temperature thermal springs emerge from diverse geological environments, including volcanic, sedimentary, and tectonic domains [4-6]. These systems provide valuable insights into subsurface hydrothermal circulation, water–rock interaction, and geothermal potential, while also offering direct applications for balneotherapy and wellness tourism [7-9].

Despite their abundance, Mexican low-enthalpy hot springs have not been systematically characterized at a national scale, and their geochemical variability, therapeutic potential, and sustainable use remain poorly documented [5,6,10]. The study of low-enthalpy geothermal waters contributes not only to the understanding of geothermal processes but also to the management of natural resources that integrate geological, hydrological, and socio-environmental components [2, 3, 11].

These thermal systems are generally formed by the percolation of meteoric waters through faulted and fractured rocks, where they undergo heating through conductive and convective processes at shallow crustal levels [1, 4, 12]. The chemical composition of thermal waters, typically rich in bicarbonate, chloride, sulfate, and minor trace elements, reflects the lithological nature of the aquifers and the depth of circulation [6, 12, 13]. Such hydrogeochemical signatures are essential for establishing the origin, classification, and potential uses of geothermal fluids [3, 6, 14].

In addition to their geological importance, Mexican thermal springs have long been used for therapeutic and recreational purposes, forming part of the country's cultural and historical heritage [15-17]. The traditional use of these waters for medical treatment, rehabilitation, and relaxation supports their inclusion in the growing field of wellness tourism, which seeks to integrate health, environment, and sustainable development [8, 9, 18]. The potential of geothermal waters as natural therapeutic resources is determined by temperature, mineral content, and the presence of trace bioactive compounds, which collectively define their balneological classification and possible health benefits [7, 9, 19].

Recent studies in Europe and Asia have demonstrated that the valorization of low-enthalpy geothermal systems can promote regional economic diversification, sustainable tourism, and environmental conservation [8, 18, 20]. However, in Mexico, most research has focused on high-enthalpy geothermal fields for electricity generation, leaving the low-enthalpy segment underexplored [5, 6, 10]. Therefore, the systematic evaluation of low-temperature geothermal waters is essential for understanding their distribution, geochemical variability, and practical applications [3, 6].

The aim of this study is to characterize the geochemical composition, spatial distribution, and therapeutic potential of low-enthalpy hot springs across Mexico. By integrating hydrogeochemical data, physiographic zoning, and thermal classifications, this work proposes a therapeutic and geochemical zonation model that highlights the relevance of these systems as sustainable natural resources. The study also explores their potential role in wellness tourism and sustainable regional development, bridging geoscience, environmental management, and health-oriented applications within the context of Mexico's geothermal diversity [6, 8, 9].

2. Methodology

This research was developed through an interdisciplinary approach that integrated bibliographic, geochemical, and cartographic methods for the characterization of low-enthalpy thermal springs in Mexico [1, 3]. Data compiled between 1975 and 2024 from 21 Mexican states were obtained from academic and governmental hydrogeochemical databases, as well as from technical and research reports [4, 6].

All information was systematically processed using georeferencing tools (Google Maps) and cartographic software (Canvas X GIS 11) to generate 21 thematic maps illustrating the spatial distribution, mineralogical composition, temperature ranges, and tourism development of the thermal springs [7, 9].

The geochemical classification of the thermal waters was based on the predominance of ionic composition, identifying the main mineromedicinal types: sulfurous, ferruginous, bicarbonate, calcium, and magnesium waters [4, 10, 11]. Temperature-based categorization followed standard geothermal criteria, classifying the springs as hypothermal (<35 °C), mesothermal (35–45 °C), or hyperthermal (>45 °C) [1, 3, 12], according to their geothermal energy level and subsurface thermal regime. For clarity, hypothermal, mesothermal, and hyperthermal springs broadly correspond to cold, warm, and hot springs, respectively, based on their temperature ranges. The degree of tourism development was assessed through the presence or absence of spa infrastructure, considering both current use and potential for future exploitation [13, 14]. Based on these variables, a preliminary therapeutic and regional zoning was proposed, dividing the country into five macro regions: North, Northeast, West, East, and South [6, 9, 15].

The choice of this integrated methodology responds to the need to consolidate heterogeneous and dispersed hydrothermal data collected over several decades into a unified national framework [2, 5, 6]. This interdisciplinary strategy, combining hydrogeochemical analysis, cartographic processing, and documentary review, was considered more appropriate than strictly hydrogeological or ethnographic approaches, as it establishes direct relationships between chemical characteristics and territorial, historical, and cultural variables [3, 9, 14]. Consequently, it provides a solid scientific and spatial foundation for understanding the diversity, therapeutic potential, and sustainable management of Mexico’s low-enthalpy thermal waters [6, 15].

2.1. Study Area

The low-enthalpy thermal springs analyzed in this study are located across 21 states of the Mexican Republic, primarily within regions exhibiting active or extinct volcanic activity and major fault zones that facilitate the ascent of geothermal fluids (Fig. **1**) [1-4]. These hydrothermal manifestations occur in both rural and peri-urban environments, where they have been historically used for therapeutic, recreational, and ritual purposes [5-7].

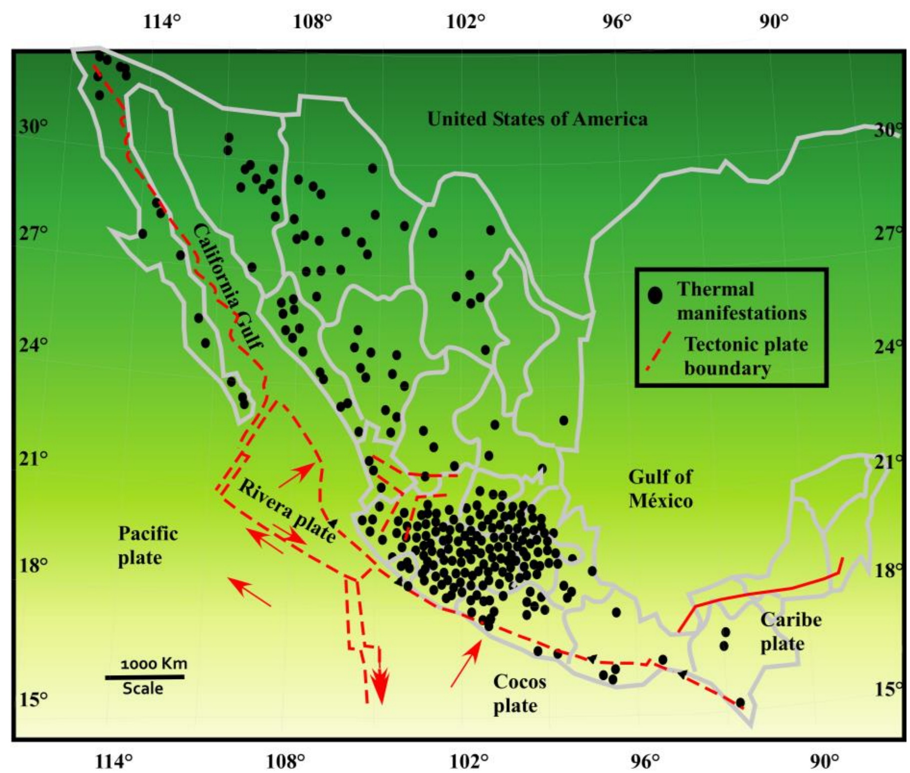


Figure 1: Map of Mexico that includes the thermal springs.

The study area holds local and national significance for several reasons. (1) It represents a unique hydrogeochemical diversity, including sulfurous, ferruginous, bicarbonate, calcium, and magnesium waters, traditionally employed in health and wellness practices [3, 8, 9]. (2) It constitutes a strategic natural and cultural resource, whose sustainable exploitation could generate economic benefits through wellness and health tourism, while simultaneously strengthening cultural identity associated with the ancestral use of thermal waters [6, 7, 10].

Many of these geothermal sites are located in environmentally fragile regions, where the sustainable management of thermal waters is essential to preserve hydrothermal heritage and enhance the climate resilience of local communities [11, 12].

Overall, the spatial extent and geological setting of these systems highlight the close interaction between geothermal processes, cultural heritage, and sustainable resource management in Mexico's diverse geotectonic landscape [4, 6, 13].

2.2. Data Collection and Systematization

An extensive review of scientific literature, technical reports, and hydrogeochemical databases produced between 1975 and 2024 was conducted to compile and systematize information on Mexico's low-enthalpy thermal springs [21-29]. Data were gathered from both academic and governmental institutions, encompassing studies published over nearly five decades of geothermal research [30-35].

Key sources included seminal and contemporary works on Mexican geothermal resources and thermal manifestations, covering national geothermal potential, hydrogeochemical characterization, and low-enthalpy systems [36]. These references provided the historical, geological, and analytical basis for identifying thermal spring locations, physicochemical properties, and reported uses across different regions of the country.

The following hydrogeochemical and physical parameters were analyzed: (1) temperature (°C); (2) pH; (3) electrical conductivity (μS/cm); (4) major ionic composition (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-); (5) type of hydrothermal manifestation (spring, geyser, or artesian well); and (6) reported therapeutic applications [7, 12, 13, 25].

These datasets were integrated into a structured geochemical database, enabling regional comparisons and the identification of associations between mineromedicinal water types and their potential therapeutic uses [6, 7, 25]. This standardized compilation provides a robust foundation for subsequent spatial, statistical, and interpretive analyses of geothermal resources across Mexico [5, 10, 34].

2.3. Georeferencing and Spatial Validation

To validate location data and facilitate spatial analysis, Google Maps and its satellite imagery functions were employed as tools for visual verification and geospatial positioning [21]. More than 1,306 thermal sites were reviewed to confirm geographical coordinates, site names, access conditions, and available historical or touristic references, based on previously published national geothermal inventories and technical compilations [6, 22].

This process ensured the accuracy and reliability of the spatial dataset, minimizing duplication and inconsistencies among sources from different periods [6, 21]. Verified coordinates were subsequently incorporated into the geospatial database for cartographic processing and thematic mapping [7, 21].

2.4. Cartographic Analysis

Cartographic processing was performed using Canvas X GIS 11, a specialized software for geospatial analysis. The methodological workflow included the following steps: (1) integration of vector layers (shapefiles) representing municipalities, state boundaries, and hydrographic regions, obtained from official national cartographic sources [21]; (2) superimposition of georeferenced points corresponding to thermal springs, combined with their respective geochemical and functional attributes derived from previously compiled geothermal inventories [6, 22]; and (3) development of 21 thematic maps illustrating the regional distribution of thermal springs, types of thermal mineral waters (bicarbonate, sulfurous, ferruginous, calcium, and magnesium types), temperature ranges (hypothermal, mesothermal, and hyperthermal), low-enthalpy geothermal potential, and predominant therapeutic applications [7, 10].

This integrative approach allowed for visual correlation between hydrogeochemical parameters and regional physiography, supporting both classification and territorial zoning of low-enthalpy geothermal systems across Mexico [5, 21].

2.5. Functional Classification and Therapeutic Zoning

Based on the compiled dataset, a functional classification of Mexican thermal waters was developed by grouping them according to their dominant chemical composition and principal therapeutic applications [6, 7, 12]. Complementarily, a preliminary therapeutic zoning was proposed, dividing the country into five macro regions North, Northeast, West, East, and South that share relatively homogeneous characteristics in terms of temperature, mineralogy, and tradition of use [4, 5, 10].

This zoning approach follows an integrative framework that combines geological, hydrogeochemical, historical, and administrative criteria [1, 5, 6]. From a structural standpoint, major tectonic provinces and their relationships with active or extinct volcanic systems were considered [4, 11]. Hydrochemically, common patterns were identified in the dominant ion concentrations and thermal ranges of the hot springs [12, 13].

In addition, cultural and socioeconomic variables were incorporated, including the ritual and ancestral use of thermal waters and the current level of tourism infrastructure, allowing the establishment of correlations between physicochemical factors, traditional therapeutic practices, and sustainable tourism potential [7, 8, 15-17].

To address the tourism and wellness dimensions, two key variables were included: (1) Tourism development level, defined through a mixed criterion that considered: (a) general indicators of regional tourism activity (infrastructure, connectivity, and complementary services); and (b) the existence, accessibility, and current use of thermal waters for recreational, medicinal, or wellness purposes [7-9, 10]. (2) Tourism potential, understood as a qualitative assessment of thermalism in each region, estimated based on: (a) the mineral diversity and therapeutic properties of the waters [12, 19]; (b) the historical and cultural significance of their use [15-17]; (c) opportunities to promote new health-oriented tourism activities [7, 8]; and (d) the level of community engagement in their management and preservation [8, 10].

The resulting functional classification and therapeutic zoning therefore reflect not only the geo-environmental and hydrochemical characteristics of Mexico's geothermal systems but also their cultural relevance and potential as sustainable resources for local development and specialized tourism [5, 7, 10].

Thematic maps were generated through the integration of georeferenced datasets validated with high-resolution satellite imagery (Google Maps) and processed using Canvas X GIS 11. For spatial analysis, vector layers from the National Institute of Statistics and Geography were incorporated, including state boundaries, municipal divisions, and hydrographic regions [21].

Thermal manifestations were organized into independent GIS layers based on variables such as temperature, chemical composition, and type of discharge (spring, geyser, or artesian well) [6, 12]. Subsequently, multivariable symbology and spatial analysis techniques (buffer zones and density-based clustering) were applied to identify regional patterns [5, 21]. Analytical cross-referencing between geochemical variables (pH, temperature, and major ions), tourism infrastructure level, and functional classification revealed clear relationships between chemical composition and reported therapeutic benefits, as well as correspondences between hydrothermal diversity and the degree of current tourism development [7, 9, 10].

3. Results

3.1. Cartographic Analysis and Thematic Mapping

To understand the spatial distribution, physicochemical properties, and therapeutic potential of Mexico's thermal springs, a series of 21 thematic maps was developed, integrating geochemical, geothermal, and balneological variables corresponding to springs located in 21 Mexican states [6, 12]. The information was systematized and processed through spatial analysis tools, primarily Canvas X GIS 11 and Google Maps, allowing for the visual representation of relationships among hydrothermal manifestations and geographic, tectonic, cultural, and tourism-related factors [21].

For analytical consistency, the thermal springs were grouped into five major geographic macro regions, defined according to tectonic, hydrogeological, and administrative criteria: North, Northeast, West, East, and South [4, 5, 10]. This functional zoning enabled the identification of regional patterns in spring density, temperature, and dominant chemical composition—sulfate, bicarbonate, chloride, ferruginous, calcium, and mixed types as well as their correspondence with traditional or clinical therapeutic uses, including dermatological, musculoskeletal, digestive, and respiratory applications [7, 9, 12]. Beyond visualization, the GIS-based integration of hydrogeochemical, thermal, and geological variables enabled the identification of spatial patterns that are not evident in isolated local studies. In particular, the national-scale analysis reveals systematic associations between dominant ionic composition, temperature ranges, tectonic setting, and physiographic regions. These relationships constitute an original analytical result derived from the spatial synthesis of heterogeneous datasets.

The generated thematic maps encompass the following categories: (1) general geographic distribution of identified thermal springs; (2) thermal classification based on temperature ranges (mesothermal <45 °C and hyperthermal >45 °C); (3) low-enthalpy geothermal potential, considering reservoirs below 150 °C; (4) thermal mineral water typologies according to dominant ionic composition; and (5) therapeutic associations linking water types with balneotherapy and hydrotherapy applications [1-3, 7, 10].

Additionally, regional maps were created to provide a more detailed spatial reading of representative zones within each macro region (Fig. **2**), based on previously established geological and geothermal frameworks [4-6]: Northern Region, including hydrothermal areas of the Sierra Madre Occidental and the Mexicali Basin (Baja California, Baja California Sur, Coahuila, Chihuahua, Durango, Nuevo León, and Sonora), characterized by sulfurous and bicarbonate waters [5, 19].

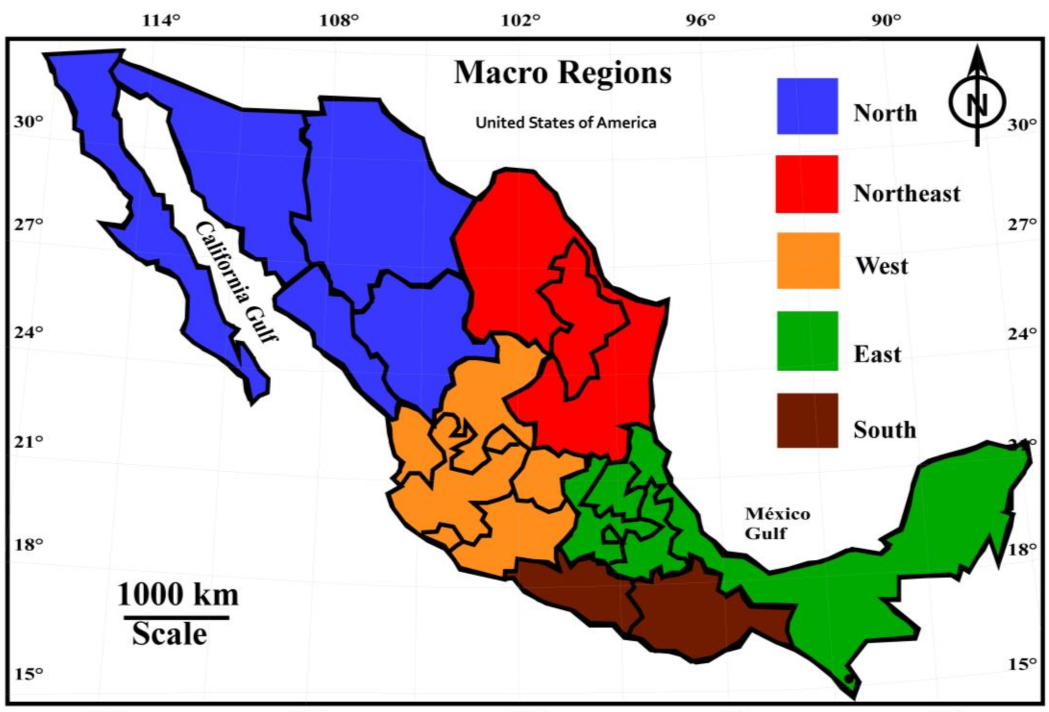


Figure 2: Geographic macro regions of thermal springs defined based on tectonic, hydrogeological, and administrative criteria: North Northeast, West, East, and South.

Northeastern Region, associated with the Trans-Mexican Volcanic Belt (Estado de México, Hidalgo, Puebla, and Querétaro), displaying high chemical diversity and a long history of therapeutic use [4, 6, 15].

Western Region, including thermal systems of the Bajío (Aguascalientes, Guanajuato) and volcanic provinces of Jalisco, Michoacán, and Nayarit, dominated by bicarbonate and chloride waters [10, 12].

Eastern Region, encompassing manifestations in Veracruz, Oaxaca, and parts of Puebla, showing a strong link between hydrothermal activity and indigenous cultural heritage [15-17].

Southern Region, including underexplored geothermal zones in Chiapas and Guerrero, exhibiting variable chemical compositions and high potential for sustainable thermal development [5, 19].

The multivariable cartographic representation not only identified areas with high hydrothermal density, but also allowed the establishment of regional typologies of therapeutic waters, revealing underutilized geothermal zones with favorable conditions for sustainable wellness tourism [7-10]. This spatial analysis provides a key tool for territorial planning, geothermal resource conservation, and the revaluation of Mexico's hydrothermal heritage as a driver of sustainable regional development [5, 21].

3.2. Regional Description of Thermal Springs and Tourism Potential

Based on the cartographic and geochemical analyses, five major geographical macro regions were identified, grouping the principal thermal manifestations across Mexico: North, Northeast, West, East, and South [4-6, 10]. This regionalization is analytically derived from the spatial clustering of temperature ranges, dominant hydrogeochemical signatures, and geological controls identified through GIS-based analysis, rather than being a purely descriptive division. This classification highlights regional hydrothermal and geochemical patterns, as well as differences in the degree of tourism development and therapeutic potential [7-9] (Table **1**).

Table 1: Regional description of Mexican thermal springs and their tourism potential.

Region	States Included	Geological Context	Predominant Chemical Type	Temperature Range (°C)	Therapeutic Applications	Tourism Development and Potential
North	Baja California, Baja California Sur, Coahuila, Chihuahua, Durango, Nuevo León, Sonora	Associated with deep fault systems and recent tectonic activity along the Sierra Madre Occidental; isolated volcanic zones	Sulfurous, chlorinated, and bicarbonate waters	35–70	Dermatological and respiratory treatments (acne, psoriasis, bronchitis)	Limited infrastructure; potential for thermal ecotourism and open-air wellness experiences in desert and mountain environments
Northeast	State of Mexico, Hidalgo, Puebla, Querétaro	Linked to the Trans-Mexican Volcanic Belt; zones of active faults and high geological permeability	Bicarbonate, sulfate, and ferruginous waters	30–75	Dermatological, rheumatic, and digestive therapies	High tourism development (spas, wellness centers, thermal routes); strong cultural and historical heritage
West	Aguascalientes, Guanajuato, Jalisco, Michoacán, Nayarit	Related to Tertiary volcanism and regional fault systems in the Bajío area	Bicarbonate-calcium and mixed waters	35–65	Hydrotherapy, rheumatology, and muscular relaxation	Growing tourism sector; integration with wine tourism, cultural routes, and rural wellness tourism
East	Veracruz, Oaxaca	Linked to subduction zones, ancient volcanic complexes, and deep faults	Ferruginous, sulfurous, and bicarbonate waters	35–60	Dermatological, respiratory, and metabolic therapies	Moderate development; high potential for community-based and alternative health tourism; strong biocultural heritage
South	Chiapas, Guerrero	Associated with volcanic complexes (Tacaná and Chichón) and geothermal gradients in mountainous zones	Bicarbonate and sulfurous waters	30–55	Respiratory and relaxation therapies	Low current development but high potential for eco-spiritual and regenerative tourism near natural and archaeological areas

3.2.1. Northern Region

This region encompasses Baja California, Baja California Sur, Coahuila, Chihuahua, Durango, Nuevo León, and Sonora (Figs. **3**-**9**). The thermal manifestations are primarily associated with deep fault systems and recent tectonic activity along the Sierra Madre Occidental, as well as with isolated volcanic zones [5, 19].

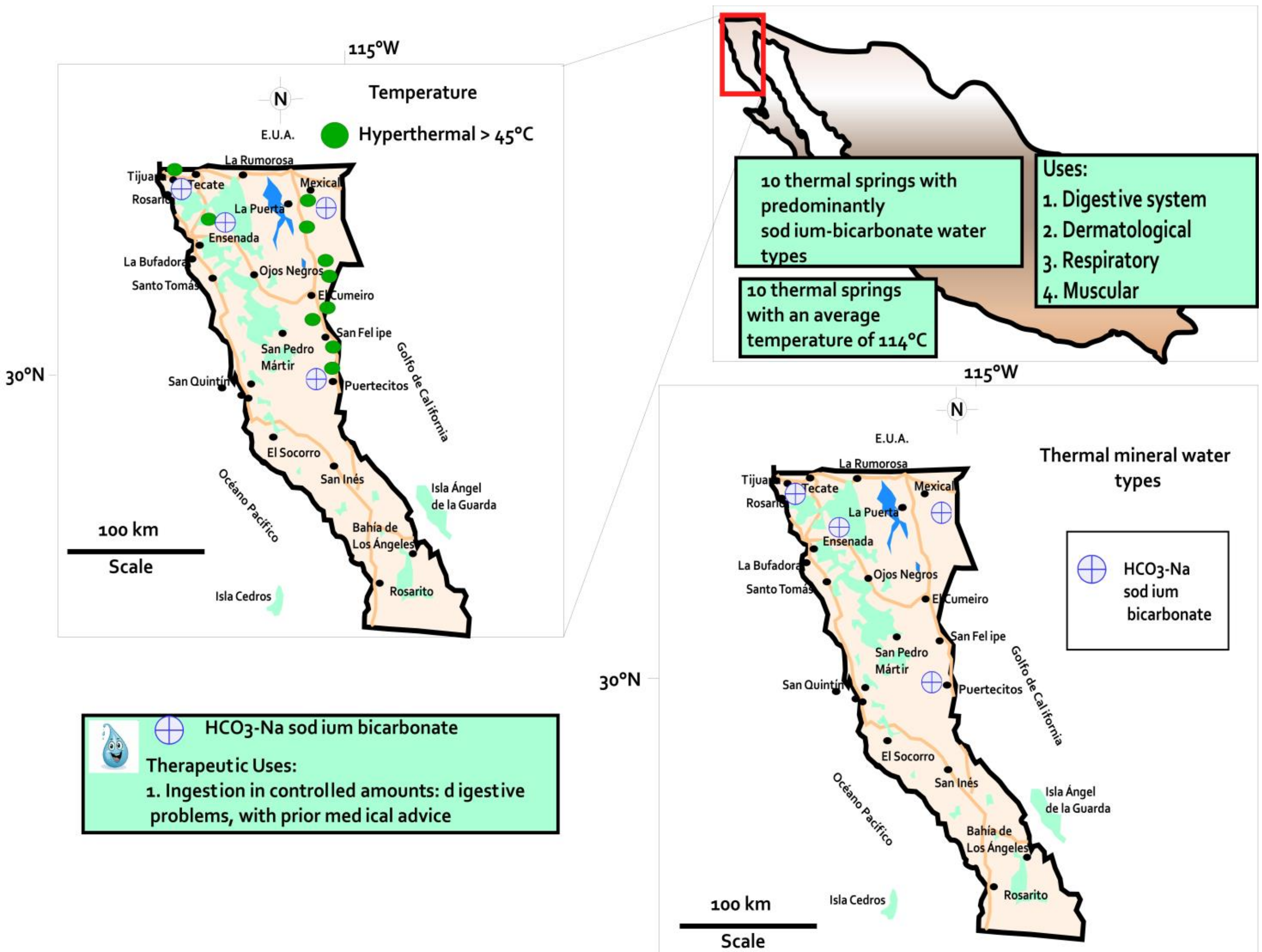


Figure 3: Thematic mapo f the state of Baja California Norte.

The thermal waters are predominantly sulfurous, chlorinated, or bicarbonate-rich, with moderate to high temperatures, making them suitable for dermatological and respiratory treatments [19]. These hydrothermal systems often emerge in semi-arid or mountainous environments, characterized by high evaporation rates and variable mineralization [5,11].

Tourism infrastructure across the region remains limited, consisting mainly of local spas and small recreational facilities near natural springs. However, significant opportunities exist to promote eco-thermal tourism experiences, integrating hiking, volcanic landscape observation, and open-air bathing within desert and highland settings [8, 9].

From a sustainability perspective, this region offers potential for low-impact geothermal tourism, where the integration of geoconservation, cultural heritage, and local community participation could enhance economic value while preserving the fragile hydrothermal ecosystems of northern Mexico [5, 7, 10].

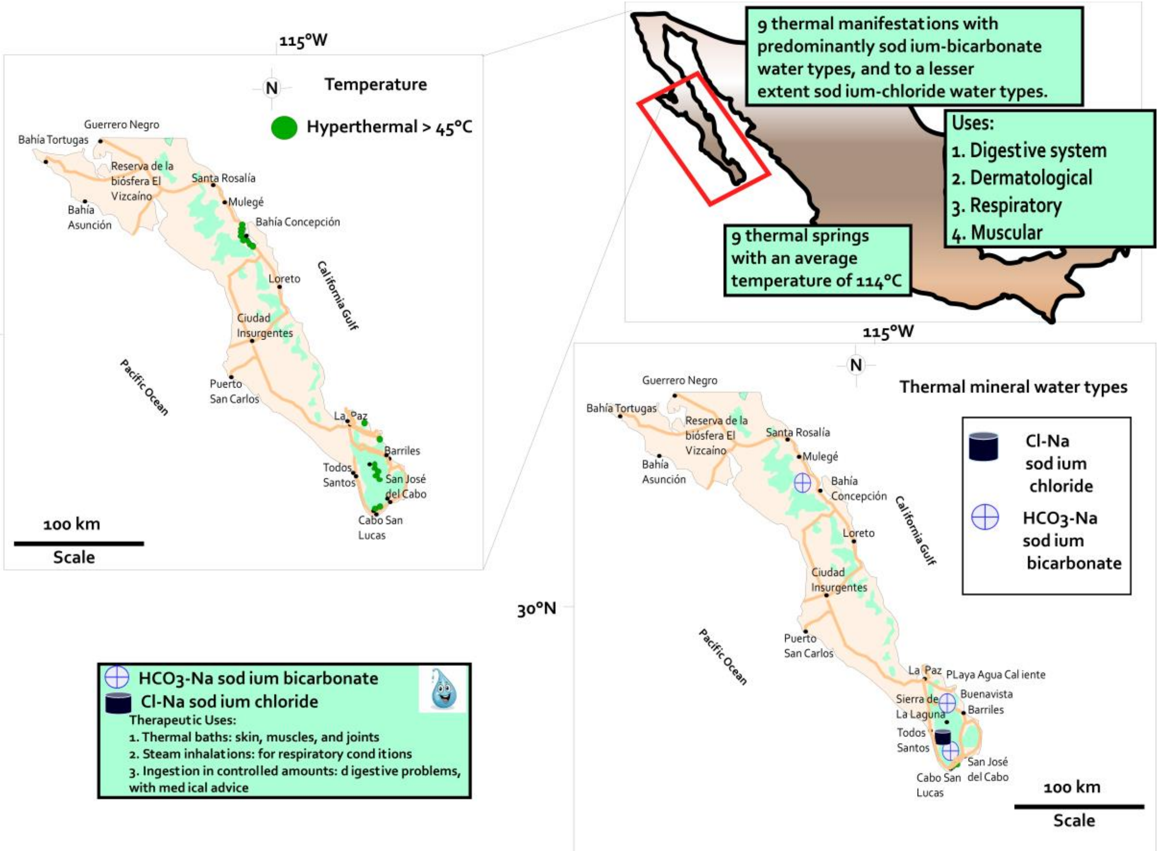


Figure 4: Thematic mapo f the state of Baja California Sur.

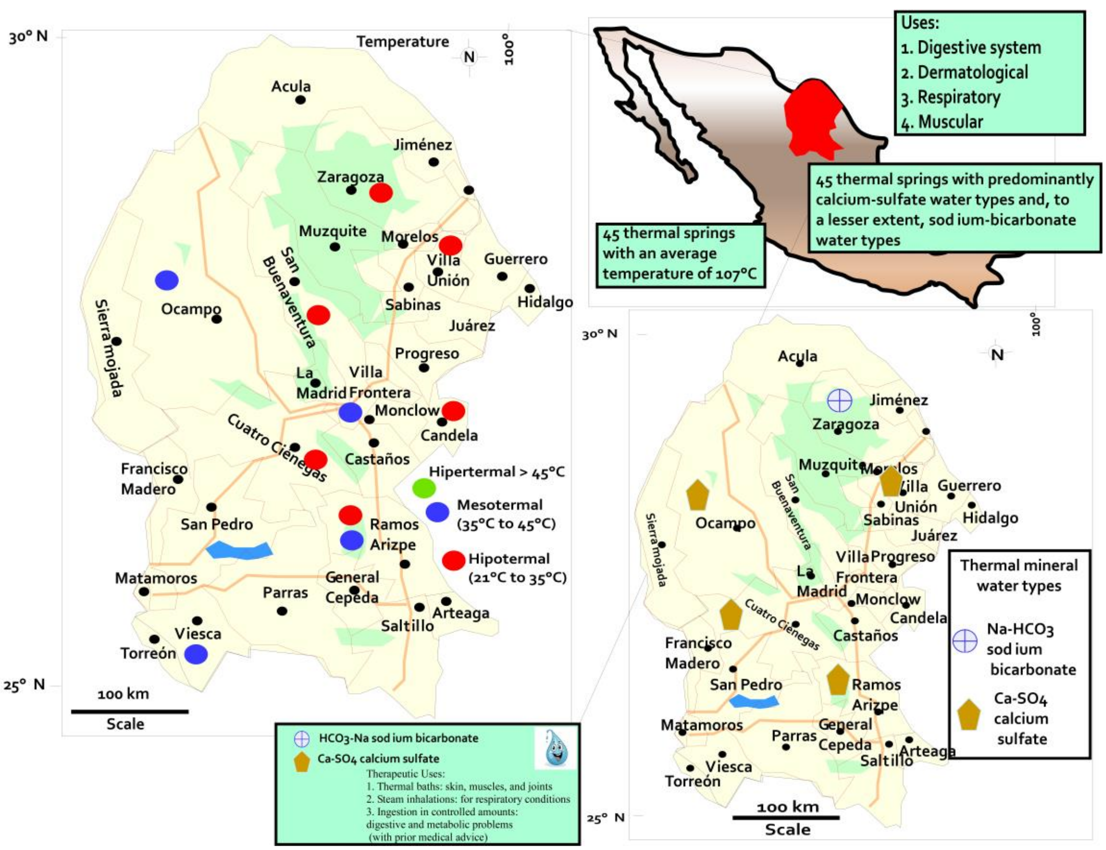


Figure 5: Thematic mapo f the state of Coahuila.

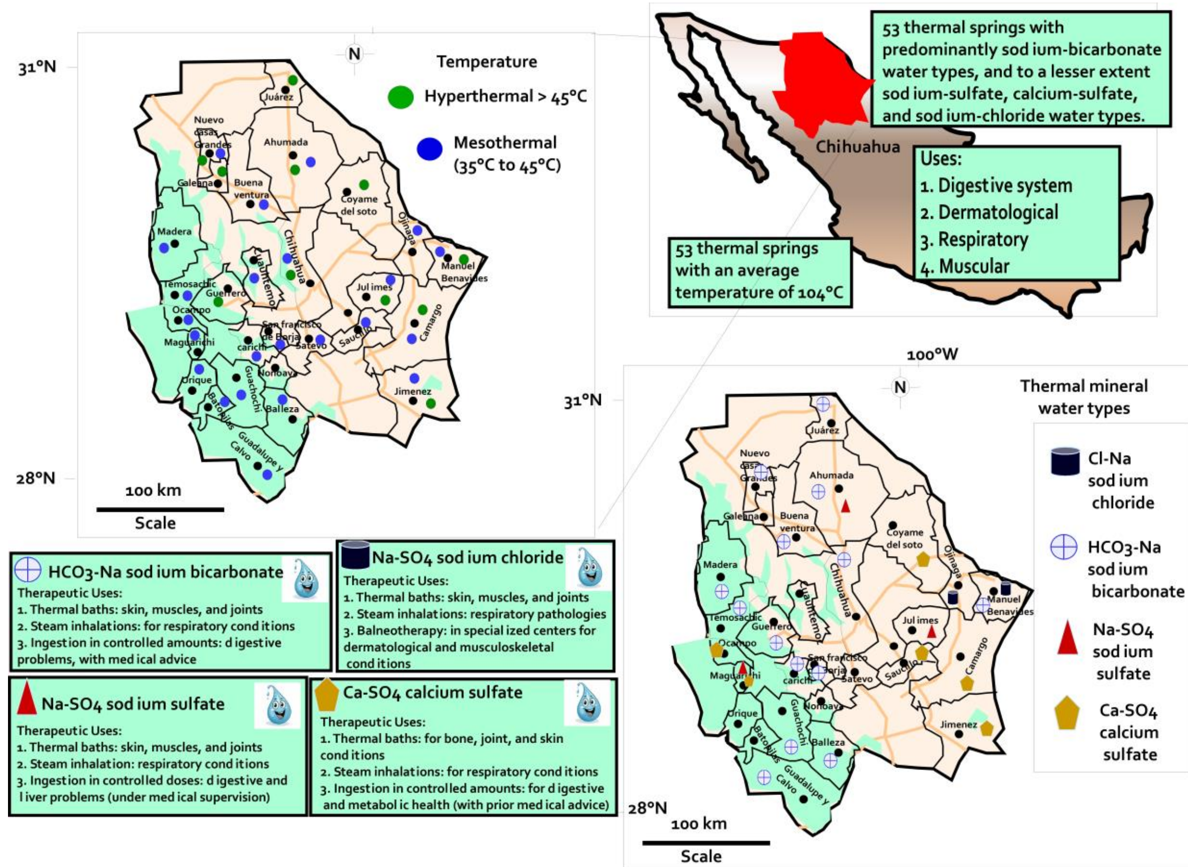


Figure 6: Thematic map of the state of Chihuahua.

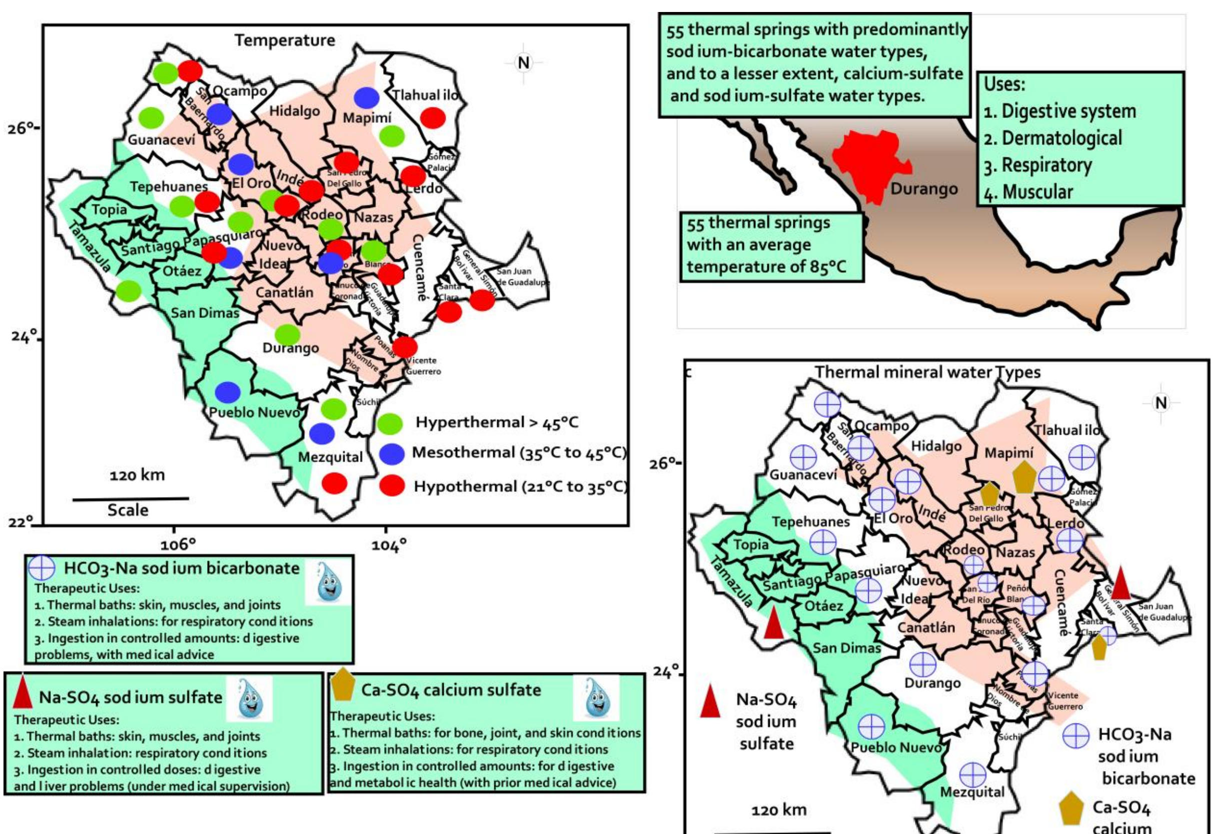


Figure 7: Thematic map of the stae of Durango.

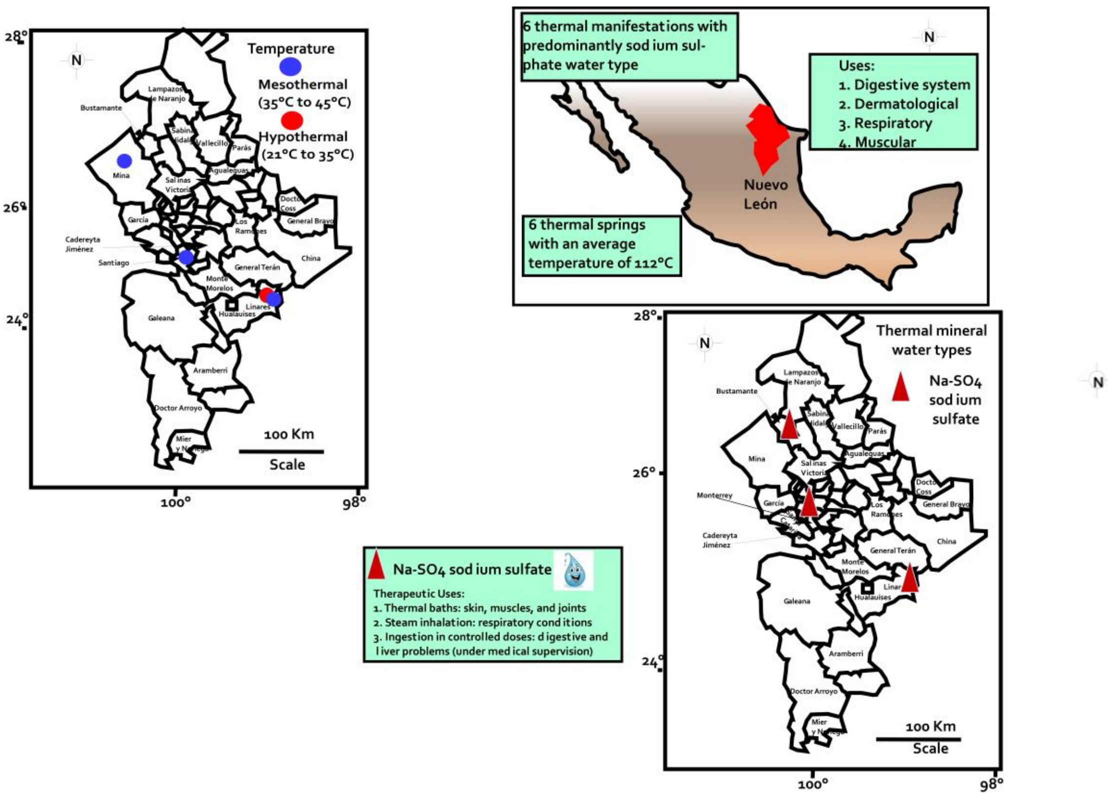


Figure 8: Thematic map of the state of Nuevo León.

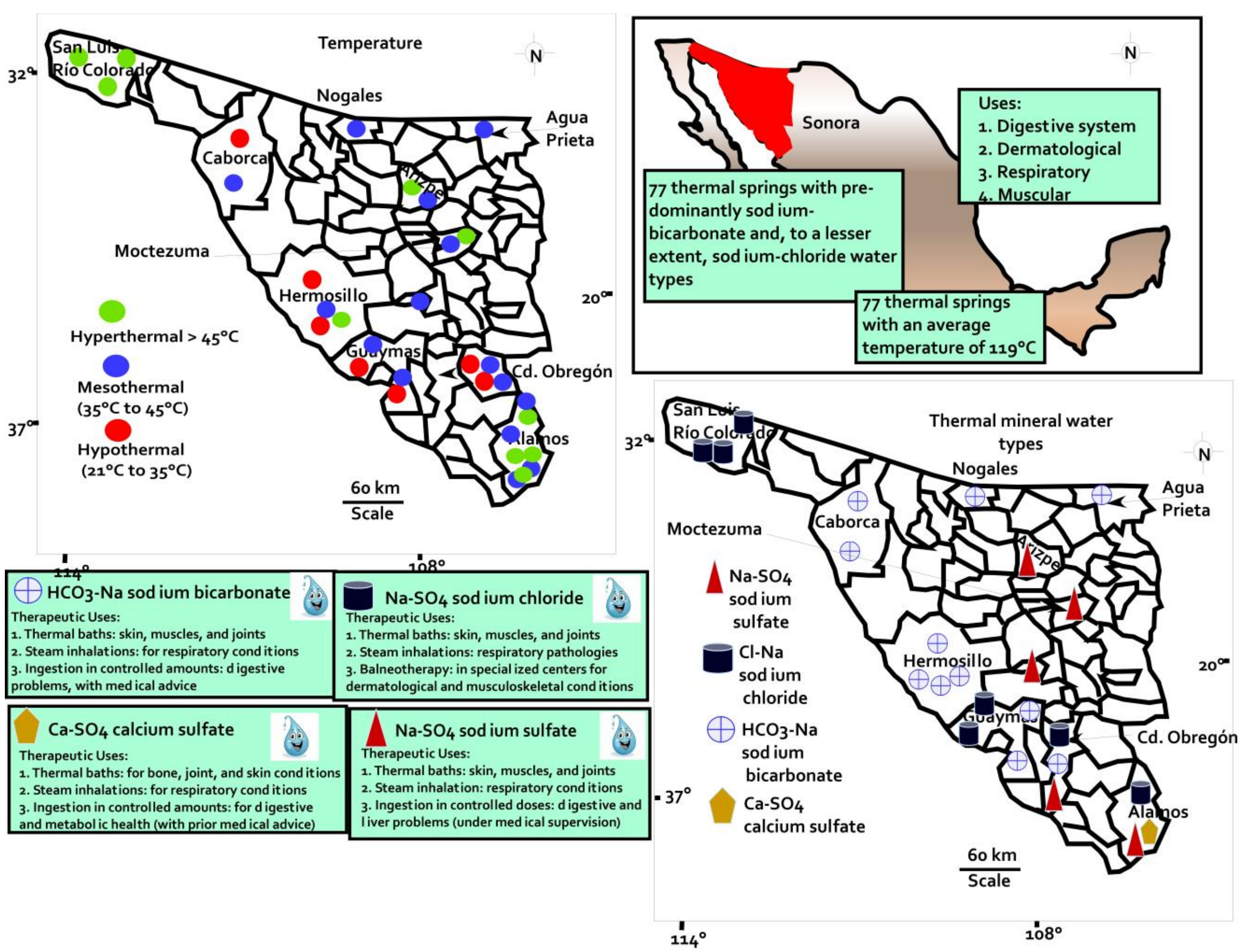


Figure 9: Thematic map of the state of Sonora.

3.2.2. Northeastern Region

This zone corresponds to the Trans-Mexican Volcanic Belt, encompassing the States of Mexico, Hidalgo, Puebla, and Querétaro (Figs. **10**-**13**). It represents the region with the highest density and diversity of thermal springs in Mexico, many of which are associated with active fault systems, recent volcanic activity, and high geological permeability [4, 5].

The thermal waters display wide geochemical variability, predominantly bicarbonate, sulfate, and ferruginous types, with temperatures ranging from 30°C to over 70°C. These systems commonly develop in hydrogeologically complex volcanic terrains, where groundwater interacts with magmatic and sedimentary formations, enriching the fluids with dissolved minerals suitable for therapeutic use [12, 13].

Historically, several of these springs have been utilized for ritual and medicinal purposes since pre-Hispanic times. Notable examples include Ixtapan de la Sal and Texcotzingo, where thermal waters were integrated into purification ceremonies and sacred architecture [15, 16]. This deep cultural connection endows the region with a unique hydrothermal heritage, linking natural healing practices with ancient cosmological beliefs [17].

At present, the Northeastern Region exhibits a well-developed tourism infrastructure, including spas, public bathhouses, and wellness centers, many of which have incorporated modern balneotherapy and holistic health approaches. Owing to its combination of geological diversity, cultural richness, and accessibility, this area holds significant potential for the development of integrated thermal routes that combine therapeutic, cultural, and sustainable tourism experiences [7, 8].

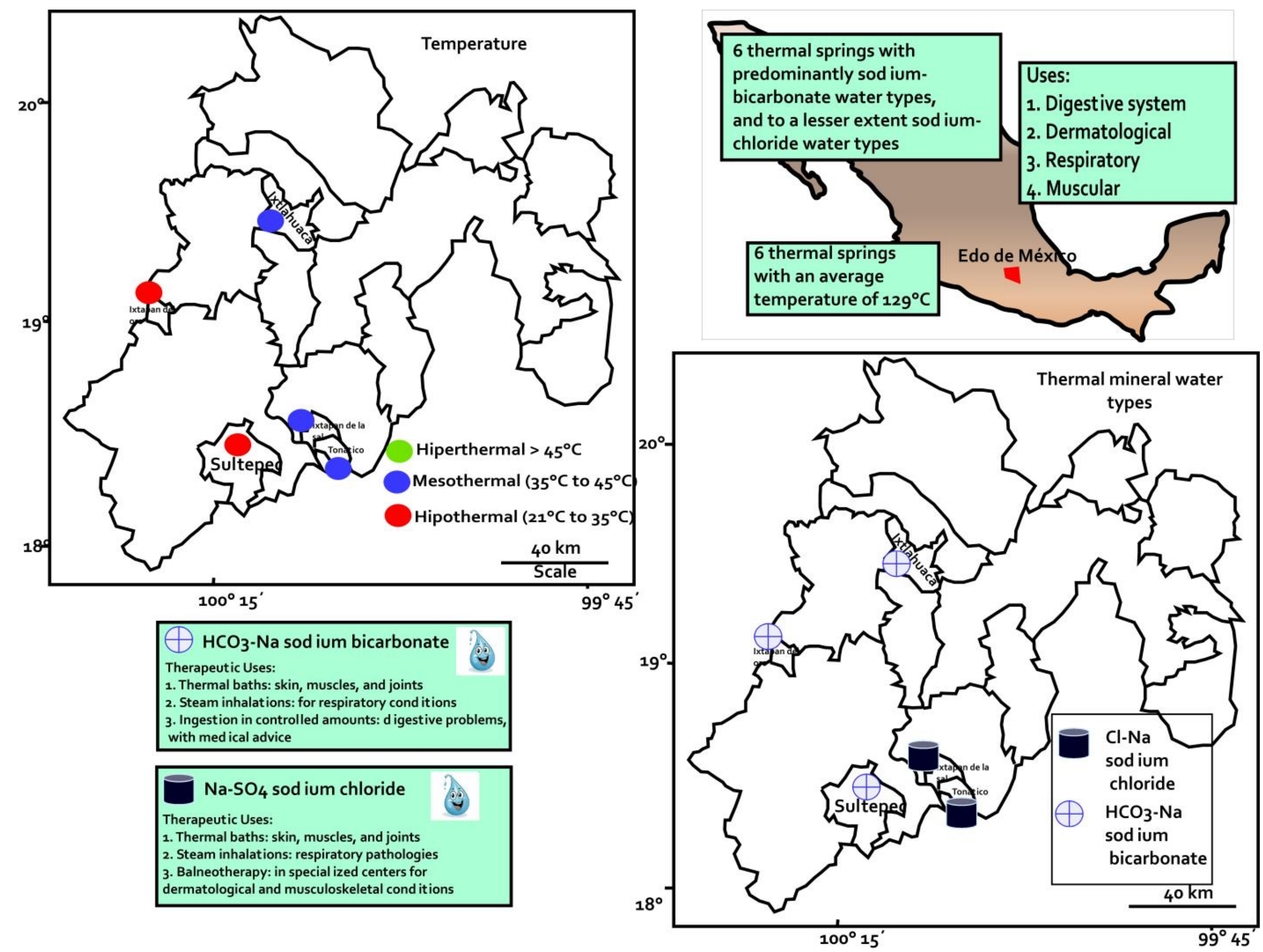


Figure 10: Thematic map of the state of México.

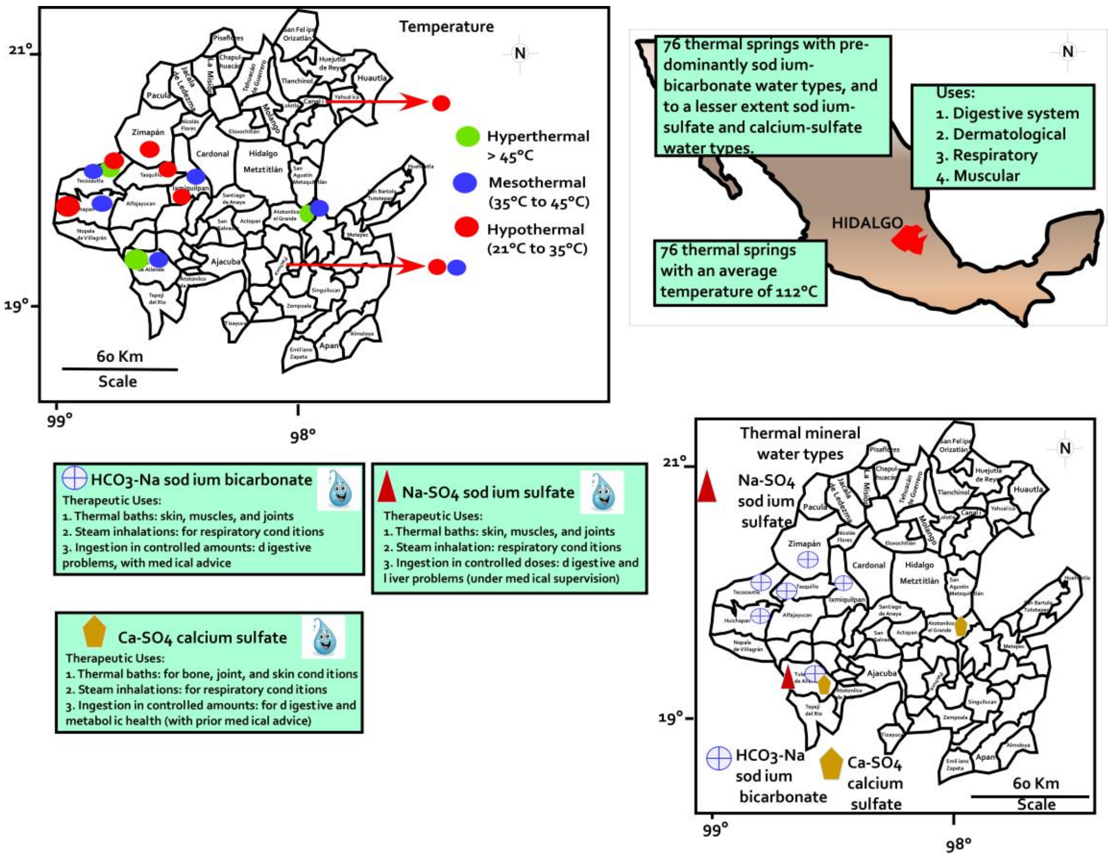


Figure 11: Thematic map of the state of Hidalgo.

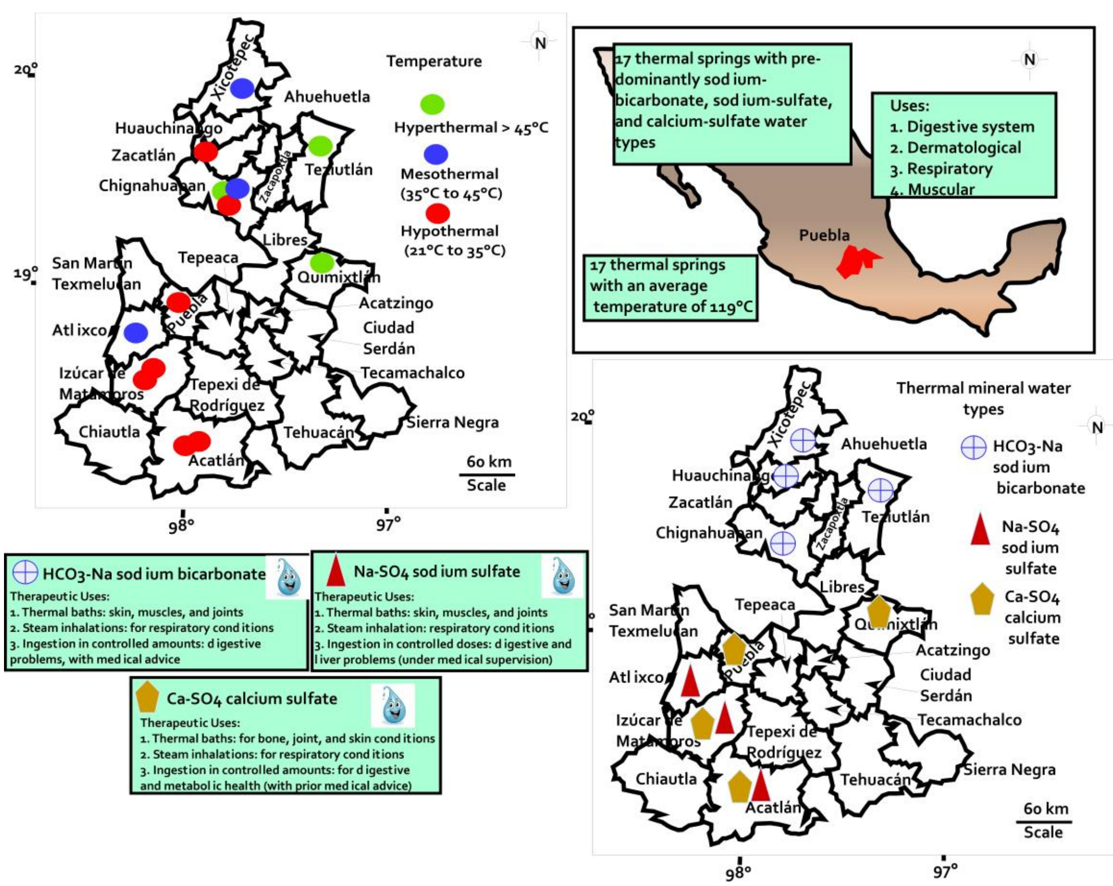


Figure 12: Thematic map of the state of Puebla.

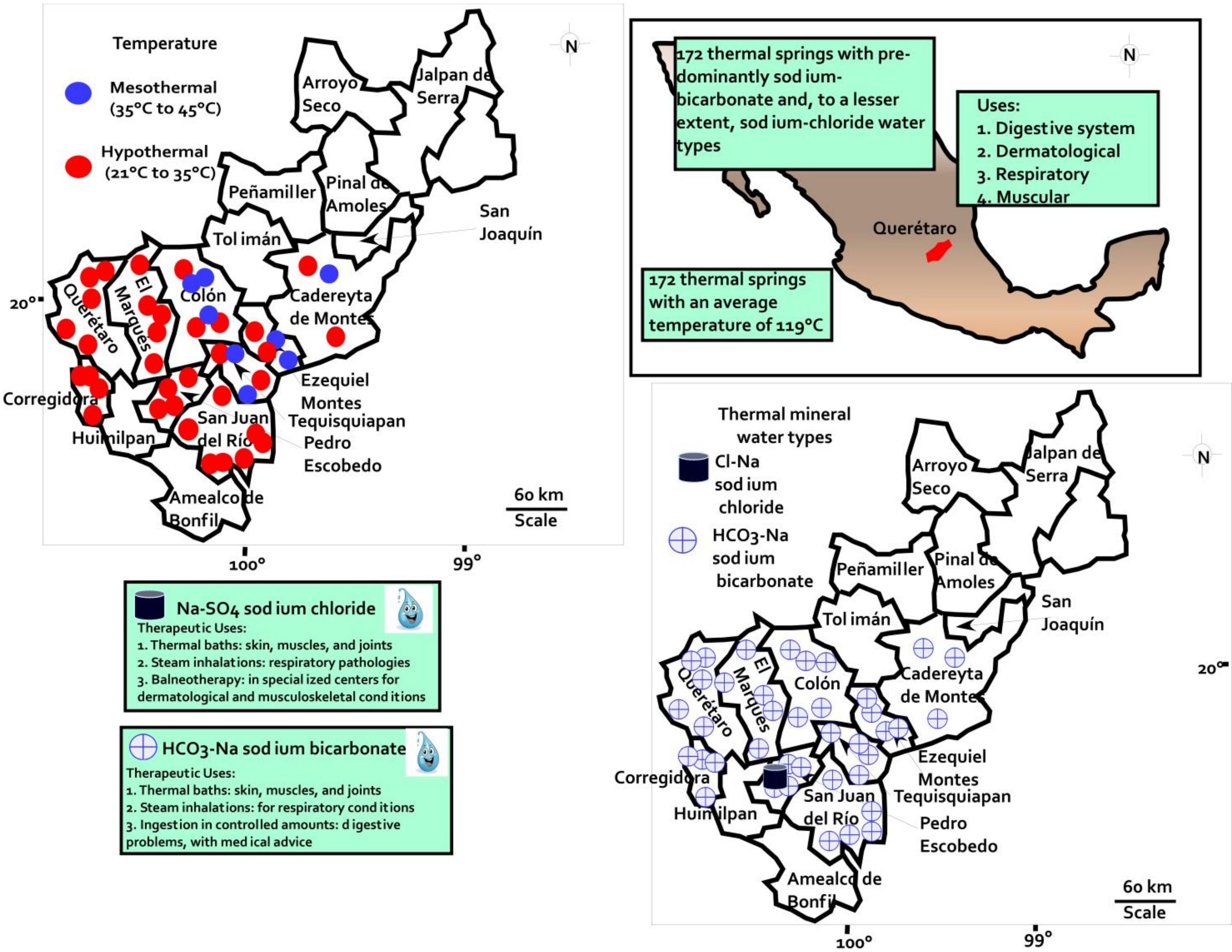


Figure 13: Thematic map of the state of Querétaro.

3.2.3. Western Region

This region encompasses the states of Aguascalientes, Guanajuato, Jalisco, Michoacán, and Nayarit (Figs. **14**-**18**). The thermal manifestations are primarily associated with Tertiary volcanism of the Bajío region and with a complex system of active and reactivated faults that traverse the area, facilitating deep groundwater circulation and heat transfer [19, 5].

The thermal waters are predominantly calcium–bicarbonate or mixed types, with temperatures ranging from 35°C to over 60°C. These hydrogeochemical characteristics make them suitable for hydrotherapy, rheumatological treatments, and muscular relaxation, while sulfur-rich waters are particularly valued for dermatological benefits [3, 12].

Representative sites include Comanjilla, San Miguel de Allende, and La Gruta, which are well known for their long-standing use in balneotherapy and recreational bathing. These sites exemplify how hydrothermal resources can be successfully integrated into broader wellness-oriented tourism networks, combining geothermal bathing, cultural heritage, and landscape appreciation [10].

The Western Region presents strong potential for integrating health and wellness tourism with other emerging forms of sustainable tourism, including wine tourism, rural tourism, and traditional medicine routes. Such cross-sectoral linkages could foster regional economic diversification while promoting the responsible use of geothermal resources and the preservation of local hydrothermal ecosystems [7, 8, 10].

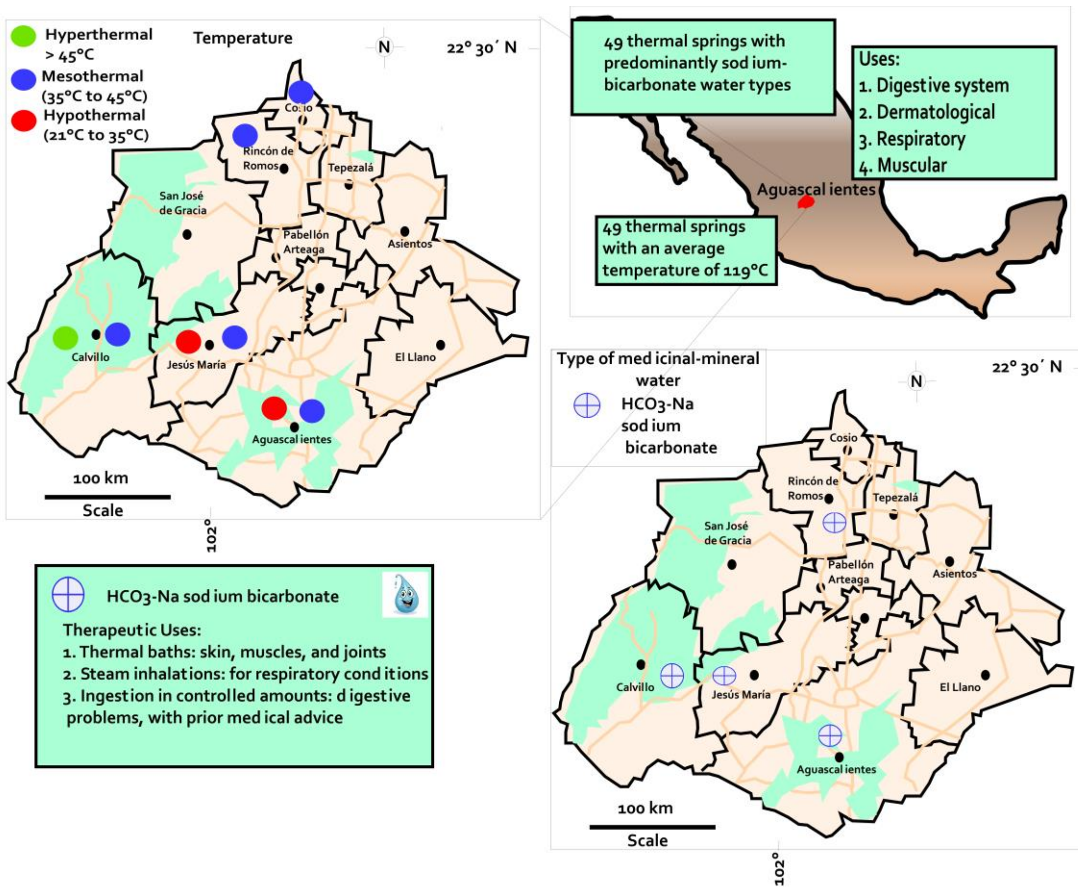


Figure 14: Thematic map of the state of Aguascalientes.

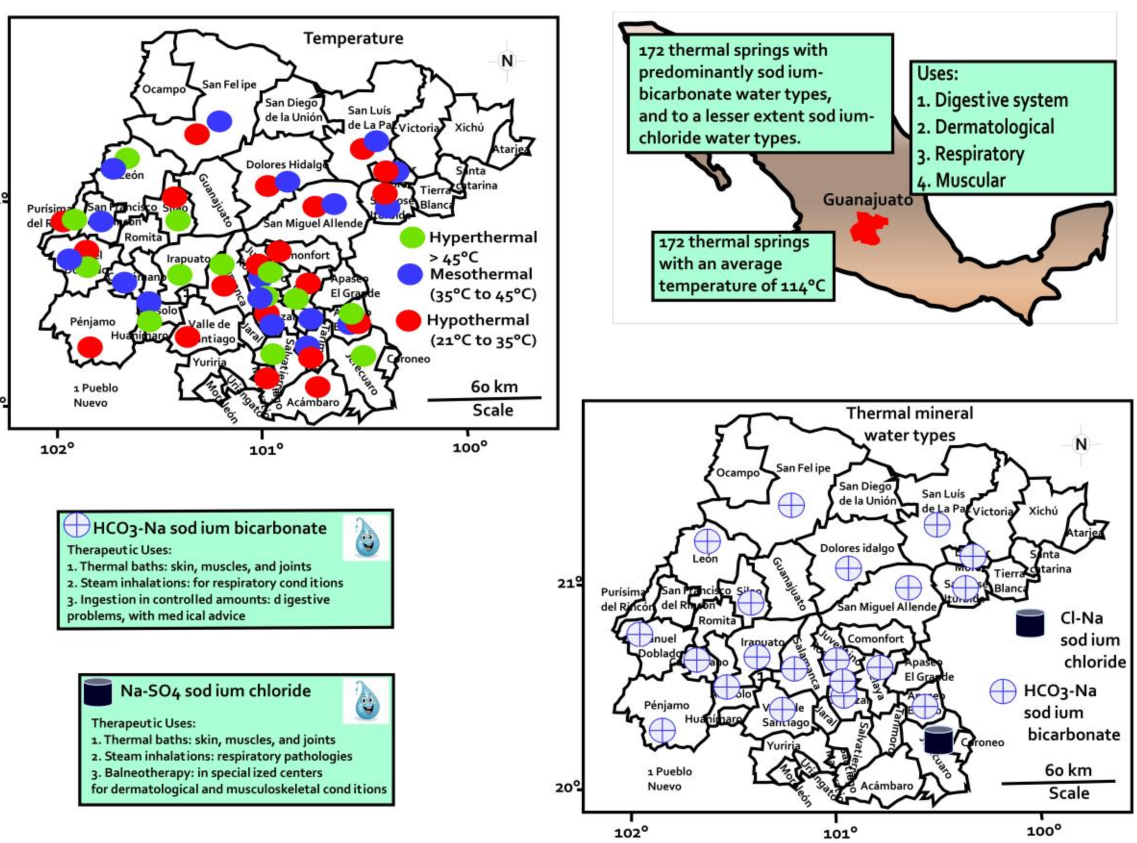


Figure 15: Thematic map of the state of Guanajuato.

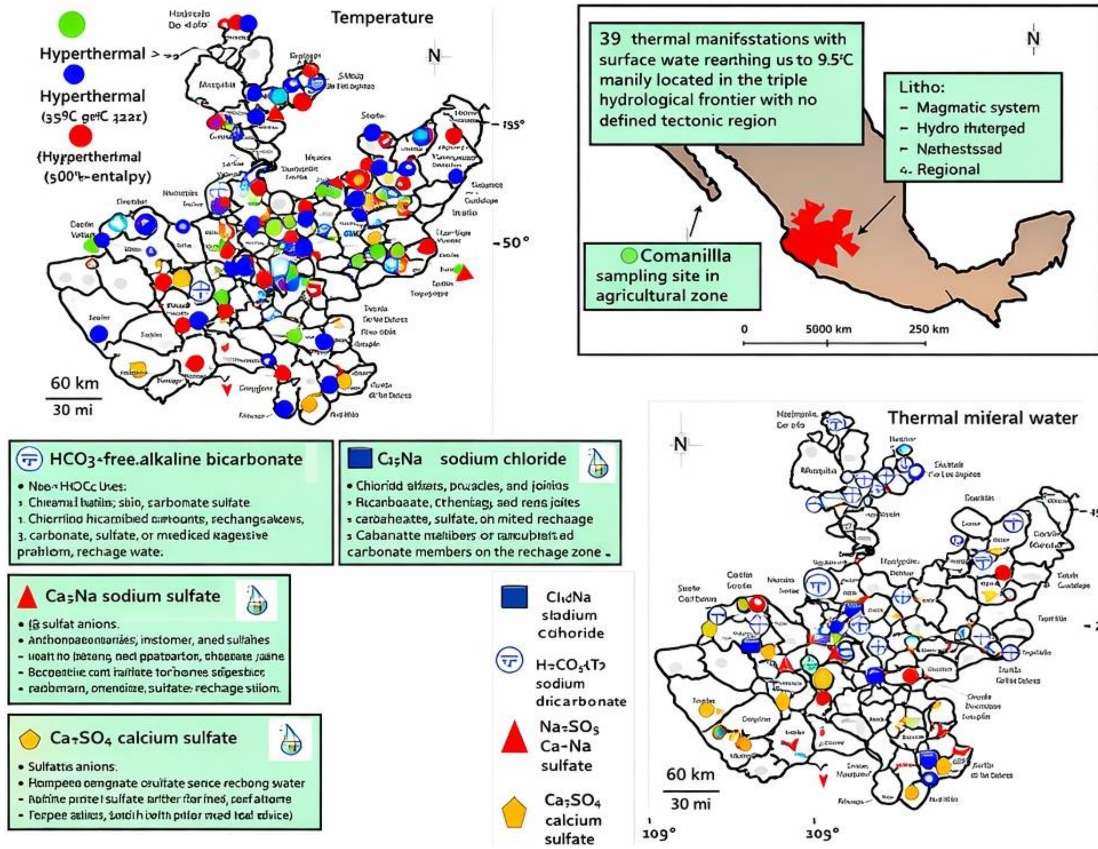


Figure 16: Thematic map of the state of Jalisco.

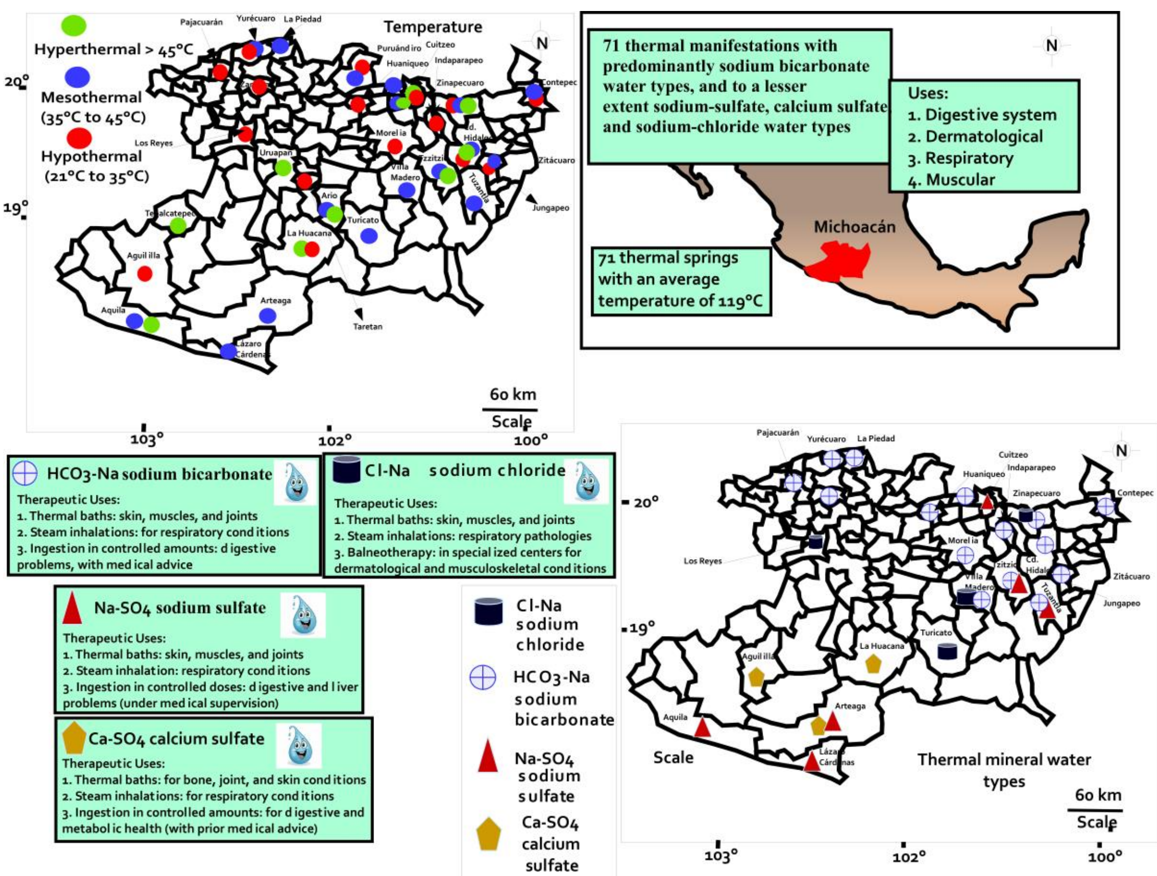


Figure 17: Thematic map of the state of Michoacan.

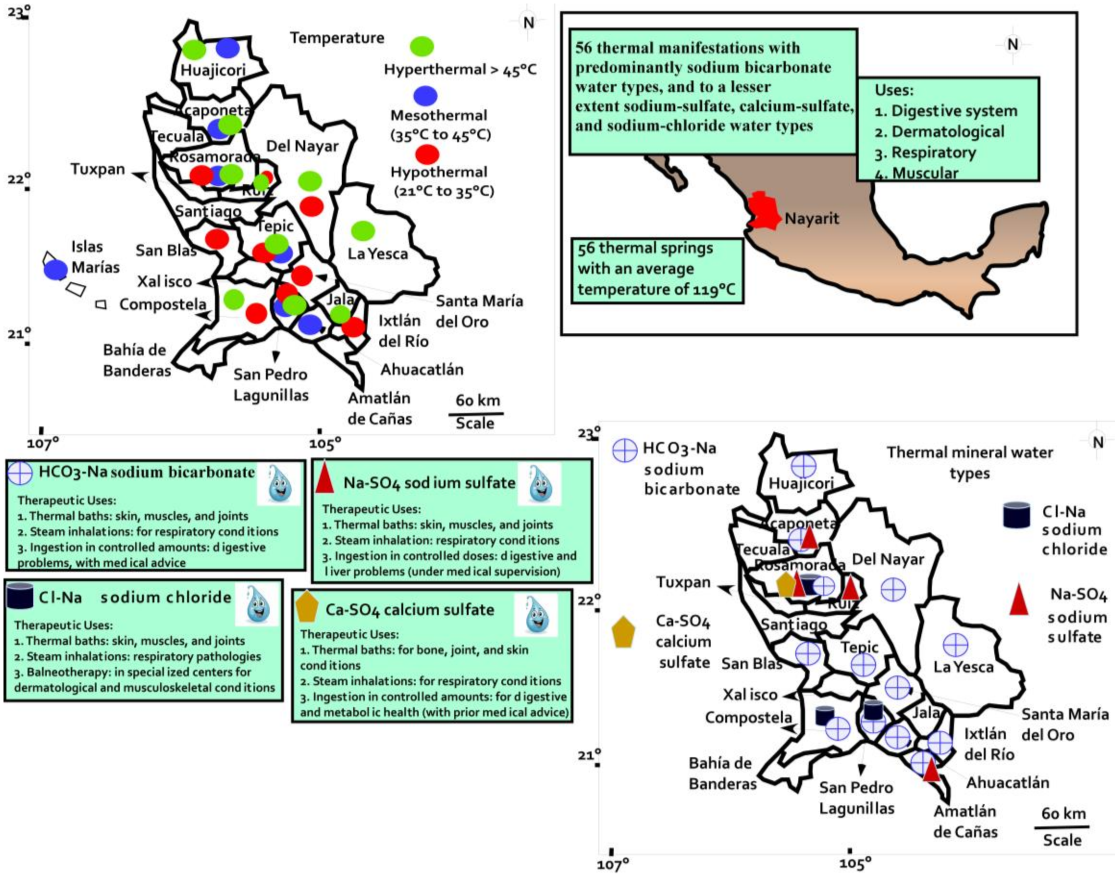


Figure 18: Thematic map of the state of Nayarit.

3.2.4. Eastern Region

This region primarily includes the states of Veracruz and Oaxaca (Figs. **19**-**20**). It exhibits a remarkable hydrothermal diversity associated with subduction zones, ancient volcanic complexes, and deep fault systems, which promote the upflow of mineral-rich geothermal fluids [4, 5]. These geological conditions favor the development of hot springs with significant geochemical and therapeutic interest.

The thermal waters in this area are commonly enriched in iron, sulfur, manganese, and bicarbonates, with temperatures ranging from 35°C to 60°C. Such mineral compositions confer notable therapeutic properties, particularly for dermatological, circulatory, and musculoskeletal treatments [5, 12].

Among the most emblematic sites is Hierve el Agua, a unique hydrothermal complex with high scenic, geological, and cultural value, where natural travertine formations are closely linked to ancient Zapotec rituals of fertility and agricultural renewal [27]. Many other springs across the region continue to be used by indigenous communities for therapeutic and spiritual purposes, preserving a living tradition of hydrothermal healing that blends ancestral cosmology with contemporary practices [17, 23].

The tourism potential of the Eastern Region lies in its capacity to promote community-based development, alternative health tourism, and the revitalization of local biocultural heritage. Integrating traditional healing knowledge with sustainable tourism strategies could enhance both environmental conservation and socioeconomic resilience [7, 8].

3.2.5. Southern Region

This region includes the states of Chiapas and Guerrero (Figs. **21-22**). Although it has a lower density of active thermal springs compared to other regions, it contains significant hydrothermal manifestations associated with the Tacaná and El Chichón volcanic complexes [5]. The thermal waters are generally temperate and enriched in bicarbonate and sulfur, offering potential applications in balneotherapy and respiratory therapies [2].

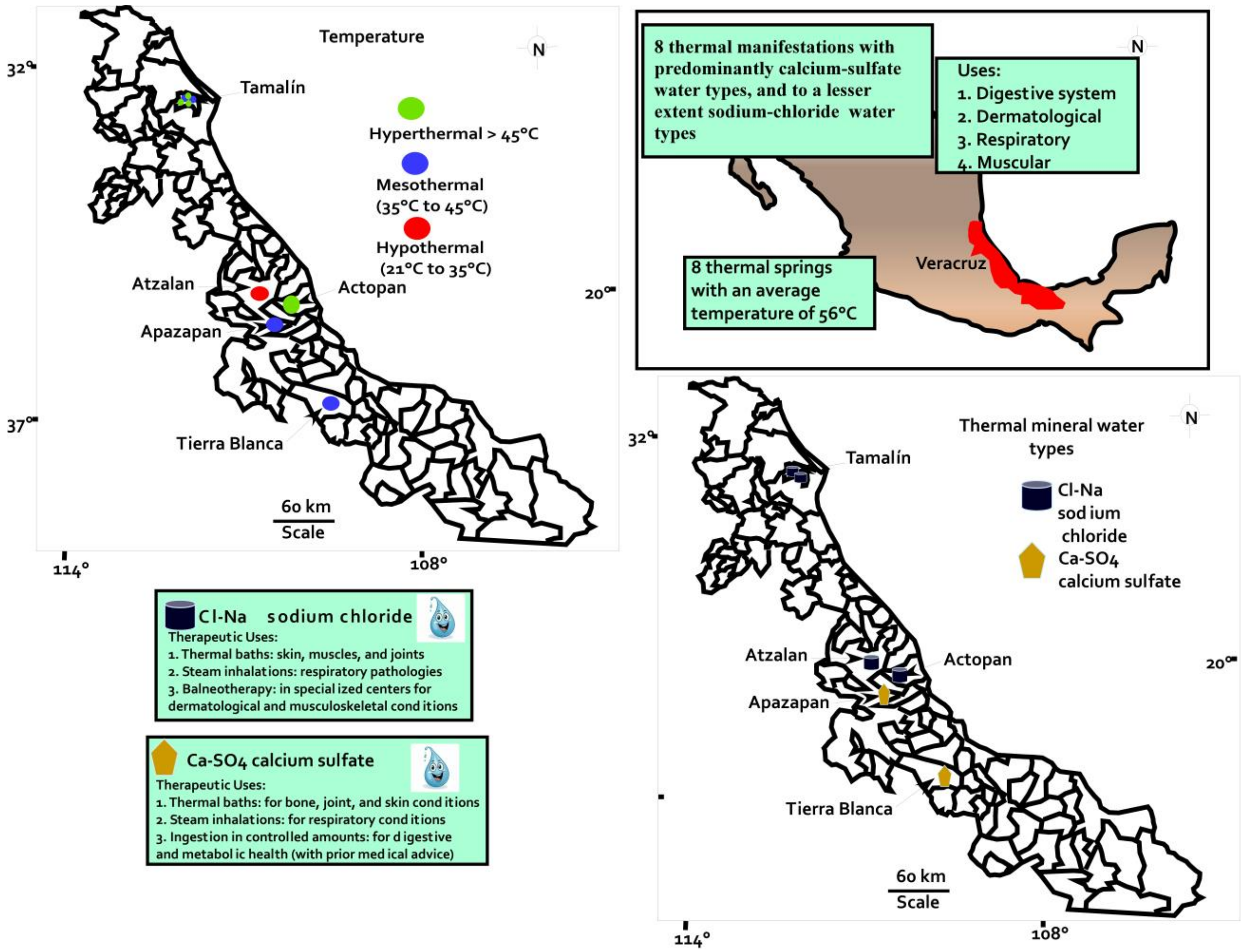


Figure 19: Thematic map of the state of Veracruz.

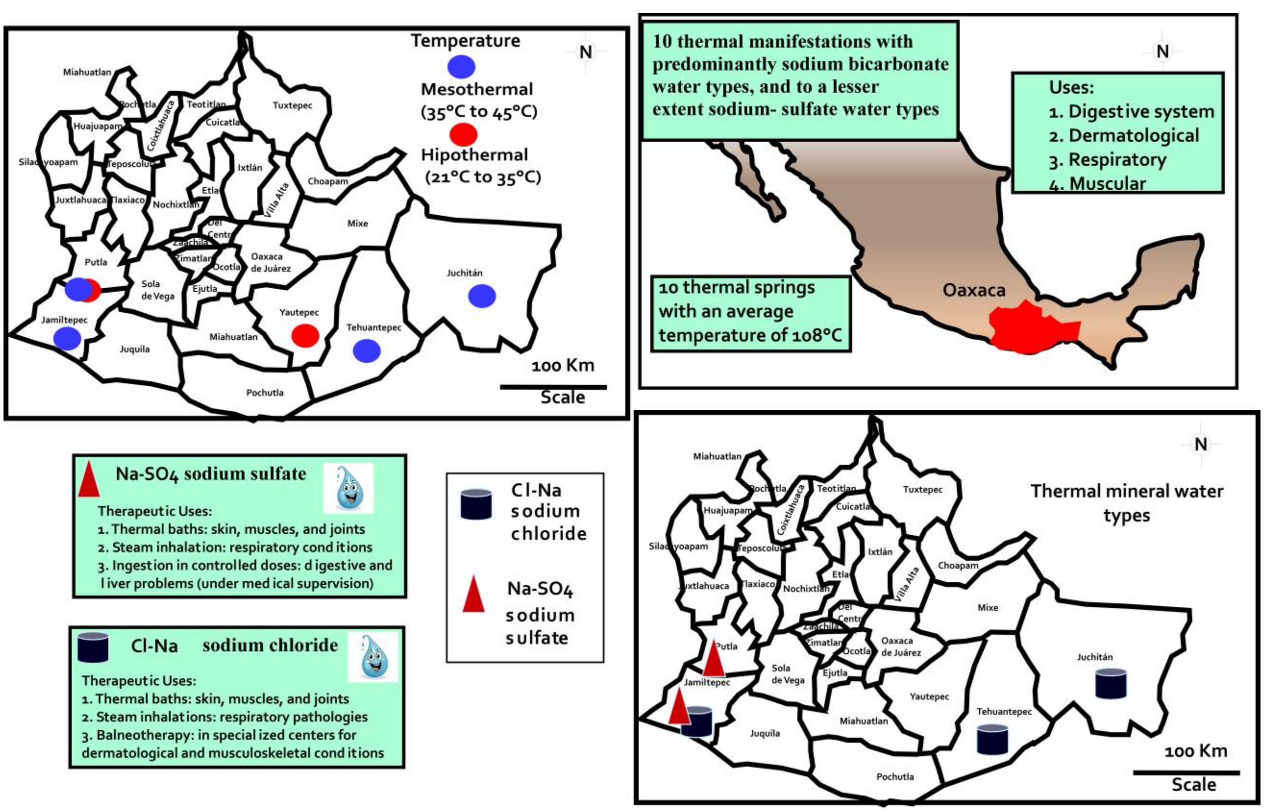


Figure 20: Thematic map of the state of Oaxaca.

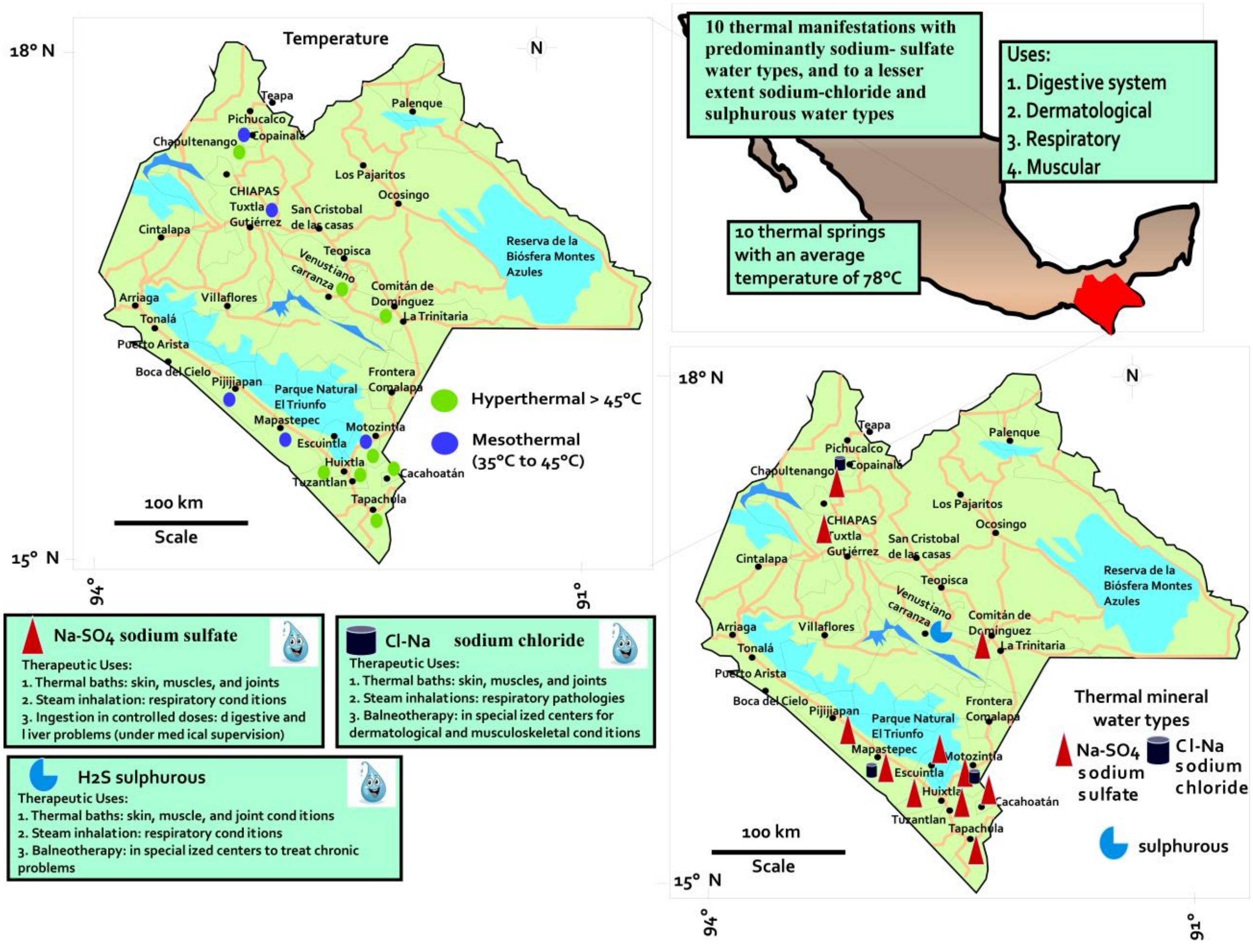


Figure 21: Thematic map of the state of Chiapas.

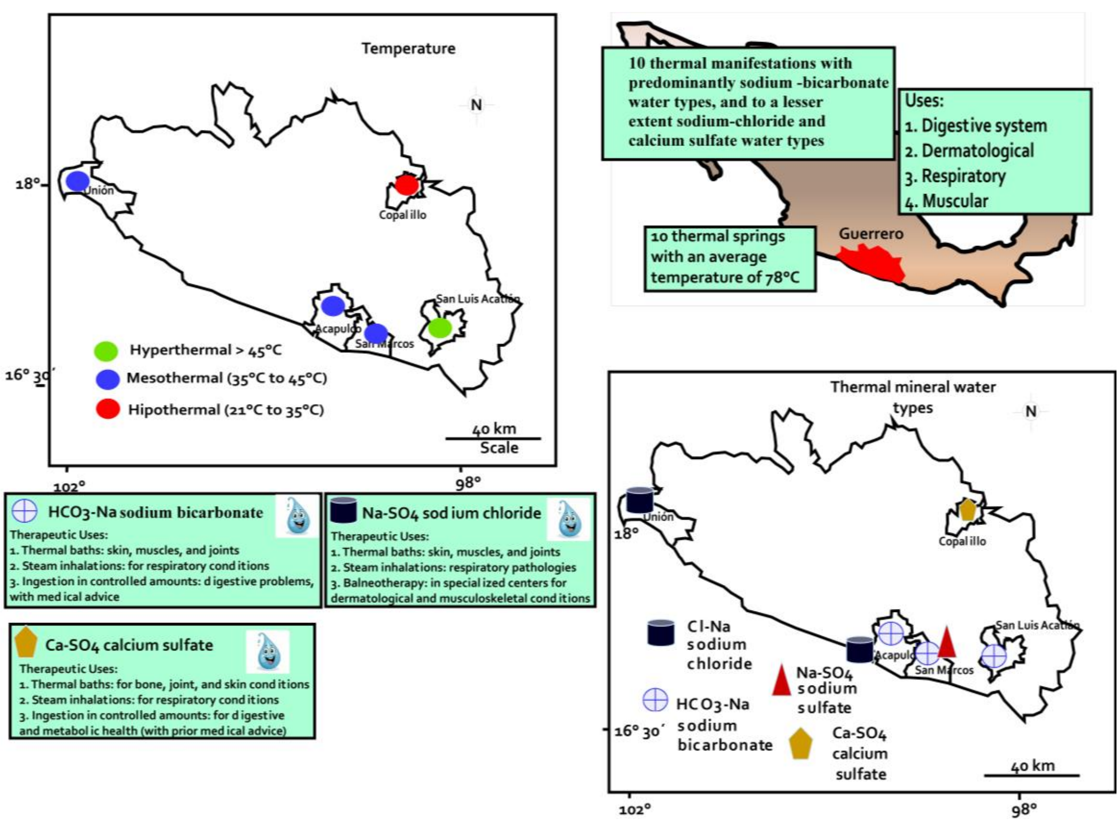


Figure 22: Thematic map of the state of Guerrero.

Tourism development in this region remains limited; however, the potential for integrated wellness and eco-thermal tourism is high, particularly when combined with traditional Maya knowledge and holistic health experiences. The proximity to protected natural areas, caves, cenotes, and archaeological sites provides a competitive advantage for the design of regenerative and spiritual tourism routes [16, 25].

While Tabasco, Campeche, Yucatán, and Quintana Roo also host isolated hydrothermal manifestations, they were not included in this study due to the lack of validated geochemical data [6].

Although the Northern and Southern regions display a lower concentration of thermal sources compared to the Northeastern and Western regions, their mineralogical diversity and location within relatively pristine natural environments represent strategic opportunities for the development of eco-thermal tourism models [7, 10]. In the south, thermal manifestations such as Los Hervores (Chiapas) and San Marcos springs (Guerrero) exemplify underutilized resources that could be integrated into eco-cultural wellness routes centered on ancestral knowledge and holistic well-being [16].

Strengthening these regions through sustainable tourism programs could foster regional economic diversification, enhance community participation, and contribute to the conservation of Mexico's hydrothermal heritage [7, 8, 10].

3.3. Chemical Composition and Therapeutic Benefits

Mexican thermal waters represent a low-enthalpy hydrogeothermal resource of remarkable mineralogical richness, resulting from their percolation through deep geological formations before emerging at the surface [5, 28]. During this process, infiltrated meteoric waters are heated by geothermal gradients or by proximity to magmatic bodies, promoting the dissolution of essential minerals such as sulfur, iron, calcium, magnesium, and bicarbonate [1, 12]. The systematic integration and comparison of hydrogeochemical data at a national scale allow the identification of recurrent geochemical patterns and mineral associations that reflect regional geological controls. These components determine both the therapeutic properties and the balneological classification of the springs [3, 7]. Across Mexico, the chemical composition of thermal waters varies according to regional geological settings, reflecting distinctive hydrochemical patterns represented in the thematic maps developed in this study [6, 12, 13]. This comparative framework enables the evaluation of similarities and contrasts among geothermal regions, providing a national-scale perspective that complements site-specific hydrogeochemical studies. The following subsections describe the main mineral components and their associated therapeutic benefits [3, 7, 19]. From a geoscientific perspective, this synthesis highlights the close relationship between water–rock interaction processes, geothermal setting, and functional classification of thermal waters, reinforcing the relevance of hydrogeochemical analysis for regional geothermal assessment.

3.3.1. Sulfur (S^{2-} / H_2S – Sulfurous Waters)

Sulfur is one of the dominant anions in many Mexican thermal springs, particularly in volcanic zones such as Los Azufres (Michoacán) and Acoculco (Puebla), where geothermal fluids interact with sulfur-bearing volcanic and sedimentary formations [5,12]. Sulfurous waters are widely recognized for their antiseptic, keratolytic, and anti-inflammatory properties, which support their use in dermatological treatments (e.g., acne and psoriasis), rheumatological therapies (arthritis and myalgia), and respiratory conditions such as rhinitis and bronchitis [3, 7].

In addition, sulfur-rich thermal waters have been associated with hepatic detoxification processes and stimulation of cellular metabolism, reinforcing their relevance in balneotherapy and hydrotherapy practices [18]. These therapeutic properties contribute to the widespread use and cultural persistence of sulfurous springs in both traditional and modern health-oriented applications across Mexico [7, 19].

3.3.2. Iron (Fe^{2+} / Fe^{3+} – Ferruginous Waters)

Iron-bearing thermal springs, such as those identified in the Tehuacán region (Puebla), are characterized by elevated concentrations of ferrous and ferric ions derived from water–rock interaction within volcanic and sedimentary formations [12, 33]. Iron plays a fundamental role in hemoglobin synthesis and oxygen transport in the human body, which explains the traditional and clinical use of ferruginous waters in revitalizing therapies.

Ferruginous waters are commonly employed in treatments for anemia, chronic fatigue, and post-illness convalescence, as they contribute to improved blood circulation, enhanced tissue oxygenation, and overall metabolic stimulation [33]. These therapeutic applications support the continued use of iron-rich thermal waters in balneotherapy and wellness practices, particularly in regions where hydrothermal activity coincides with long-standing medicinal traditions [7, 19].

3.3.3. Magnesium (Mg^{2+})

Magnesium plays a key role in the regulation of neuromuscular activity and stress response in the human body. Thermal springs with elevated magnesium concentrations, such as those found in Ixtapan de la Sal (State of Mexico), exhibit relaxing, antispasmodic, and sedative effects, making them particularly suitable for the treatment of muscle tension, contractures, insomnia, and stress-related disorders [7, 12].

Transdermal absorption of magnesium during balneotherapy has been shown to enhance relaxation processes, support neuromuscular recovery, and contribute to oxidative stress reduction, reinforcing the use of magnesium-rich waters in physical recovery and wellness-oriented therapies [3, 7].

3.3.4. Calcium (Ca^{2+})

Calcium is a fundamental element for bone metabolism, neuromuscular transmission, and cardiac regulation in the human body. Thermal waters enriched in calcium contribute to the strengthening of bones and joints, and are commonly recommended in balneotherapy for the prevention and complementary treatment of osteoporosis, muscle cramps, and neuromuscular disorders [3, 7].

In addition, calcium-rich thermal waters play a role in maintaining skin pH balance and promoting epidermal regeneration, supporting their use in dermatological and rehabilitative therapies [12, 19]. These properties explain the frequent inclusion of calcium-dominated waters in therapeutic bathing programs aimed at musculoskeletal recovery, post-traumatic rehabilitation, and general wellness [7, 10].

3.3.5. Bicarbonate (HCO_3^- – Bicarbonate Waters)

Bicarbonate-rich thermal waters, abundant in locations such as Chignahuapan (Puebla), exhibit alkalizing, digestive, and mucolytic properties that make them particularly effective for relieving gastrointestinal disorders, including dyspepsia, gastritis, and gastric acidity [3, 12]. These waters are also commonly used in inhalation therapies for respiratory ailments, owing to their capacity to facilitate mucus dissolution and improve airway function [3].

In dermatological applications, bicarbonate contributes to stabilizing skin pH and promoting tissue regeneration, supporting its use in balneotherapy programs aimed at skin care and post-inflammatory recovery [7, 19]. Collectively, these properties endow Mexican bicarbonate-rich thermal waters with a broad therapeutic value that encompasses physical well-being as well as complementary wellness practices [7, 10].

The geochemical classification illustrated through thematic mapping in this study supports a preliminary therapeutic zoning that is useful for the design of thermal routes, balneotherapy programs, and sustainable health tourism strategies [5, 7, 10]. The identification of waters with specific chemical compositions can guide visitors and health professionals in selecting the most suitable thermal resources according to individual physiological needs and therapeutic objectives [3, 10].

4. Discussion

The comprehensive analysis of low-enthalpy thermal springs in Mexico reveals the extraordinary richness and diversity of these resources from a multidimensional perspective that integrates historical, geochemical, cultural, and tourism-related components. Beyond previous site-specific or localized studies, this research provides a national-scale analytical synthesis that links hydrogeochemical patterns, geothermal setting, and functional use within a unified territorial framework. The spatial distribution and physicochemical characterization of thermal waters enable the identification of regions with differentiated therapeutic potential, which constitutes a fundamental basis for designing territorial strategies focused on wellness, health tourism, and sustainable geothermal resource management [3, 5].

The proposed regional zoning highlights pronounced differences in geochemical and thermal conditions among the Northern, Northeastern, Western, Eastern, and Southern macro-regions, reflecting the complex interaction between Mexico's geodynamic framework and its long-standing cultural heritage [4, 5]. This interaction demonstrates that the distribution, utilization, and valuation of thermal waters cannot be fully understood in isolation from their geological controls and historical patterns of human use [15-17]. Consequently, geothermal systems are interpreted here as coupled natural–cultural resources, shaped simultaneously by tectonic processes, hydrogeochemical evolution, and sustained human interaction over time.

Regions characterized by a high concentration of sulfurous and hyperthermal springs exhibit not only favorable physicochemical conditions for the development of thermal infrastructure, but also coincide with territories that preserve deep-rooted ritual and therapeutic traditions [7, 12]. In contrast, bicarbonate-dominated and hypothermal systems, despite their abundance and suitability for relaxation and hydrotherapy, are often located in areas with limited hydrothermal traditions or insufficient infrastructure, restricting their current utilization [9, 10]. These contrasts indicate that tourism development depends not solely on resource availability, but on the synergy between environmental attributes, cultural continuity, and socioeconomic context that collectively shape their contemporary value [7, 8].

The ancestral use of thermal waters as spaces for healing, purification, and spiritual connection in Mesoamerican cultures underscores the importance of preserving not only the hydrothermal systems themselves, but also the traditional knowledge frameworks that give them meaning [15, 16]. This symbolic and therapeutic dimension adds significant value to modern wellness tourism, which increasingly seeks holistic experiences that integrate physical health, emotional balance, and spiritual well-being [7]. In this sense, geothermal heritage represents both a scientific and cultural asset, requiring integrated approaches for its conservation and responsible use.

The integration of GIS-based tools such as Canvas X GIS 11 and Google Maps for the validation and analysis of thematic maps has facilitated the correlation of geochemical, thermal, and geographic variables, enhancing spatial interpretation and decision-making for sustainable territorial planning [21, 25]. These tools demonstrate the value of spatial analysis for integrating heterogeneous geothermal datasets at regional and national scales, and for identifying priority areas for conservation, promotion, and sustainable geothermal development [5, 10].

Furthermore, the results highlight the potential to strengthen community-based wellness tourism in underdeveloped regions, particularly in the Eastern and Southern macro-regions, where hydrothermal richness remains significant but largely underutilized [10, 19]. The active participation of local communities in the management of thermal resources is essential to ensure long-term social benefits, environmental protection, and cultural continuity [17].

In this context, the convergence of geoscientific research, cultural heritage, and tourism planning enables the construction of an integrated model of geothermal utilization that supports local economies, preserves natural and cultural assets, and promotes healthier lifestyles [5, 7, 10]. Achieving efficient and sustainable management will require continuous environmental monitoring, clinical evaluation of therapeutic effects, and the development of innovative tourism products aligned with sustainability principles [2, 8].

Finally, the relationship between low-enthalpy geothermal resources and health tourism represents an emerging field with high potential in Mexico. The scientifically supported therapeutic properties of mineral-rich waters justify the development of differentiated tourism products, including medical spas, therapeutic bathhouses, healing retreats, and thematic thermal routes [3, 7]. International experiences in countries such as Hungary, Iceland, and Japan demonstrate that the sustainable valuation of geothermal resources can generate economic resilience, local employment, and environmental preservation [3, 5]. From a geoscientific perspective, this study demonstrates how low-enthalpy geothermal systems can be evaluated beyond energy production, emphasizing their hydrogeochemical complexity, territorial distribution, and functional relevance as strategic resources for sustainable development.

5. Conclusions

This study represents the first comprehensive systematization of 1,306 low-enthalpy thermal springs across Mexico, developed through an interdisciplinary approach that integrates hydrogeochemical analysis, thematic cartography, and functional evaluation. The results demonstrate that the geochemical diversity of thermal waters is closely linked to their therapeutic properties, spatial distribution, and degree of utilization, confirming that tourism development and infrastructure are influenced not only by physicochemical characteristics but also by sociocultural and historical processes embedded within the territory.

From a geographical and geoscientific perspective, this research underscores the relevance of territorial and multiscalar approaches for understanding and managing low-enthalpy geothermal resources. Its main scientific contribution lies in the national-scale integration and spatial reinterpretation of dispersed hydrogeochemical data, the generation of hydrogeochemical thematic maps, and the proposal of a preliminary therapeutic zoning model encompassing five macro-regions (North, Northeast, West, East, and South). This systematization provides an unprecedented analytical framework for the sustainable management of Mexico's hydrothermal heritage and establishes a replicable methodology applicable to other regions with underutilized geothermal potential.

From an applied standpoint, the resulting cartographic products and functional classification constitute strategic tools for regional planning, the design of integrated thermal routes, and the identification of priority areas for sustainable tourism, preventive health, and community well-being. These outcomes reinforce the role of applied geography by articulating natural, cultural, and economic dimensions within a coherent territorial framework.

Future research should advance along three complementary axes: (a) environmental and sanitary monitoring of thermal springs to evaluate hydrogeochemical evolution and potential risks; (b) clinical and social validation of the associated therapeutic benefits; and (c) the development of participatory local governance models that strengthen resource conservation and its integration into regional development strategies.

Overall, this study demonstrates that Mexico's low-enthalpy geothermal systems constitute not only an energy or recreational resource, but a complex geoscientific and territorial asset, whose responsible management can contribute to sustainable development, public health, and the preservation of both natural and cultural heritage.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The study received no financial support.

Acknowledgments

The authors also acknowledge the valuable contributions of local communities and field collaborators across the studied regions, whose traditional knowledge and historical records were fundamental for understanding the cultural dimension of hydrothermal resources. This study benefited from the integration of data shared by academic and governmental institutions dedicated to geothermal, hydrogeochemical, and environmental research between 1975 and 2024. Their commitment to open and collaborative science made this national-scale synthesis possible.

References

[1] Hochstein MP, Browne PRL. Surface manifestations of geothermal systems with volcanic heat sources. In: Sigurdsson H, Ed. Encyclopedia of volcanoes. San Diego: Academic Press; 2000. p. 835-55.

[2] Lund JW, Freeston DH. Worldwide direct uses of geothermal energy 2000. Geothermics. 2001; 30(1): 29-68. https://doi.org/10.1016/S0375-6505(00)00044-4

[3] Lund JW, Boyd TL. Direct utilization of geothermal energy 2015 worldwide review. Geothermics. 2016; 60: 66-93. https://doi.org/10.1016/j.geothermics.2015.11.004

[4] Arellano-Gil J, Hernández-Medrano VH, Lermo-Samaniego J. Evaluación del potencial geotérmico en México: una aproximación regional. Rev Mex Cienc Geol. 2015; 32(3): 476-95.

[5] Prol-Ledesma RM, Canet C, Torres-Vera MA. Geothermal resources in Mexico: review and challenges. Renew Sustain Energy Rev. 2012; 16: 5309-17.

[6] Torres-Rodríguez V, Venegas-Salgado S, Herrera-Franco J, González-Partida E. Manifestaciones termales de la República Mexicana. México: UNAM; 1993.

[7] Smith M, Puczkó L. Health, tourism and hospitality: spas, wellness and medical travel. 2nd ed. London: Routledge; 2014.

[8] Morales MC, Díaz-Caravantes RE. Termalismo, turismo y territorio: el caso de los balnearios en Aguascalientes. Investig Geogr. 2015; (88): 63-76.

[9] Pacheco GJA, Rojas HRG. Turismo de salud por medio del aprovechamiento de aguas termales. Econ Soc. 2014; 18(31): 121-43.

[10] Gutiérrez-Negrín LCA. El aprovechamiento geotérmico en México: situación actual y perspectivas. Geotermia. 2018; 31(1): 55-70.

[11] Tamburello G, Chiodini G, Ciotoli G, Procesi M, Rouwet D, Sandri L, *et al*. Global thermal spring distribution and relationship to endogenous and exogenous factors. Nat Commun. 2022; 13: 6378. https://doi.org/10.1038/s41467-022-34115-w

[12] González-Partida E, Birkle P, Torres-Alvarado I. Hydro-geochemical evolution of the Los Azufres geothermal field, central Mexico. Appl Geochem. 2005; 20: 23-39. https://doi.org/10.1016/j.apgeochem.2004.07.006

[13] Villanueva-Estrada RE, Prol-Ledesma RM, Rodríguez-Díaz AA, Canet C, Torres-Alvarado IS, González-Partida E, *et al*. Geochemical processes in an active hydrothermal system. Int Geol Rev. 2012; 54(8): 907-19. https://doi.org/10.1080/00206814.2011.588496

[14] Mercado S. The geothermal potential evaluation of Mexico by geothermal chemistry. In: Proceedings of the International Congress on Thermal Waters, Geothermal Energy and Volcanism; Athens, Greece: 1976, pp. 379-93.

[15] López Austin A. Tamoanchan y Tlalocan: dos espacios míticos del México antiguo. México: Fondo de Cultura Económica; 1996.

[16] Aguilar-Moreno M. Handbook to life in the Aztec world. Oxford: Oxford University Press; 2006.

[17] Florescano E. El mito de Quetzalcóatl. México: Fondo de Cultura Económica; 2000.

[18] Hernández-Hernández MA, Sánchez-Quispe ST, López H Aída. Caracterización física de los manantiales localizados al sur del Sistema hidrotermal de Acoculco (Puebla, México) (Physical characterization of springs located south of the Acoculco Hydrothermal System (Puebla, Mexico)). In: Ibero-American Seminar on Water and Drainage Networks (SEREA 2017); 2017 Nov 30; https://doi.org/10.2139/ssrn.3108253

[19] Sosa-Ceballos G, García-García A, López-Hernández A. Geothermal energy in Mexico: current status and future perspectives. Renew Energy. 2022; 181: 1125-40.

[20] Hernández-Zúñiga OJ. Potencial geotérmico de México. México: Secretaría de Energía; 2014.

[21] Instituto Nacional de Estadística y Geografía (INEGI). Marco geoestadístico nacional, versión 2020. Aguascalientes: INEGI; 2020.

[22] Alonso H. Potencial geotérmico de la República Mexicana. In: Proceedings of the 2nd United Nations Symposium on the Development and Use of Geothermal Resources. Vol 1; 1975. p. 17-24.

[23] Mercado S, Sequeiros J, Fernández H. Low-enthalpy geothermal reservoirs in Mexico. Geotherm Resour Counc Trans. 1985; 9: 523-26.

[24] Torres-Rodríguez V, González-Partida E. Métodos de prospección geotérmica. In: Torres-Rodríguez V, Ed. Geotermia en México. México: UNAM; 1993. p. 23-30.

[25] Torres-Rodríguez V, Venegas-Salgado S, Herrera-Franco J, González-Partida E. Evaluación del potencial geotérmico de las manifestaciones termales mexicanas. Geotermia. 1994; 7(1): 15-32.

[26] Maya-González R, Gutiérrez-Negrín LCA. Recursos geotérmicos para generar electricidad en México. Rev Dig Univ. 2007; 8(12): 1-13.

[27] Hiriart G. Evaluación de la energía geotérmica en México. México: Comisión Reguladora de Energía/Banco Interamericano de Desarrollo; 2011.

[28] Prol-Ledesma RM. Geotermia y sustentabilidad en México. Geotermia. 2020; 33(2): 89-102.

[29] Canet C, Prol-Ledesma RM, Torres-Alvarado IS. Hydrothermal systems and geothermal resources in Mexico. Appl Geochem. 2010; 25: 1-15.

[30] González-Partida E, Tello-Hinojosa E, Verma SP. Evolution of the hydrothermal system at the Los Azufres geothermal field. J Volcanol Geotherm Res. 2000; 104: 277-96. https://doi.org/10.1016/S0377-0273(00)00211-0

[31] González-Partida E, Tello-Hinojosa E, Verma SP. Interacción agua-geotermia-manantiales en Los Humeros. Ing Hidráulica Mex. 2001; 16(2): 185-94.

[32] Gómez de Jesús L. Identificación, caracterización y categorización de las manifestaciones termales del Estado de México, 2015.

[33] Cruz González A. Composición química de las aguas termales en el Estado de México: implicaciones para sus usos (master's thesis). Toluca: Universidad Autónoma del Estado de México; 2017.

[34] Venegas GJQ. El turismo termal en Chignahuapan, Puebla. Desarro Econ Soc. 2021; 10(1): 26-43. https://doi.org/10.38017/23228040.737

[35] Amador CF, Vargas ARB, Rodríguez EB, Rivera FJV. Turismo y comunalidad en el Balneario El Geiser, Hidalgo. Bol Cient Investigium. 2023; 9(Esp): 56-65. https://doi.org/10.29057/est.v9iEspecial.11563

[36] Castillo-Reyes O, Prol-Ledesma RM, Corbo-Camargo F, Rojas O. Geothermal resources in Latin America. Geotherm Energy. 2024; 12: 34. https://doi.org/10.1186/s40517-024-00314-5