Analysis of the evolution of the aridity index in Mexico using geographic information technologies

Analyse de l'évolution de l'indice d'aridité au Mexique à l'aide des technologies de l'information géographique

Lidia Yadira PÉREZ-AGUILAR[1], Ramón Fernando LÓPEZ-OSORIO[1*], Yedid Guadalupe ZAMBRANO-MEDINA[2], Evangelina AVILA-ACEVES[2], María Alejandra QUINTERO-MORALES[3], Sergio Alberto MONJARDIN-ARMENTA[2]

[1] Facultad de Informática Culiacán, Universidad Autónoma de Sinaloa, Culiacán, Sinaloa, México.
[2] Facultad de Ciencias de la Tierra y el Espacio, Universidad Autónoma de Sinaloa, Culiacán, Sinaloa, México.
[3] Facultad de Biología, Universidad Autónoma de Sinaloa, Culiacán, Sinaloa, México.

* Correspondence to: LÓPEZ-OSORIO Ramón Fernando. E-mail: ferrlop@uas.edu.mx.

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ABSTRACT: Arid regions cover over 43% of the world's surface and characterized by low water availability and significant changes in precipitation and temperature. In Mexico, these regions cover more than half of the territory and 40% of the national population live in these ecosystems. The primary objective of this study was to identify, classify, and analyze arid regions in Mexico using the Aridity Index (AI), Geographic Information Systems (GIS), and satellite images for the period 1980-2023. The results showed that arid and semi-arid zones predominate in Mexico, reflecting an increase of 15% and 4%. In comparison, humid regions reduced their surface area by 17%, showing a trend of increasing aridity in Mexico. The states most affected by this condition are Baja California, Baja California Sur, Chihuahua, Coahuila de Zaragoza, Durango, Nuevo Leon, Oaxaca, San Luis Potosi, Sinaloa, Sonora, Tamaulipas, Zacatecas, which are in the northern and central regions of the country.

KEY WORDS: Aridity, arid regions, aridity index, Geographic Information Systems, remote sensing.

RÉSUMÉ : Les régions arides couvrent plus de 43 % de la surface terrestre mondiale et se caractérisent par une faible disponibilité en eau et des variations importantes des précipitations et des températures. Au Mexique, elles occupent plus de la moitié du territoire, avec environ 40 % de la population nationale concentrée dans ces écosystèmes. Cette étude visait à identifier, classer et analyser les régions arides du Mexique en utilisant l'indice d'aridité (IA), les systèmes d'information géographique (SIG) et des images satellite sur la période 1980-2023. Les résultats montrent que les zones arides et semi-arides ont augmenté de 15 % et 4 % respectivement, tandis que les régions humides ont perdu 17 % de leur surface, indiquant une tendance croissante à l'aridité. Les États les plus touchés sont Baja California, Baja California Sur, Chihuahua, Coahuila, Durango, Nuevo León, Oaxaca, San Luis Potosí, Sinaloa, Sonora, Tamaulipas et Zacatecas, situés dans le nord et le centre du pays. Cette évolution souligne l'importance de stratégies d'adaptation face aux changements climatiques.

MOTS CLÉS : Aridité, régions arides, indice d'aridité, systèmes d'information géographique, télédétection.

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1. Introduction

Arid regions cover over 43% of the earth's surface. A dry climate, low water availability, and important changes in precipitation and temperatures, and soil moisture deficits, which cause a significant increase in water evapotranspiration characterizes them. Despite the water deficit, they are home to a wide variety of species and support important economic activities, such as agriculture and livestock, which are essential for many communities (Dunkerley, 2020; ONU, 2019; Quichimbo et al., 2020; Sánchez-Cano, 2019).

In Mexico, these regions cover more than half of the territory, in the north and center of the country, and a large part of the national population concentrates on these ecosystems, which also host several endemic species (Briones et al., 2018; Pontifes et al., 2018). Likewise, changes in temperature and precipitation in Mexico's arid regions favor the frequency and intensity of droughts, which have serious social, economic, and environmental effects (Del-Toro-Guerrero & Kretzschmar, 2020; Ortega-Gaucin et al., 2018). One of the most serious problems affecting these regions is soil degradation and desertification caused by anthropogenic actions derived from agriculture and livestock farming, making these ecosystems very sensitive to climate variability and global change (Oertel et al., 2018; Pontifes et al., 2018).

There are several ways to model and analyze aridity, one technique employed his Multi-Criteria Evaluation (MCE), which uses methods such as the Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC) to identify prizing factors causing aridity, these techniques combine a set of maps, standardize the suitability of criteria, assign importance weights to factors and model the relevance of indicators in terms of their effects on aridity hazards (Akbari et al., 2019; Aldababseh et al., 2018; Charabi & Gastli, 2011; Perez-Aguilar et al., 2021; Ullah & Mansourian, 2016).

Another technique used to classify and quantify the level of aridity in a region, which is quick and easy to implement because of the small number of variables required, is the use of Aridity Indices (AI) and climatic classification such as Martonne's AI (Mercado Mancera et al., 2010; Tabari et al., 2014) y Köppen (Spinoni et al., 2015), where its main factors are precipitation and temperature. Another AI widely used worldwide is proposed is by the Food and Agriculture Organization of the United Nations, better known as FAO (Li et al., 2017; Zomer et al., 2022) the United Nations Environment Programme (UNEP) (Campos-Aranda, 2016; Díaz-Padilla et al., 2011) which require precipitation and evapotranspiration data to be generated with the support of Geographic Information Systems (GIS) which are widely used for soil suitability analysis and evaluation (Ahmed et al., 2021; Delgado & Barredo, 2005; Hernández-Zaragoza et al., 2019; Monjardin-Armenta et al., 2020; Perez-Aguilar et al., 2021, 2022).

Since there is no updated cartography of arid regions in Mexico, the main objective of this study was to identify and classify these regions in the country, using a methodology that included the use of AI, GIS, and remote sensing images for the period 1980-2023 to analyze the evolution of aridity in the Mexican territory. The resulting arid zone maps provide important information on the past and present behavior of the aridity index since the results showed that arid and semi-arid regions predominate in the country, covering 27% and 35% of the country's surface while humid regions represent 32%. The results also showed that over the years evaluated, the arid and semi-arid regions increased by 20%, while the humid regions decreased by 17% of their surface area.

2. Study area

The United Mexican States is in the geographic location 14° 32' 27'' to 32° 43' 06'' North Latitude and 86° 42' 36'' to 118° 27' 24'' West Longitude. To the north, it borders with the United States of America, to the southeast with Guatemala and Belize, to the west with the Pacific Ocean, and the east with the Gulf of Mexico. It covers an area of 1,953,162 km2 and has a population of 118 million inhabitants (Figure 1) (INEGI, 2024b, 2024a; *Información General Sobre México*, 2024).

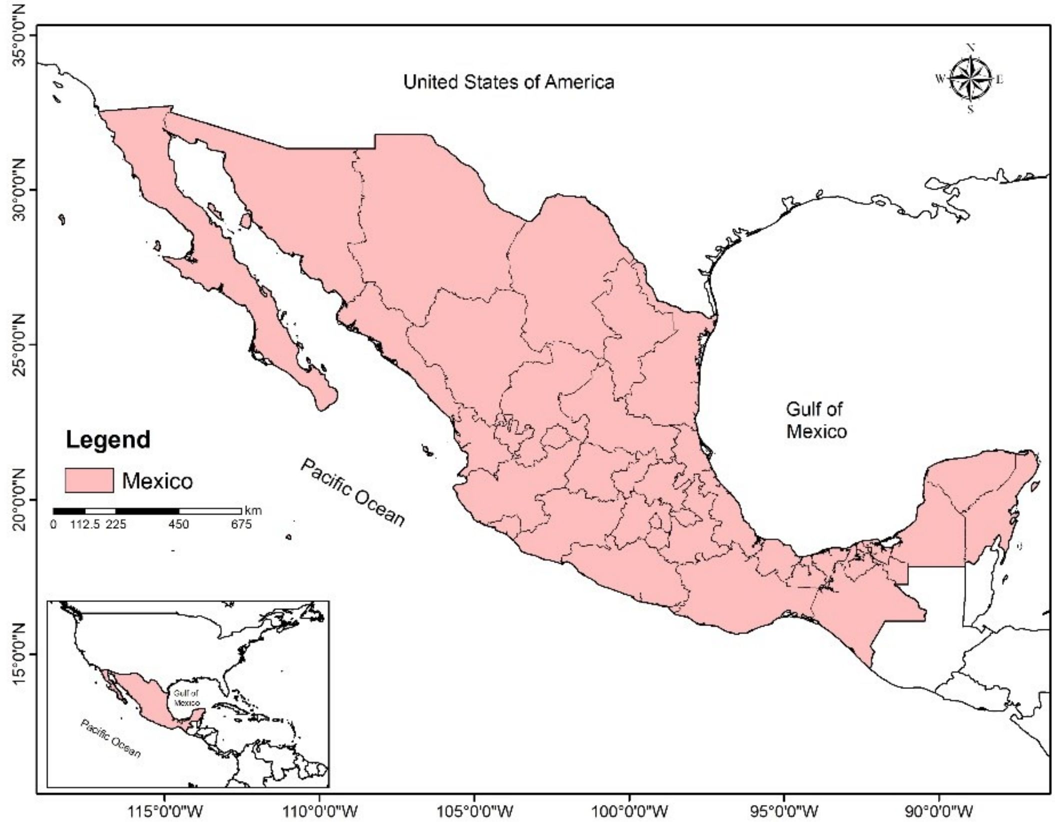


Figure 1 Study area location. The United Mexican States.

Mexico has a great climatic diversity, with climates varying from dry to humid over short distances. The northwest is arid and semi-arid, while the south is humid and semi-humid. 56% of the country is arid or semi-arid, 37% is sub-humid, and only 7% is humid. 39% of the territory is semi-hot, 23% is temperate, and 1% is cold in terms of temperature. Rainfall varies, from 100 mm in the northwest to between 2,000 and 4,000 mm in the southeas (Chapman, 2024; Morillon Galvez David, 2004; UNAM, 2024).

3. Methods

3.1. Data

Data selection and preparation was the first fundamental step in our aridity analysis from México. This methodology was based on the classification of arid regions using the aridity index proposed by UNEP. We conducted the analyzes in 5-year periods from 1980 to 2023.

Table 1 Data used for AI analysis.

Data	Data Type	Resolution Spatial/ Scale	Resolution Temporary	Units	Source / Link
Mean annual precipitation	Raster	4 km	Montly	Millimeters	TerraClimate https://app.climateengine.org/climateEngine
Potential evapotranspiration					(accessed on June 15 2024).
State political division	Vector	1:250,000	-	-	CONABIO (INEGI) http://www.conabio.gob.mx/informacion/gis
National political division					https://app.climateengine.org/climateEngine (accessed on June 15 2024).

The aridity index uses mean annual precipitation and potential evapotranspiration as the main data. We searched different platforms to make the data available and freely downloadable, and we showed the selected precipitation and evapotranspiration variables for the periods 1980-2023 in Figures 2 and 3.

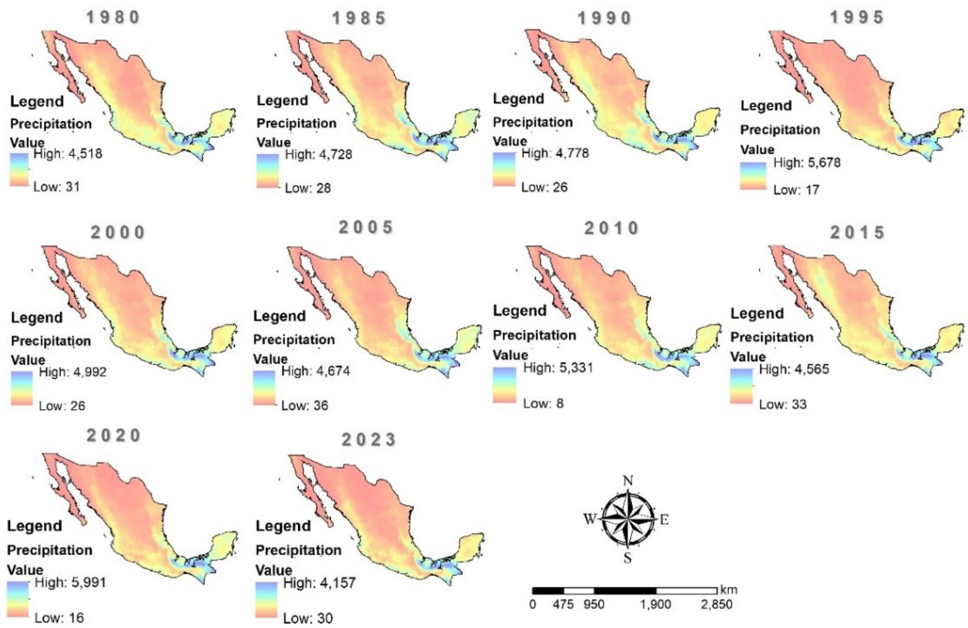


Figure 2 Average annual precipitation data for the years 1980-2023.

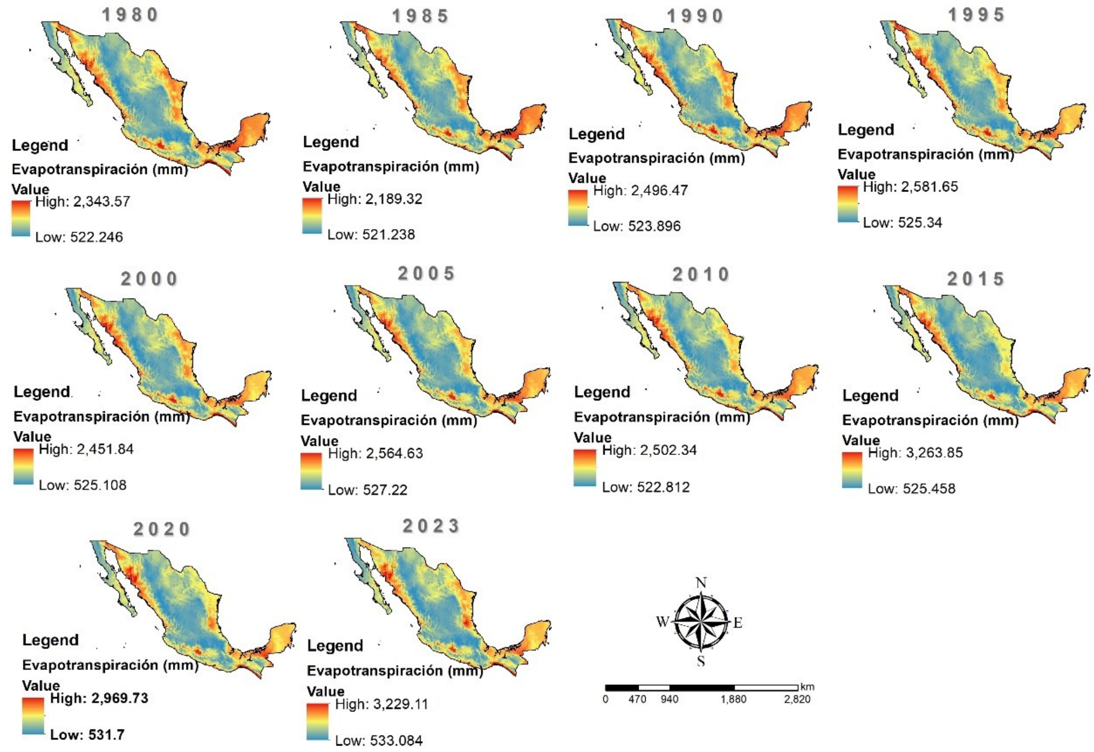


Figure 3 Potential Evapotranspiration Data for the years 1980-2023.

3.2. Methodology

The methodology applied in this research to determine arid zones for the entire Mexican territory was based on the use of the Aridity Index, which began with the selection and downloading of the data for processing. Afterward, the researchers preprocessed and standardized the data to meet the technical specifications of the study area.

Next, we used the UNEP proposal to calculate the AI, and then we classified the resulting maps into arid regions, showing the level of aridity in the different regions of the Mexican territory. We analyzed the got data geo (Figure 4).

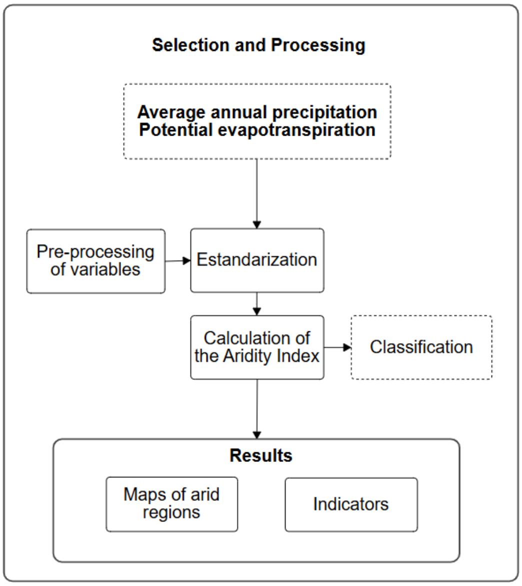


Figure 4 Methodological scheme of the process to get arid zones.

3.2.1. Data Standardization

Data standardization is adjusting and transforming geographic data to make it comparable and uniform, facilitating processing, analysis, and interpretation [33], [34]. In this analysis, we employed the study area mask as a constraint, a binary map that denotes excluded areas with a value of 0 and the region with varying levels of aridity with a value of 1; all data used in the study must meet the properties and characteristics of this constraint map (Figure 5).

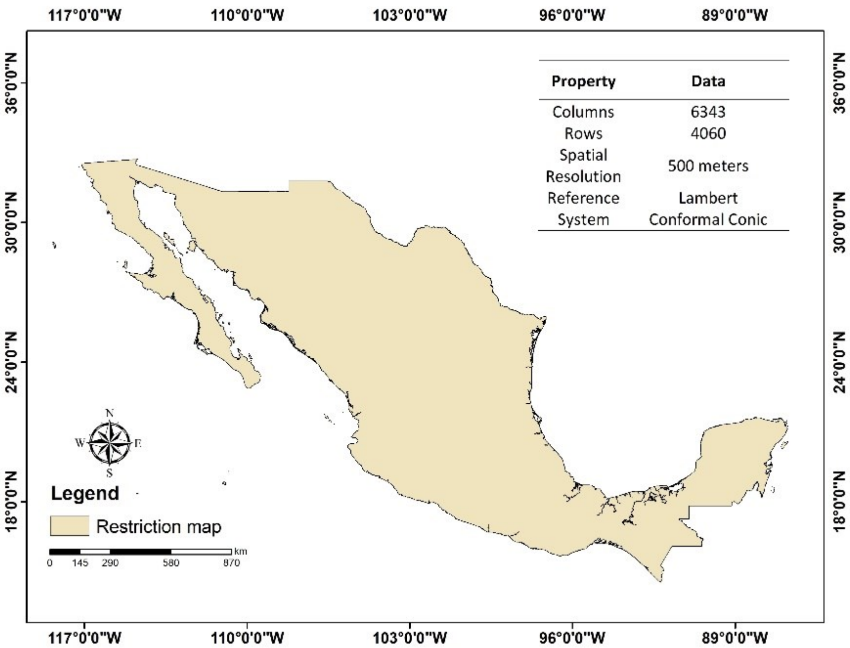


Figure 5 Study area restriction map.

3.2.2. Aridity Index

GIS software was used to generate the IA from 1980 to 2023 with periods of 5 years, using the UNEP formula, which expresses the relationship between mean annual precipitation and potential evapotranspiration. (Boschetto et al., 2010; Sohoulande et al., 2022; Zomer et al., 2022), as expressed in Equation 1:

$$IA = Pr/EvP \qquad \text{Equation 1}$$

Where: IA represents the Index of Aridity, Precipitation average annual and EvP is the potential evapotranspiration.

3.2.3. Classification Criteria

They categorized the resulting AI maps of the generated periods into five different aridity classes based on the classification proposed by the UNEP, which defines them according to the value of each pixel. (Barrow, 1992; Cherlet et al., 2018), as shown in table 2.

Table 2 The aridity index classification of the UNEP.

Index	Climate
<0.05	Extremely arid
0.05-0.2	Arid
0.2–0.5	Semiarid
0.5–0.65	Subhumid–dry
>0.65	Humid

4. Results and discussion

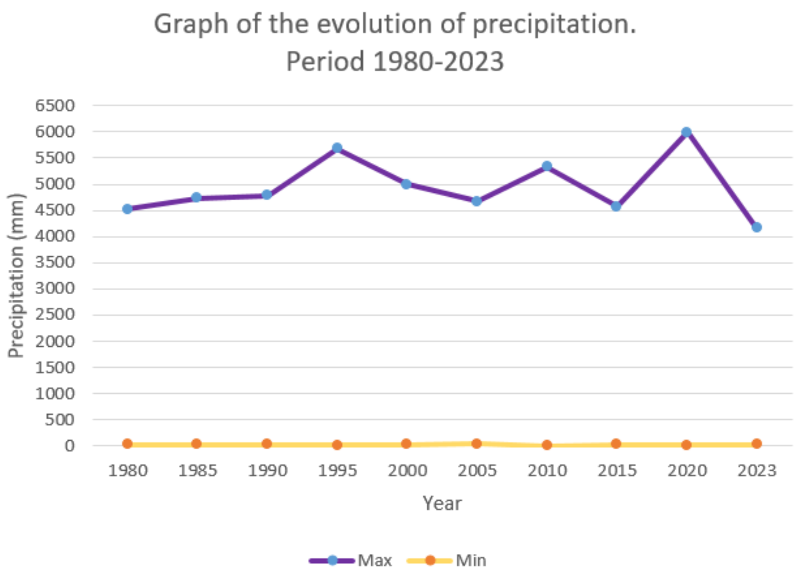
4.1. Analysis of the temporal evolution of precipitation and evapotranspiration

Maximum precipitation increased between 1980 and 1995, culminating in a high of 5678 mm in 1995. Despite a 2020 high of 5991 mm, the figure fell to 4157 mm by 2023, hinting at a climate irregularity. Minimum rainfall varied, bottoming out at 8 mm in 2010 before rising to 30 mm by 2023, showing possible periods of drought or insufficient rainfall (Table 3).

Table 3 Variability of Maximum and Minimum Precipitations (1980-2023).

Precipitation (mm) by year										
	1980	1985	1990	1995	2000	2005	2010	2015	2020	2023
Max	4,518	4,728	4,778	5,678	4,992	4,674	5,331	4,565	5,991	4,157
Min	31	28	26	17	26	36	8	33	16	30

Maximum precipitation has shown significant variability, declining since 1995, whereas minimum precipitation has remained low. Climatic phenomena could influence these patterns, as well as global climate change, which could alter long-term rainfall patterns and affect the distribution and amount of precipitation in various regions (Graph 1).



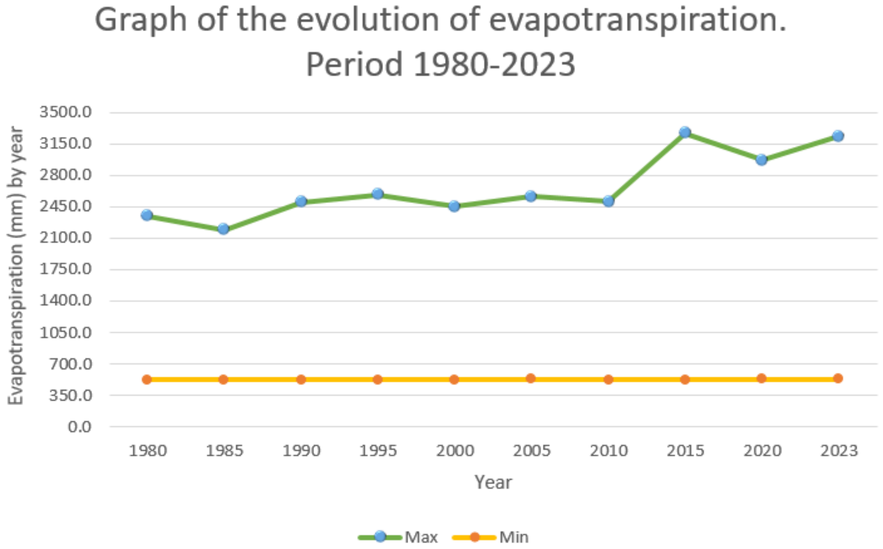
Graph 1 Evolution of precipitation. Period 1980-2023.

Evapotranspiration data from 1980 to 2023 reveals significant fluctuation in maximum and minimum values, showing climate variability and shifts in environmental conditions. From 2343.6 mm in 1980 to 2969.7 mm in 2020, maximum evapotranspiration increased by 26.7%, with 2015 and 2023 showing the highest values (3263.9 mm and 3229.1 mm). Variations in temperature, precipitation, and land use could explain the increase, suggesting that present conditions support higher rates of evaporation and transpiration (Table 4).

Table 4 Variability of Maximum and Minimum Evapotranspiration (1980-2023).

	Evapotranspiration (mm) by year									
	1980	1985	1990	1995	2000	2005	2010	2015	2020	2023
Max	2343.6	2189.3	2496.5	2581.7	2451.8	2564.6	2502.3	3263.9	2969.7	3229.1
Min	522.2	521.2	523.9	525.3	525.1	527.2	522.8	525.5	531.7	533.1

Despite a more gradual increase, minimum evapotranspiration has risen 2.1% since 1980, reaching 533.1 mm in 2023. Although minimum values have increased, their variability is more stable, showing less drastic change in lower evaporation/transpiration conditions. A widening gap between maximum and minimum values may show growing water stress or shifts in climate affecting moisture (Graph 2).



Graph 2 Evolution of evapotranspiration. Period 1980-2023.

4.2. Aridity Vulnerability Maps

Once we applied the AI formula, we got resulting maps for each evaluation period, where each pixel held a value ranging between >0.5, showing greater vulnerability to aridity, and <0.65, showing less aridity (Figure 6).

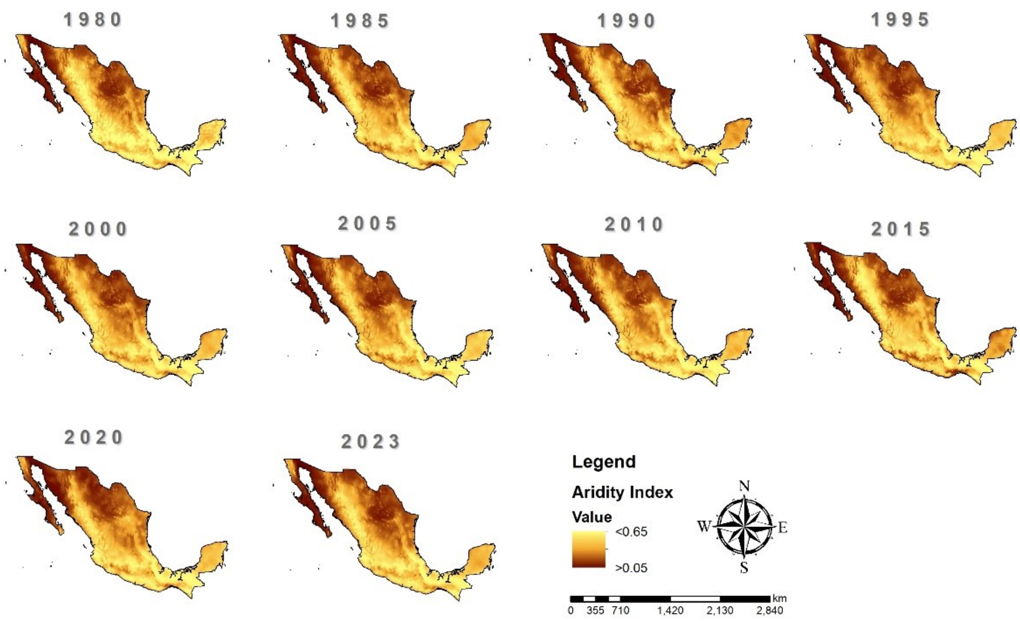


Figure 6 Aridity index. Vulnerability maps.

From each AI, we extracted the minimum values that represent more arid regions and maximum values that show more humid regions. In this way, we can analyze each situation of aridity that occurs in the different periods evaluated. In Table 5 we can analyze the minimum value, from 1980 to 2023, the AI has been increasing, so the hyper-arid, arid, and semiarid regions have increased, while, observing the maximum value, we can affirm that the sub-humid and humid regions have been decreasing

Table 5 Minimum and maximum AI values for 1980-2023.

Year	Minimum Value	Maximum Value
2023	0.027	3.10
2020	0.026	3.20
2015	0.025	3.71
2010	0.024	4.71
2005	0.023	4.09
2000	0.013	4.48
1995	0.010	4.63
1990	0.017	4.38
1985	0.024	4.41
1980	0.010	4.50

4.3. Spatial Distribution of Aridity

Once the arid regions have been classified, the temporal analysis and the data got from 1980 to 2023 showed that the increase in aridity is occurring in the hyper arid, arid and semiarid regions of the northern and northwestern regions of Mexico, where hot, dry and semi dry climates predominate, while the humid and sub humid regions are decreasing in the southern and southeastern regions, which are characterized by dry and hot climates with some temperate parts (Figure 7).

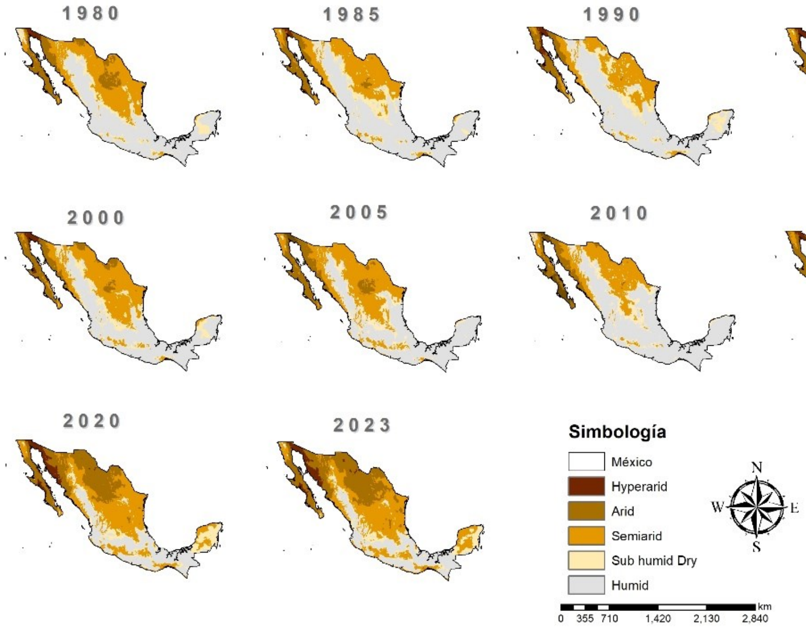


Figure 7 Classified arid zone maps.

4.4. Geostatistical and geospatial indicators in arid zones at a state level

Analyzing the data at both national and state levels was necessary to get quantitative and percentage information regarding surface areas of the aridity level. The results show that hyperarid, arid, and semiarid regions cover 66.5% of the Mexican territory, compared to 45.8% in 1980, representing a 20.7% increase in aridity over the last 43 years. The data shows that today hyperarid regions make up 4% of the Mexican territory, Arid regions represent 27%, and semiarid zones represent 35% of the country (Figure 8, Table 6, and Graph 3).

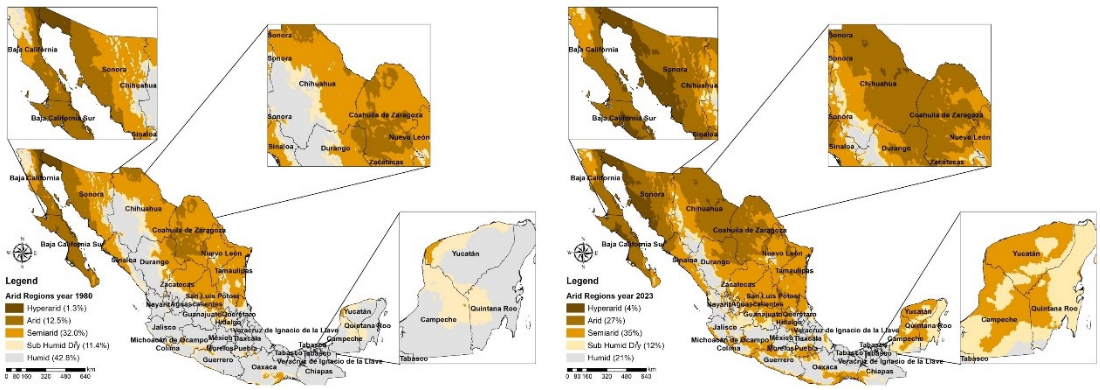
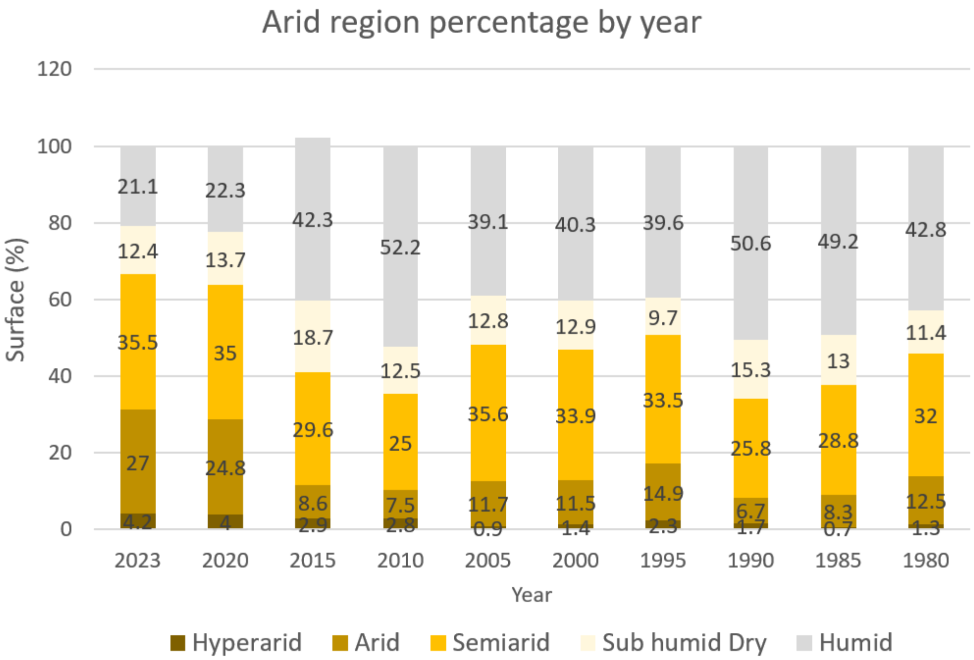


Figure 8 Maps of arid zones, focusing on the most notable changes between 1980 and 2023. On the left, 1980; on the right, 2023.

Table 6 Aridity percentage and surface area (km^2) of arid regions by year.

Year	Hyperarid	%	Arid	%	Semiarid	%	Sub humid Dry	%	Humid	%
2023	88,013	4.2	521,912	27.0	685,115	35.5	239,346	12.4	407,981	21.1
2020	71,263	4.0	478,971	24.8	677,237	35.0	264,161	13.7	430,737	22.3
2015	18,013	2.9	165,679	8.6	571,209	29.6	360,835	18.7	816,653	42.3
2010	53,390	2.8	145,195	7.5	482,388	25.0	242,490	12.5	908,910	52.2
2005	16,460	0.9	225,985	11.7	686,991	35.6	248,019	12.8	754,928	39.1
2000	27,675	1.4	222,638	11.5	654,157	33.9	250,027	12.9	777,879	40.3
1995	44,513	2.3	287,756	14.9	646,917	33.5	187,714	9.7	765,493	39.6
1990	32,149	1.7	129,756	6.7	497,670	25.8	295,125	15.3	977,661	50.6
1985	14,165	0.7	160,579	8.3	556,033	28.8	251,180	13.0	950,417	49.2
1980	24,634	1.3	241,746	12.5	617,838	32.0	220,760	11.4	827,394	42.8



Graph 3 Graph of arid region surfaces by year.

Our analysis of state-level aridity indicators shows that hyperarid regions are concentrated mainly in Sonora, Baja California Sur, Baja California, and Chihuahua. The states most affected by arid regions are Chihuahua, Coahuila de Zaragoza, Sonora, Baja California Sur, Baja California, Durango, Nuevo León, and Sinaloa, while the states with the largest semiarid zones are Tamaulipas, Zacatecas, Chihuahua, San Luis Potosí, Durango, Nuevo León, Coahuila de Zaragoza and Sinaloa (Table 7 and Figure 9).

Figure 9 Arid zones map by state year 2023.

Table 7 Aridity percentage and surface area of arid regions by state year 2023.

State	Hyperarid	%	Arid	%	Semiarid	%	Sub humid Dry	%	Humid	%
Aguascalientes	0	0.00	0	0.00	5139	0.27	420	0.02	0	0.00
Baja California	5945	0.31	39707	2.06	22580	1.17	3506	0.18	349	0.02
Baja California Sur	11805	0.61	49482	2.56	7564	0.39	544	0.03	369	0.02
Campeche	0	0.00	0	0.00	23868	1.24	24226	1.25	6715	0.35
Chiapas	0	0.00	0	0.00	6761	0.35	9280	0.48	56199	2.91
Chihuahua	3388	0.18	157918	8.18	56305	2.92	16168	0.84	12892	0.67
Coahuila de Zaragoza	0	0.00	110487	5.72	36892	1.91	2017	0.10	908	0.05
Colima	0	0.00	43	0.00	3484	0.18	974	0.05	1127	0.06
Ciudad de México	0	0.00	0	0.00	0	0.00	305	0.02	1181	0.06
Durango	0	0.00	28392	1.47	49142	2.55	13264	0.69	31333	1.62
Estado de México	0	0.00	0	0.00	2094	0.11	2662	0.14	17470	0.90
Guanajuato	0	0.00	39	0.00	17012	0.88	10315	0.53	2974	0.15
Guerrero	0	0.00	0	0.00	17014	0.88	12009	0.62	34201	1.77
Hidalgo	0	0.00	0	0.00	10425	0.54	4763	0.25	5467	0.28
Jalisco	0	0.00	132	0.01	19337	1.00	24388	1.26	33982	1.76
Michoacán	0	0.00	293	0.02	18298	0.95	11605	0.60	27995	1.45
Morelos	0	0.00	0	0.00	477	0.02	2232	0.12	2150	0.11
Nayarit	0	0.00	0	0.00	2535	0.13	8678	0.45	16139	0.84
Nuevo León	0	0.00	11809	0.61	48263	2.50	2306	0.12	1176	0.06

State	Hyperarid	%	Arid	%	Semiarid	%	Sub humid Dry	%	Humid	%
Oaxaca	0	0.00	2225	0.12	24687	1.28	11005	0.57	54375	2.82
Puebla	0	0.00	325	0.02	11564	0.60	5740	0.30	16524	0.86
Querétaro	0	0.00	0	0.00	9098	0.47	1197	0.06	1294	0.07
Quintana Roo	0	0.00	0	0.00	10198	0.53	31147	1.61	1083	0.06
San Luis Potosí	0	0.00	4749	0.25	54181	2.81	1568	0.08	1	0.00
Sinaloa	0	0.00	10509	0.54	33863	1.75	5309	0.27	4689	0.24
Sonora	56742	2.94	98711	5.11	21194	1.10	2673	0.14	62	0.00
Tabasco	0	0.00	0	0.00	0	0.00	1070	0.06	22804	1.18
Tamaulipas	0	0.00	6138	0.32	69839	3.62	611	0.03	9	0.00
Tlaxcala	0	0.00	0	0.00	57	0.00	384	0.02	3533	0.18
Veracruz	0	0.00	449	0.02	11236	0.58	10410	0.54	47359	2.45
Yucatán	0	0.00	0	0.00	27888	1.44	11011	0.57	0	0.00
Zacatecas	0	0.00	218	0.01	63634	3.30	7381	0.38	3246	0.17

4.5. Comparative Analysis of the Results with Previous Research

We compared the results with previous studies on arid regions in Mexico. By 2010, Mexico's land comprised 2.8% hyperarid, 7.5% arid, 25% semiarid, 12.5% dry sub-humid, and 52.2% humid regions. Compared to the 2011 Universidad Autónoma Chapingo study (using the UNCCD classification), which showed 15.7% arid, 58% semi-arid, and 26.3% dry sub-humid zones (Figure 10), these values are different. In contrast, our data suggests a reduced proportion of drylands, within arid and semi-arid classifications. Differences in method, data resolution, or analysis periods may explain these discrepancies. Adding the hyperarid class in this study could have altered the percentage distribution of other aridity categories.

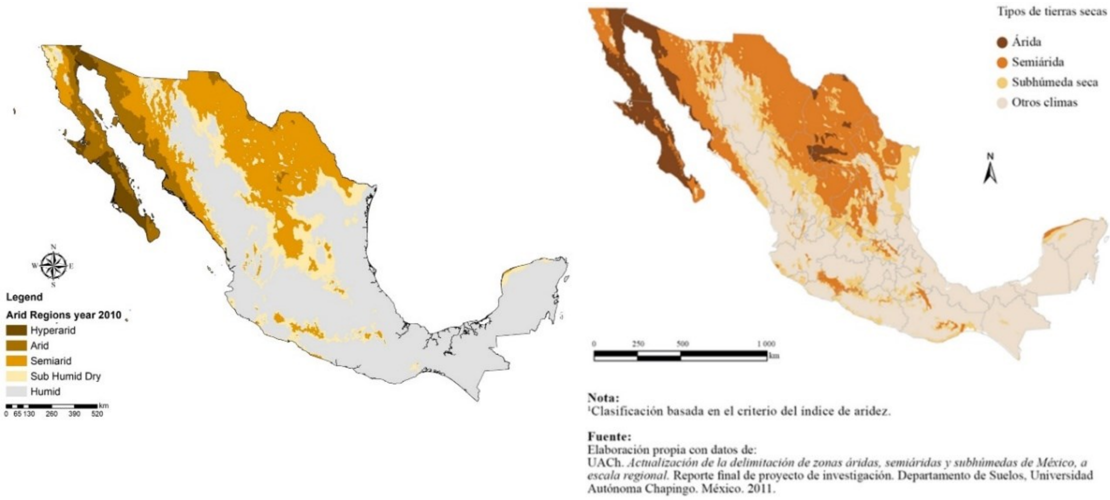


Figure 10 Comparative image of arid regions in Mexico. Left: 2010 map of arid regions got for this study; right: 2011 maps of arid regions prepared by the Autonomous University of Chapingo. Source: (SEMARNAT, 2014).

Comparing the 2020 Aridity Index with the 2017 UNDP/INECC study shows differing aridity categories in Mexico. In 2020, 4.0% of the land was hyper-arid, 24.8% arid, 35.0% semi-arid, 13.7% dry sub-humid, and 22.3% humid; however, in 2017, only 0.69% was hyper-arid, 19.01% arid, 34.01% semi-arid, and 11.17% dry sub-humid (Figure 11). Drylands saw a reduction in 2020 versus 2017, showing shifts in climate because of recent environmental changes. However, because the two studies' methodologies differ, a unified approach is necessary for a more precise assessment of increasing aridity in Mexico.

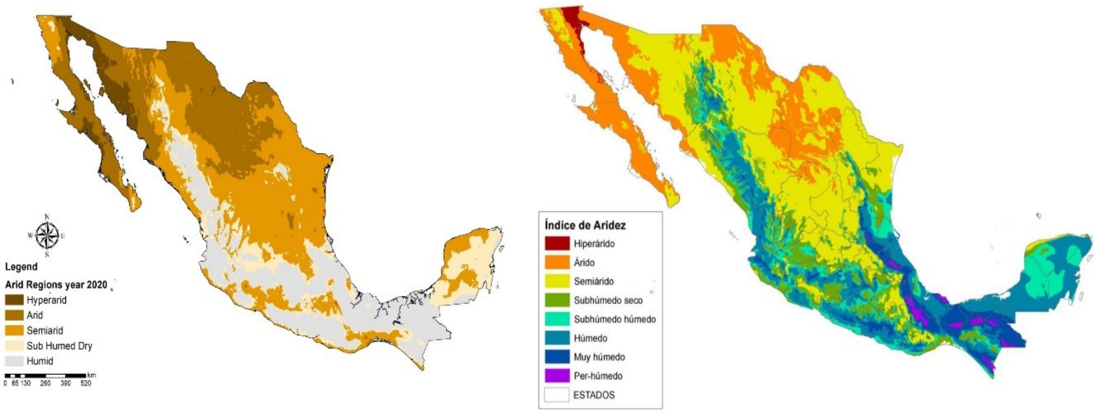


Figure 11 Comparative image of arid regions in Mexico. Left: 2020 map of arid regions got in this study; right: 2017 maps of arid regions prepared by PNUD-INECC. Source: (PNUD-INECC, 2017).

We also compared drought data (Monitor de Sequia en Mexico) with our 2015, 2020, and 2023 aridity index (Figure 12), concentrating on peak drought months. This analysis showed a weak correlation between drought and the aridity index. The aridity index focuses on precipitation and evapotranspiration to determine a region's climate. This index shows the balance between precipitation and water loss (evaporation and transpiration), helping pinpoint drier or wetter areas within a time frame.

Drought is far more intricate than a lack of rainfall; it encompasses temperature, plant stress, soil dampness, and unusual weather patterns, none of which the aridity index accounts for. The Standardized Precipitation Index (SPI), the Satellite Vegetation Health Index (VHI), and similar models incorporate different variables affecting water availability and ecosystem conditions to monitor drought. Therefore, the aridity index, though helpful in assessing regional climates, falls short of explaining drought, a phenomenon influenced by a broader spectrum of climatic and environmental factors.

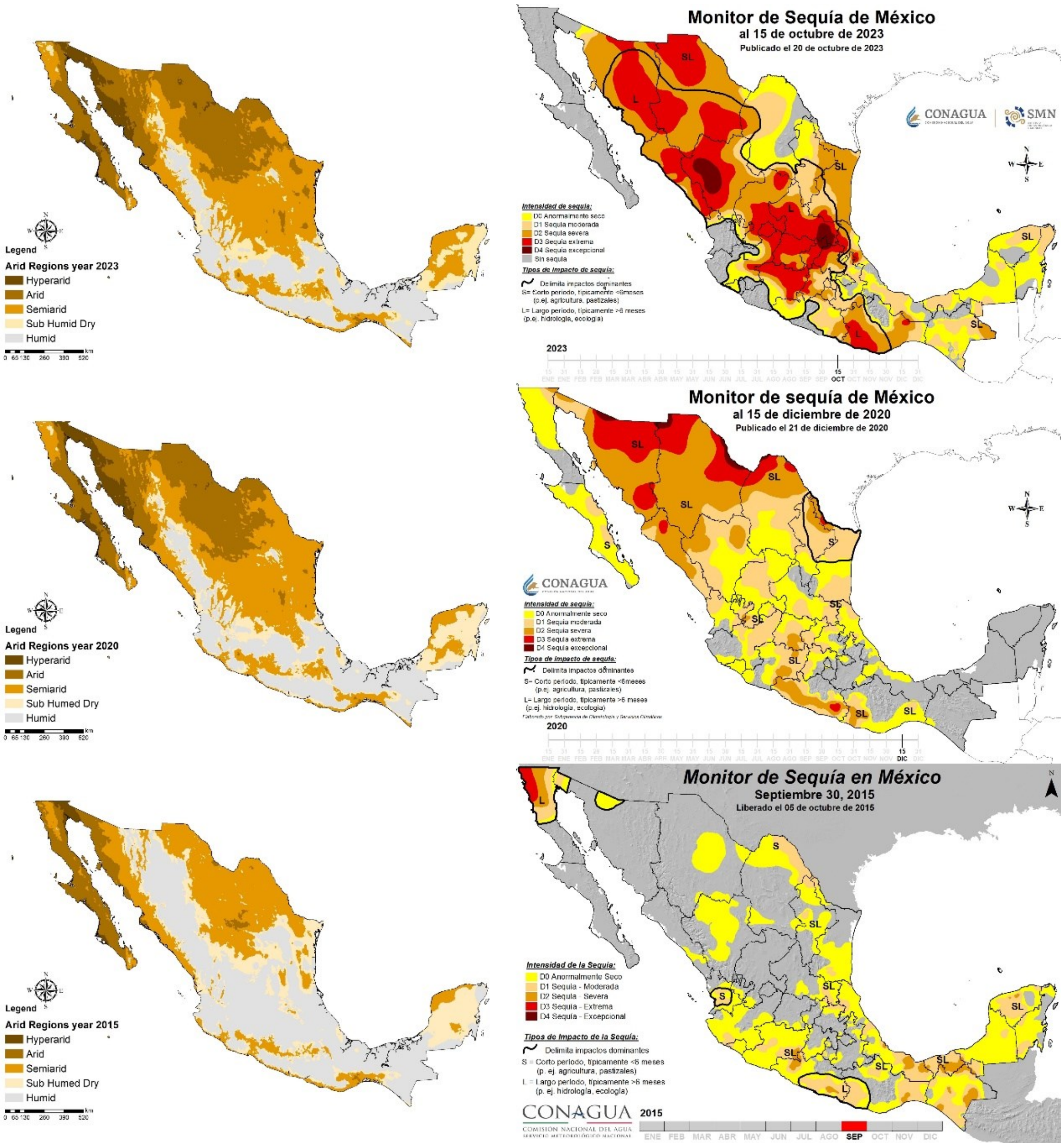


Figure 12 Comparative image of arid regions and drought-affected areas for the years 2015, 2020, and 2023. Source: (CONAGUA, 2024).

6. Conclusion

The main conclusions of the study must be presented hereIncreasing aridity leads to other environmental problems such as desertification, either through increased variability in rainfall and rising temperatures or because of prolonged periods of drought. Various studies have been based on climate data to determine the global distribution of arid zones. These arid conditions pose a threat to many places in the world, including Mexico, as the country experiences high levels of aridity, particularly because most arid regions are on degraded soils that could expand if the same land use and water resource management practices persist.

This research used a methodology that uses AI, GIS, and remote sensing meteorological images to identify and classify arid regions at the national and state levels and thus get maps of vulnerability to aridity from 1980 to 2023. The resulting arid zone maps provided relevant information on the past and current state of these regions. The results showed that, in Mexico, arid and semi-arid zones predominate, which is consistent with previous studies on arid zones, such as the Atlas of Arid Zones of Mexico (SAGARPA & SIAP, 2014), the INEGI climate map (INEGI., 2018) and the humidity range map from the CONABIO geo-information portal (CONABIO, n.d.).

At the national level, the results showed that the most affected areas are regions with hyperarid, arid, and semiarid conditions, which are found in the northwest and center of the country. At the state level, the most affected states are Baja California, Baja California Sur, Chihuahua, Coahuila de Zaragoza, Durango, Nuevo León, San Luis Potosí, Sinaloa, Sonora, Tamaulipas and Zacatecas. Using AI is a simple method to implement and provides very accurate results on the impact of aridity risks. Future research could focus on older years and annual intervals to get a more precise view of the evolution of aridity in Mexico. Therefore, this research is very useful to contribute to the use of water, natural, and land resources and thus protect arid ecosystems.

We consider it very important to know the levels of aridity in the Mexican territory and its evolution over the years, since this shows that these regions are increasing. Therefore, the results got in this study could establish priorities in the fight against desertification, develop strategies for the sustainable management of natural resources, improve the sustainable management of water resources, guide policies to mitigate the effects of climate change, and guarantee food security for the population in the arid regions of Mexico.

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