The water crisis at the Miguel Alemán dam in Valle de Bravo, State of México

La crise de l'eau au barrage Miguel Alemán à Valle de Bravo, État de Mexique

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ABSTRACT: The laboratory focuses on monitoring socio-environmental indicators related to the degradation and environmental impact generated by human activities in forest areas and any other activities associated with environmental sites. In this sense, it is highlighted that the country's forests offer a wide range of ecosystem services (ES), understood as benefits that ecosystems offer to people and that directly or indirectly influence their well-being. Urban peripheries offer ES at multiple temporal and spatial scales, and the subsistence of cities depends on them. The development and enhancement of Earth Observation through the construction of GIS will allow the capture, storage, analysis, and visualization of geographic data. Understanding temporal and spatial socio-ecological changes is necessary to identify historical trends and project future changes, and, with this, propose guidelines for informed decision-making and integrated territorial planning, with a view to the sustainability and resilience of societies.

KEY WORDS: socio-environmental indicators, environmental impact, ecosystem services.

RÉSUMÉ : Le laboratoire se concentre sur le suivi des indicateurs socio-environnementaux liés à la dégradation et à l'impact environnemental générés par les activités anthropiques sur les zones forestières et toutes autres zones associées aux sites environnementaux. En ce sens, il convient de souligner que les forêts du pays offrent une large gamme de services écosystémiques (SE), compris comme des avantages que les écosystèmes offrent aux personnes et qui influencent directement ou indirectement leur bien-être. Les périphéries urbaines offrent des SE à de multiples échelles temporelles et spatiales et la subsistance des villes en dépend. Le développement et la potentialisation de l'observation de la Terre à travers la construction de TIG qui permettront la capture, le stockage, l'analyse et la visualisation de données géographiques. Connaître les changements socio-écologiques temporels et spatiaux est nécessaire pour identifier les tendances historiques et projeter les changements futurs et, avec cela, proposer des lignes directrices pour une prise de décision durable et une planification territoriale intégrée, en vue de la durabilité et de la résilience des sociétés.

MOTS CLÉS: indicateurs socio-environnementaux, impact environnemental, services écosystémiques.

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1. Introduction

Since the covid-19 pandemic, the Miguel Alemán dam has significantly reduced its water storage levels, to the point of registering only 29.3% of its capacity in March 2024. Among the factors contributing to this decrease are the low amount of rainfall, the excessive extraction of water as part of the Cutzamala System complex that supplies water to Mexico City, uncontrolled construction in the localities within the basin, private dams, cisterns and pools that are fed by the main flows into the dam, the increase in population and the dispersion of services and commerce throughout the Amanalco-Tiloxtoc basin. In this basin, the capacity of the water network is crucil in the water supply system in the reservoir. Additional factors include the deterioration of the natural environment, land use change due to excessive deforestation, erosion, urban sprawl, and human activities contributing to further land use changes. The drop in the water level has become a major problem to the point of threatening the very existence of this large body of water.

The objective of this research is to analyze the environmental and social elements that prevail in the Municipality of Valle de Bravo, State of Mexico, and to determine the factors that intervene in the filling of the Miguel Alemán Dam.

2. Study area

For papers that focus on an area, provide a brief synopsis of the physical characteristics of the area, sufficient to give the new work context, but avoid a detailed literature survey.

Background on Dam Construction in Mexico

The planning of any dam, due to its technical characteristics and economic requirements, involves the coordination of multiple actors: international organizations, the federal government, government secretariats, federal commissions, state and local governments, international and national banks, universities, engineering associations, construction companies, business owners, transporters, and others. This process of political coordination can and should take as long as necessary, even years. However, it is common for the last to be notified of the populations of communities and towns that will have to relocate to carry out the project.

The dams were initially built to store water for agricultural irrigation in areas where it was scarce due to the country's own geographical conditions. The only way to develop at the beginning of the last century was through agriculture, which was essential not only to meet domestic food needs, but also for export and, secondarily, for the generation of hydroelectric energy.

In Mexico, 4,500 dams have been built, more than 700 of which are classified as large due to the size of their dam walls or reservoirs. Together, they store 80 percent of the available surface water. Of this total, 80% is stored in only fifty large dams, which are considered the most important hydraulic infrastructure in the country (Olvera, 2012). However, 80 percent of dams are contaminated (Arredondo Figueroa, 2007); although several have reached the end of their useful lives, they have not been dismantled and continue to obstruct the cleaning of rivers.

In a country as heterogeneous and extensive as Mexico, dams ensure the supply of water to important sectors of the population, sustain fundamental activities such as agriculture, protect people from extreme weather events, and even allow the generation of electricity.

In Mexico, there is a total of 6,325 dams and storage dams. As they are publicly owned, most of them are the heritage of all Mexicans: 3,618 belong to the National Water Commission (Conagua); the Ministry of Agriculture and Rural Development (including the National Commission for Arid Zones) has 995; different state and municipal governments have 275; and the Federal Electricity Commission (CFE) has 60. The rest are managed by other federal agencies, the International Boundary and Water Commission, and even private individuals, as shown in figure 1.

The function of the dams operated by the CFE is to generate electricity by taking advantage of the fall of water to operate large turbines that generate and conduct electricity. The higher the water level in the dam, the more energy is produced. In contrast, the dams operated by Conagua have several objectives. Although some of them also generate electricity, the vast majority store water for users, control flood protecting people and their property—or help to conduct water to the places where it is needed. In the latter case, they are called diversion dams.

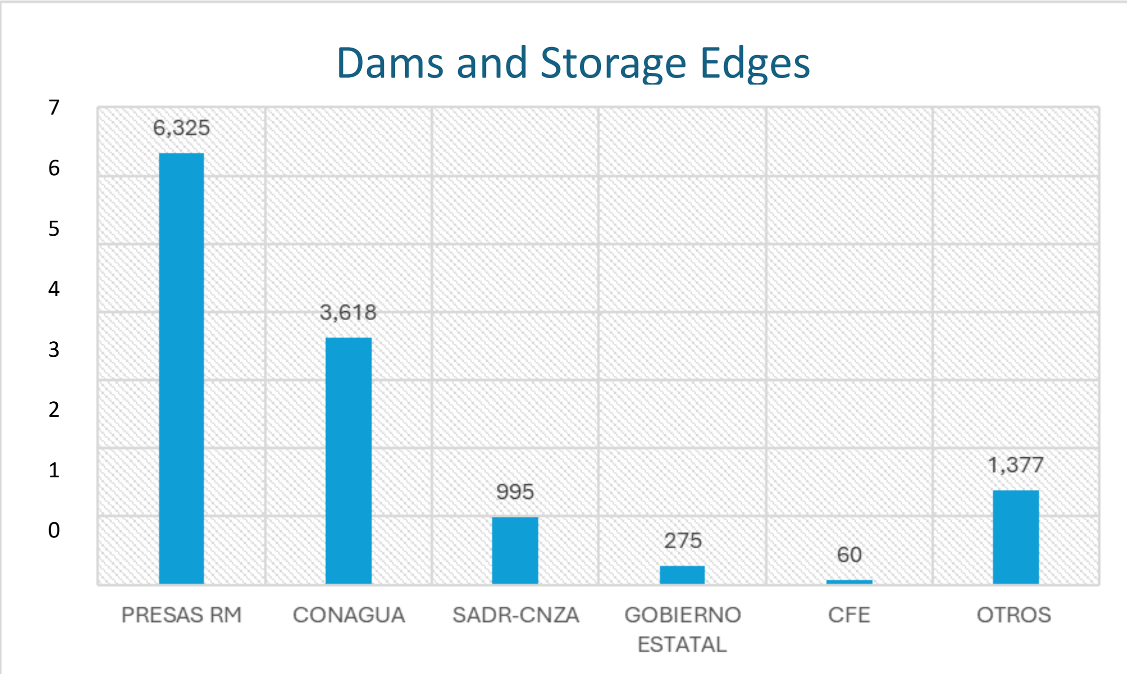

Figure 1 Dams and Storage Borders in Mexico. Source 1 Own elaboration based on CONAGUA (2020).

The fundamental objective of the dams managed by Conagua is to supply water to population centers or agriculture. This activity has been maintained even during the current health contingency to ensure the supply to the population and sustain the viability of agriculture. Agriculture uses water in batches and at very specific periods of the year, which depend on the type of crop and whether it rains or not. On the other hand, the needs of the villages are more constant, although they also vary throughout the day (less water is used at night) or during the year (more is consumed in hot weather). It is these variations in demand that make it necessary to save and manage water, releasing it when and as required. Conagua also operates flood control dams, known as peak breakers. Unlike the previous ones, these maintain a low water level, or even remain empty, as is the case with several located west of Mexico City.

The dams break peaks, cushion the massive arrival of water due to rain, and store it to release it in a controlled way, avoiding flooding or reducing damage to populations, crops, or other assets.

Socioeconomic Characteristics of Valle de Bravo

According to INEGI (2020), the total population of Valle de Bravo in 2020 was 61,590 inhabitants, with 51.2% women and 48.8% men.

The age groups that concentrated on the largest population were 0 to 4 years old (5,744 inhabitants), 5 to 9 years old (5,669 inhabitants), and 10 to 14 years old (5,627 inhabitants). Together, they accounted for 27.7% of the total population.

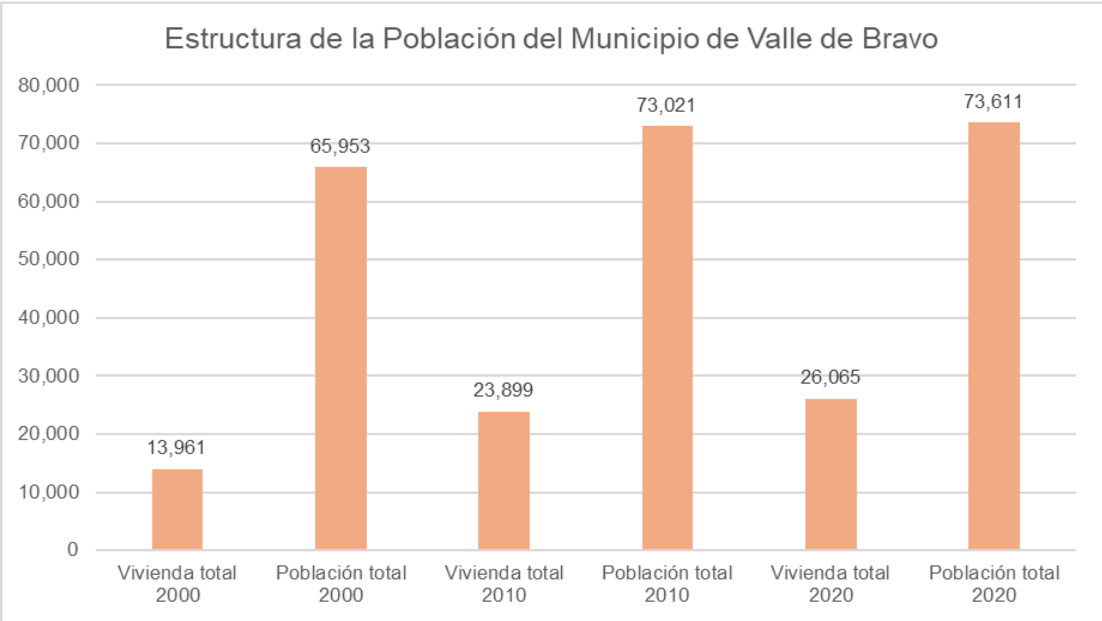

Figure 2 Population Structure of the Municipality of Valle de Bravo. Source 1 Own elaboration with INEGI database (2020).

Regarding the speakers of an indigenous language, we have the following data: the population aged 3 years and over who speaks at least one indigenous language was 254 people, which corresponds to 0.41% of the total population of Valle de Bravo. The most widely spoken indigenous languages were Mazahua (196 inhabitants), Huastec (18 inhabitants), and Otomi (11 inhabitants).

Migration plays an important role in understanding the number of resources that the population needs because the more people arrive at the place, the more water is required to meet their needs. Therefore, the following data is available: the largest number of migrants who entered Valle de Bravo in the last 5 years came from the United States (74 people), France (10 people), and Colombia (5 people).

The main causes of migration to Valle de Bravo in recent years were family (30 people), housing (29 people), and work (19 people).

Regarding homes, it is important to highlight the following data: in 2020, most inhabited private homes had 3 and 4 bedrooms, 30.7% and 21.2%, respectively. In the same period, 39.1% and 30.1%, respectively, stand out from inhabited private homes with 2 and 1 bedrooms.

Education is no less an important element to analyze in the Municipality of Valle de Bravo, and according to the government of the State of Mexico, the following data is available: In 2020, the main academic levels of the population in Valle de Bravo were Secondary (31.2% of the total), Primary (29.2% of the total), and Preparatory or General Baccalaureate (20% of the total). That is, the higher education level for this municipality has little relevance, or the percentages are zero, indicating that there is still much to be done in the field of education. In addition to the above data, the illiteracy rate in Valle de Bravo in 2020 was 6%. Of the total illiterate population, 40% were men, and 60% were women.

A no less important sector to highlight is the issue of health, and for the municipality, the following data is provided: The most used healthcare options in 2020 were the Health Center or Hospital of the SSA (Popular Insurance) (31.2%), Pharmacy Office (9.34%), and IMSS (Social Security) (8.93%).

In 2020, 50.5% of the population was in moderate poverty, and 9.5% in extreme poverty. The vulnerable population due to social deprivation reached 27.7%, while the vulnerable population by income was 4.18%.

The main social deprivations in Valle de Bravo in 2020 were lack of access to social security, lack of access to health services, and educational lag.

3. Methods

The Miguel Alemán Dam, commonly known as the Valle de Bravo Dam, was started in 1947 and completed in 1955. This hydraulic structure is part of the Cutzamala System, one of the main drinking water supply systems for Mexico City and its metropolitan area.

Located in the municipality of Valle de Bravo, in the State of Mexico, the dam has a storage capacity of approximately 391 million cubic meters of water. In addition to its primary function of water supply, the dam is also used for hydroelectric power generation and for recreational and tourist activities.

This reservoir, fed by several rivers, is a fundamental resource both for the economic development of the region and for the well-being of millions of people who depend on the water it provides (Conagua, 2005).

Cutzamala System

In 1972, the Water Commission of the Valley of Mexico conducted studies in which it determined that the Cutzamala River basin met the conditions to supply drinking water to the metropolitan area of Mexico City. For this, it was only necessary to change the use from electricity generation to drinking water supply in a way that would not cause damage to the region, since reserves of 3,000 L/s would be maintained for electricity generation and a similar amount to meet local demands and future developments (Conagua, 2005).

The Cutzamala System takes advantage of the water from the upper basin of the river that bears its name. It is made up of the Tuxpan and El Bosque dams, in Michoacán; and the Colorines, Ixtapan del Oro, Valle de Bravo, Villa Victoria, and Chilesdo dams, in the State of Mexico.

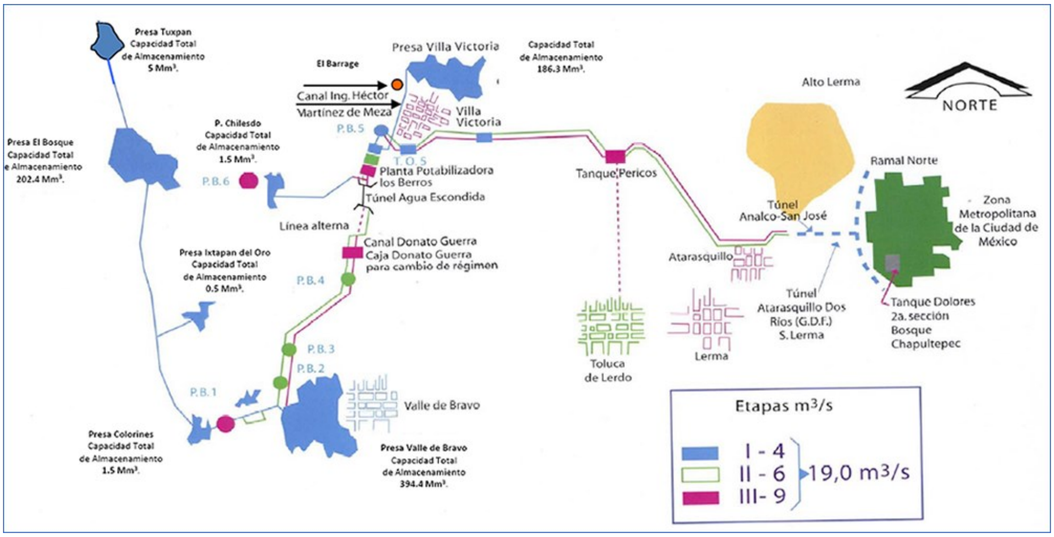

Figure 3 Schematic of the Cutzamala System. Source 2 CONAGUA (2005).

The Valle de Bravo Dam is a fundamental element of the Cutzamala System, a large-scale hydraulic infrastructure that supplies drinking water to millions of inhabitants in the Metropolitan Area of the Valley of Mexico. Located in the State of Mexico, this impressive engineering work has been crucial in guaranteeing the water supply to one of the most populated regions of the country.

For the collection of data, an analysis of the behavior of the Valle de Bravo Dam was conducted, and a comprehensive hydrological and climatological database was compiled. To thoroughly analyze the behavior of the dam, storage and extraction data were obtained, and monthly information was gathered from the Hydrological Information System (SIH) for the period of 30 years (1994-2023). This data made it possible to accurately determine the volumes of water stored in the dam and the quantities extracted for distribution.

In addition, monthly rainfall data from various weather stations near the dam, belonging to the National Meteorological Service (SMN), were integrated. The selected stations were 15374, 15368, 15174, 15165, and 15130, located in the sub-basins of Temascaltepec, upper Ixtapan, Valde River, and middle Ixtapan. Due to the long consultation period, the stations had missing data for various reasons. Therefore, it was decided to use historical climatological data from a platform (Climate Engine, 2024), obtaining a continuous record of the variables for their analysis.

4. Results and discussion

The municipality of Valle de Bravo is in the western part of the Balsas River basin, at an average altitude of 1,800 meters above sea level. Its environment consists of mountains and coniferous forests. The municipality is bordered to the north by Villa de Allende and Donato Guerra, to the east by Amanalco, to the south by Temascaltepec, and to the west by Santo Tomás and Ixtapan del Oro, as shown in Figure 4.

The climate of Valle de Bravo is temperate and subhumid. In the highest areas of the municipality, the climate is cooler, which favors the presence of abundant vegetation. The surrounding mountains, such as Monte Alto and Cerro de la Cruz, make it a municipality of great tourist relevance, in addition to being considered an ecological conservation area and a natural refuge.

Furthermore, it is known for its cultural festivals, colonial architecture, and the practice of extreme sports, making it a municipality with a strong tourist vocation.

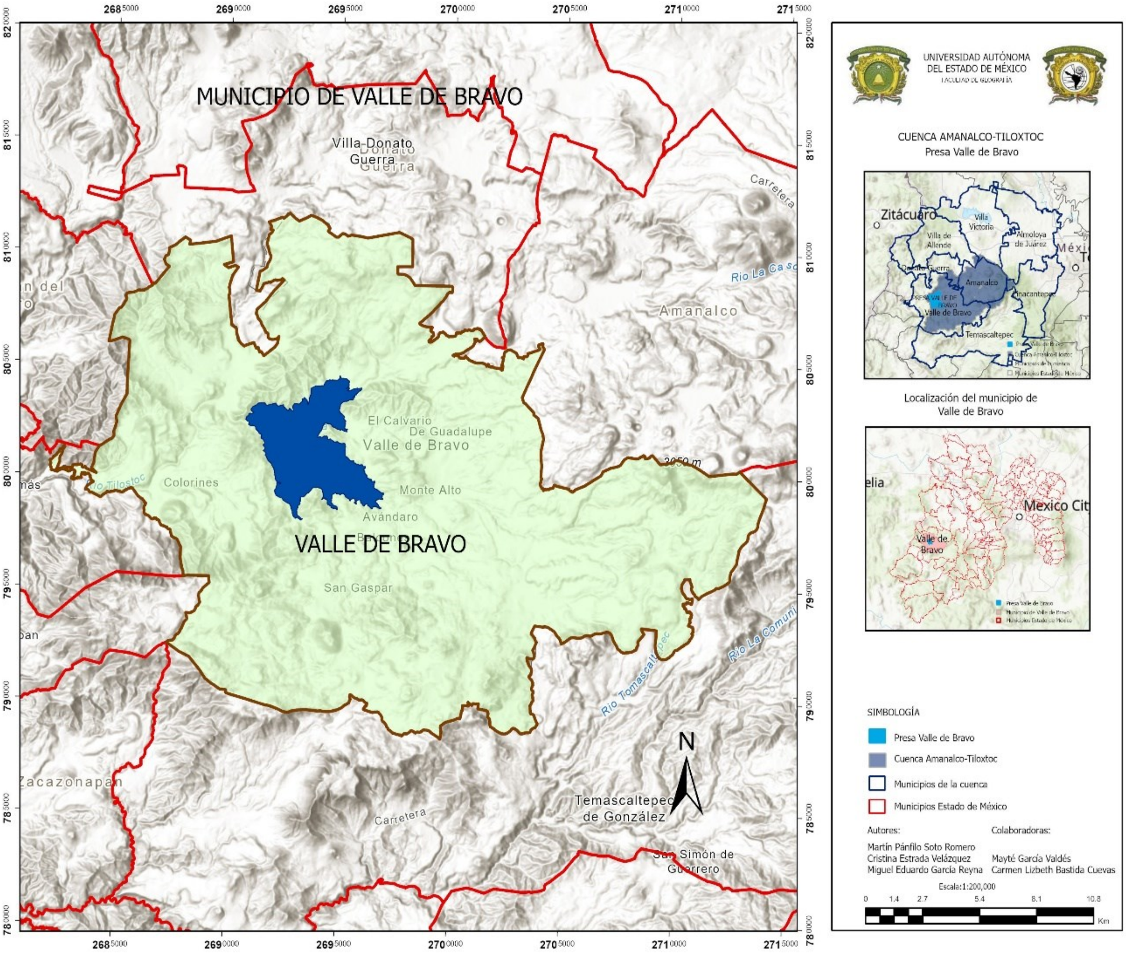

Figure 4 Geographical location of the municipality of Valle de Bravo. Source 4 Own elaboration with INEG database, (2024).

The figure 4 illustrates the geographical dimension of the Amanalco-Tiloxtoc Basin, which supplies the Miguel Alemán Dam, part of the Cutzamala System's water supply. The basin consists of 8 municipalities, primarily Valle de Bravo and Amanalco, due to the almost total contribution of their water network to the Valle de Bravo Dam. The remaining 6 municipalities—Donato Guerra, Villa de Allende, Villa Victoria, Almoloya de Juárez, Zinacantepec, and Temascaltepec—partially contribute to the filling of the reservoir of said dam.

It is important to note that within the basin, according to the INEGI population census (2020), 84 localities are circumscribed, concentrated in 4 municipalities: 29 in Amanalco, 3 in Donato Guerra, 51 in Valle de Bravo, and 1 in Villa de Allende, registering a total population of 73,611 inhabitants. Additionally, the surface area of the basin is 526,099 km², with a perimeter of 16,545 km.

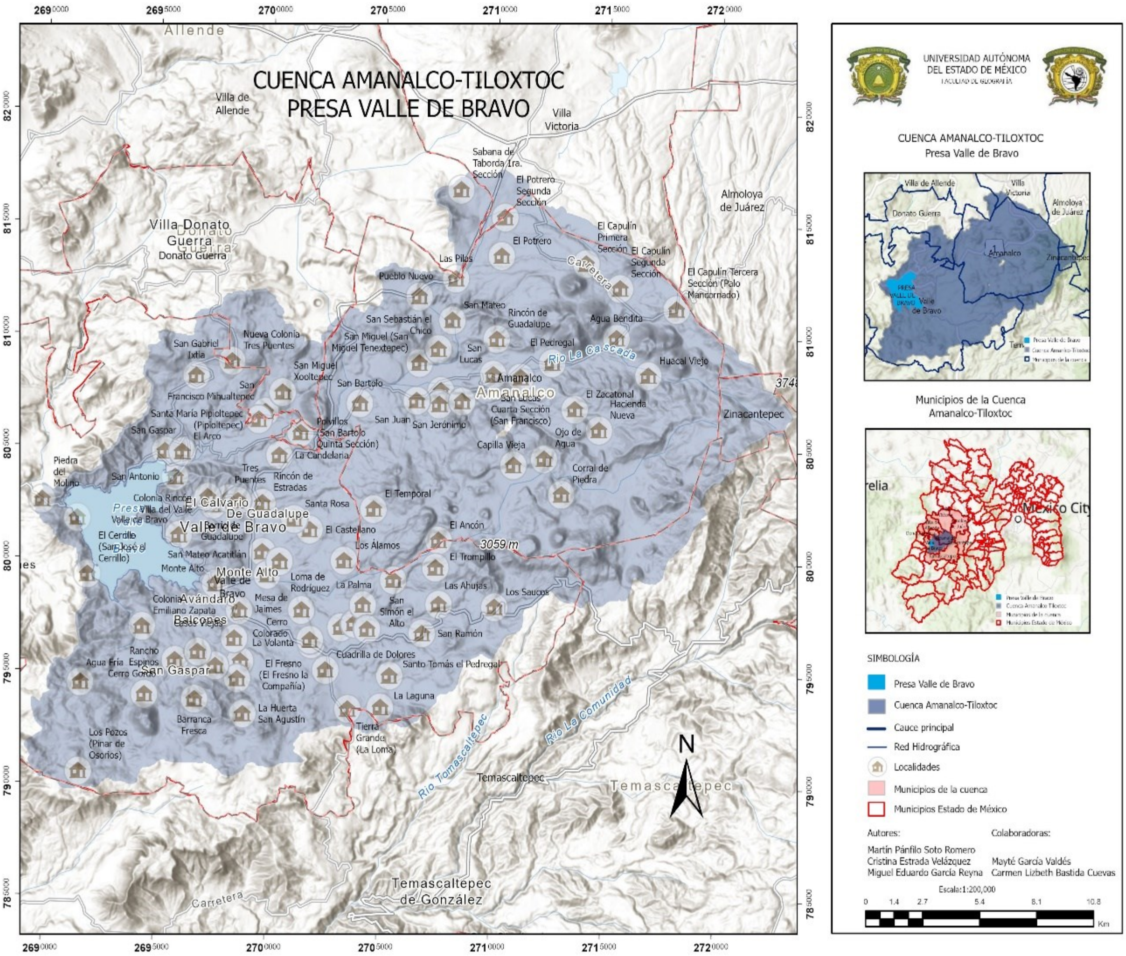

Figure 5 Location of the Valle de Bravo Dam. Amanalco-Tiloxtoc Basin. Source 5 Authors' elaboration based on data from INEGI, (2024).

The highest concentration of localities within the basin is observed along 5 of the 6 main channels through which the water supply to the Valle de Bravo Dam flows, as shown in figure 5. This means that the flow of this precious resource suffers a considerable reduction due to the diverse uses by the population. Additionally, coinciding with the concentration of the population in Amanalco, Avándaro, and Valle de Bravo, according to (DENUE, 2024), 3,171 businesses and services are in these areas, further contributing to the decrease in the flows of the Amanalco River, Las Flores Creek, Ojo de Agua Creek, La Hierbabuena River, San Diego River, and the Tiloxtoc River, which supply the Miguel Alemán Dam.

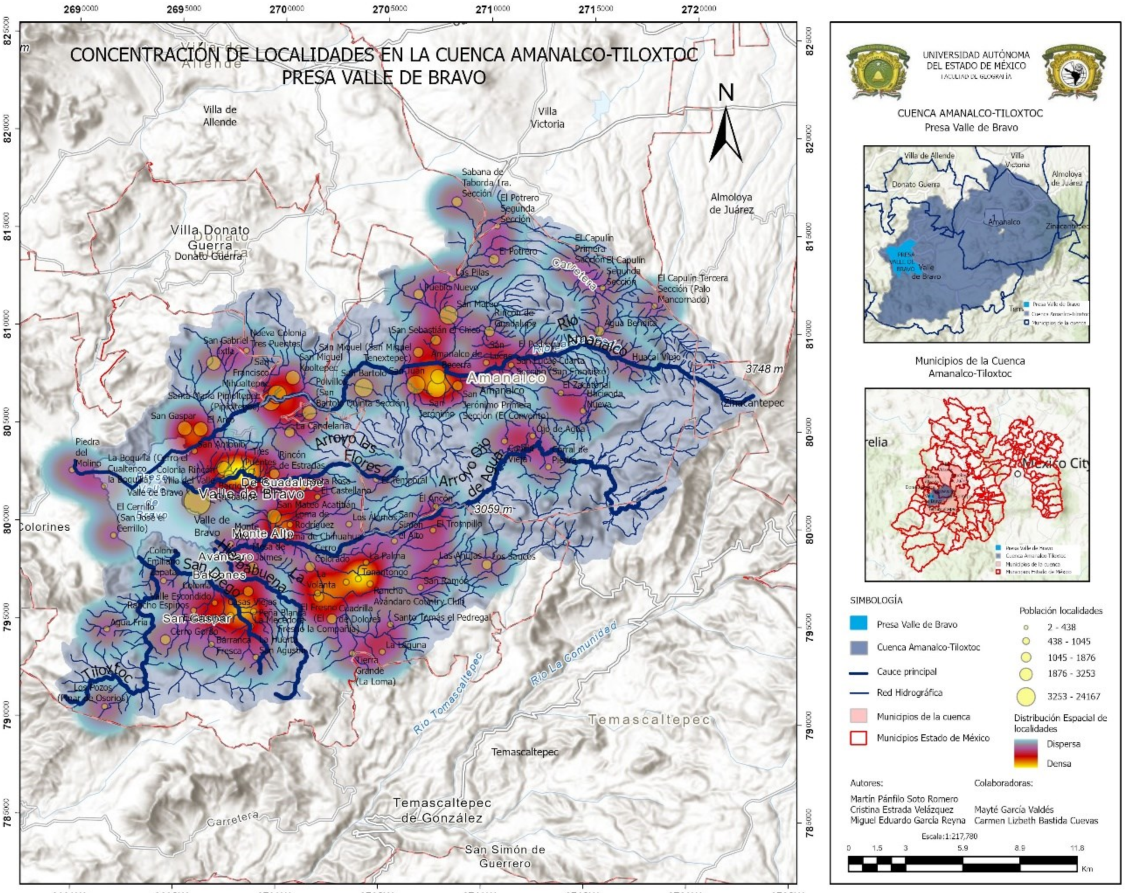

Figure 6 Concentration of localities in the Amanalco-Tiloxtoc Basin. Source 3 Own elaboration based on INEGI data (2024).

Likewise, Graph 3 shows four crucial moments in the storage levels of the Miguel Alemán Dam during the period from 1994 to 2023. The first period, called 'Average Level 1994-2004,' shows that during this decade, the storage levels of the Miguel Alemán Dam remained between 300 and 350 Hm³. The second period, called 'Moderate Decline' (2005-2013), shows a downward trend in the dam's filling, with clear turning points, where a consistent decline is observed. In 2005, the storage level reached 275 Hm³, slightly exceeding the 300 Hm³ threshold in 2007. However, from 2007 to 2009, the storage levels fell to 250 Hm³. In 2010, the levels approached those from previous decades, reaching 350 Hm³. However, following a rebound, the levels of the precious liquid continuously declined until early 2012, when they remained just above 250 Hm³. The third period, called 'Recovery' (2013-2019), was characterized by a rise in storage levels above 360 Hm³ at the end of 2013, a record figure. The levels remained above 300 Hm³ until the end of 2019. The fourth period, called 'Drastic Decline,' was marked by a significant reduction in storage levels, which registered just above 150 Hm³, coinciding with the beginning of the COVID-19 pandemic.

The Cutzamala System has faced challenges regarding water availability, reflected in fluctuations in its storage levels. It is important to consider that these changes may be related to factors such as variations in rainfall patterns, increased demand due to population growth, and water management practices.

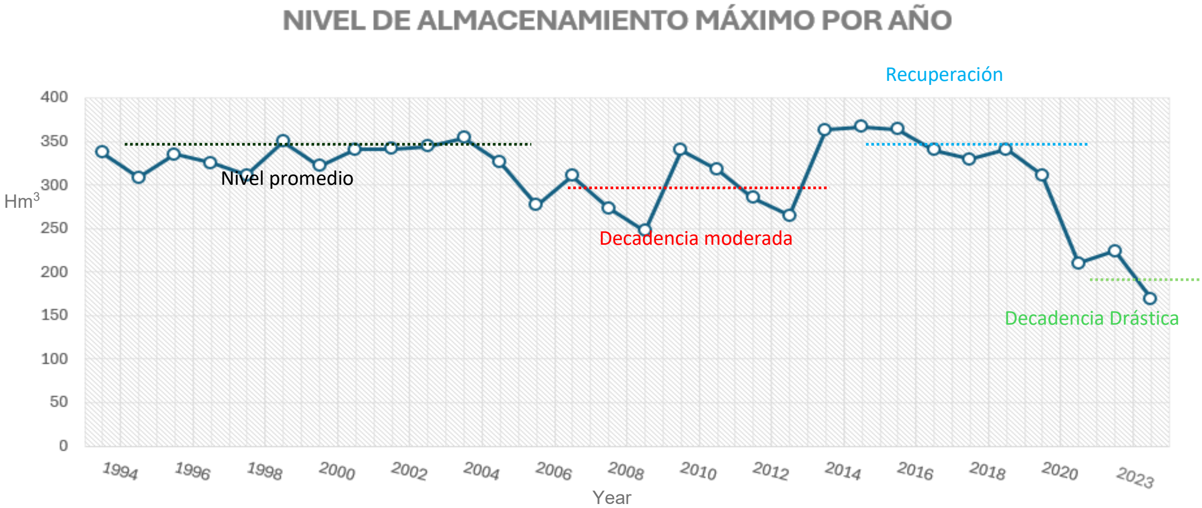

Figure 7 Storage level of the Miguel Alemán Dam in the period 1994-2023. Source 4 Authors' elaboration based on data from CONAGUA, (2024).

The figure 7 shows five moments of maximum water extraction from the Valle de Bravo reservoir. The first occurred in 1995, registering the highest extraction ever recorded at 140 Hm³. The second moment was in 2004, when 90 Hm³ were extracted, followed by the third in 2011 with 80 Hm³, the fourth in 2016 with slightly over 80 Hm³, and the last in 2019, when 90 Hm³ were extracted. It should be noted that the years 2000, 2005, 2009, and 2012 exhibited the lowest amounts of Hm³ extracted, all below 60 Hm³. Between these years, the fluctuation in the extraction of the precious liquid ranged between 60 and 80 Hm³.

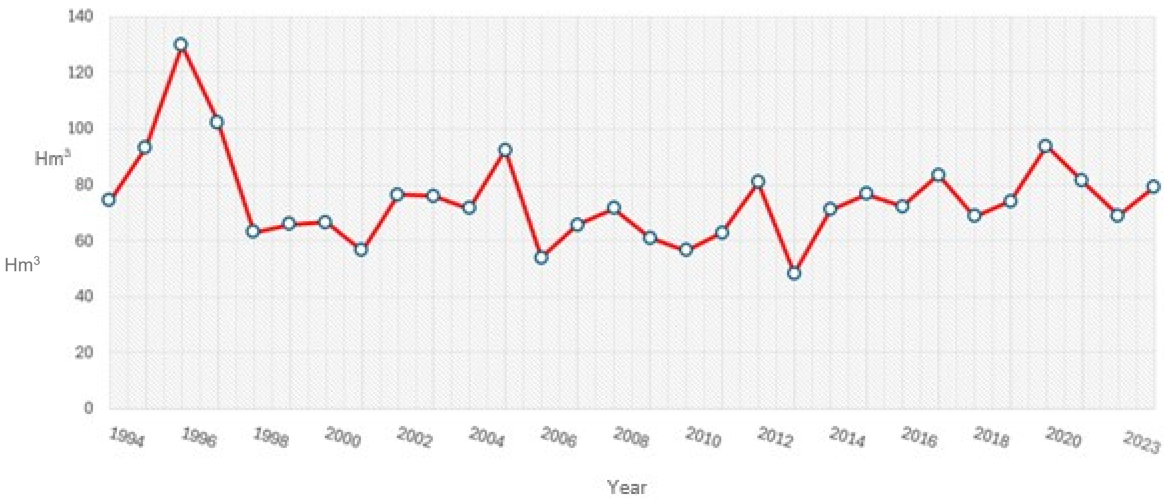

Figure 8 Maximum extraction level of the Miguel Alemán Dam in the period 1994-2023. Source 5 Authors' elaboration based on data from CONAGUA, (2024).

The figure 8 shows that in the period from 1994 to 2005, called 'Average Precipitation,' the rain gauge registered a range of 1050 to 1200 mm. The second period, from 2006 to 2018, called 'High Precipitation,' presents readings ranging from 1200 to 1800 mm. The third period, recorded from

2018 to 2023 and designated 'Low Precipitation,' collects data within the threshold of 800 to 900 mm.

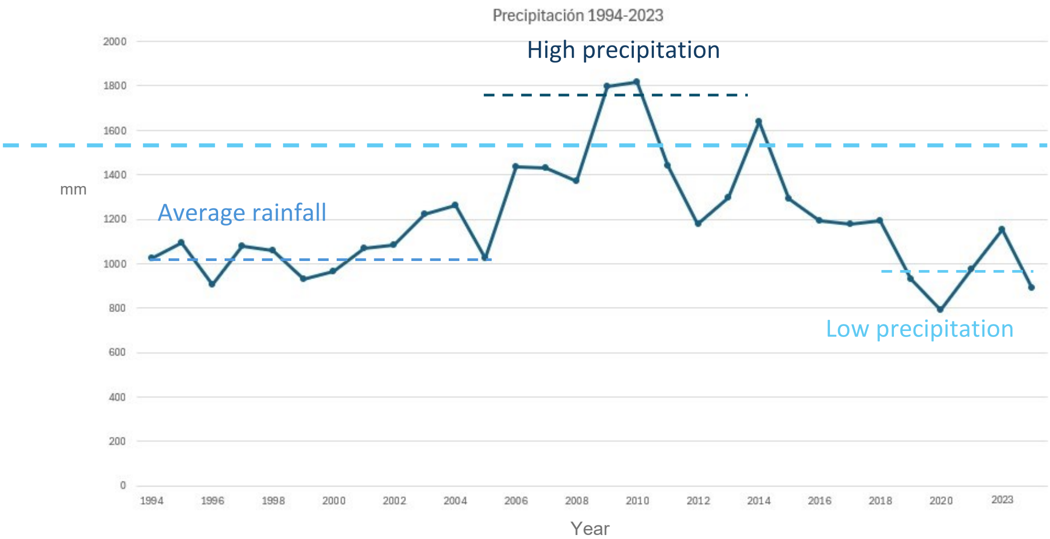

Figure 9 Total accumulated precipitation 1994-2023.

Table 1 allows for a quick comparative analysis of Graphs 7,8, and 9 A comparison of the data reveals a lack of correspondence between the precipitation, extraction, and storage data.

Table 1 Comparative data record of the Miguel Alemán Dam.

GRAPH	Period 1	Period 2	Period 3	Period 4
3. Storage Level	Average level 1994-2004 300 and 350 Hm^3	Moderate decline from 2005 to 2013 250 to 300 Hm3	Recovery from 2013 to 2019 300 to 360 Hm3	Drastic decline 2020-2024 150 Hm3
4. Extraction level	1995 140 Hm3	2004 and 2019 90 Hm3	2011 and 2016 80 Hm3	2000, 2005, 2009 and 2012 below 60 Hm3
5. Precipitation Level	Average rainfall 1994 to 2005 1050 to 1200 mm	High precipitation 2006 to 2018 1200 to 1800 mm	Low precipitation 2018 to 2024 800 to 900 mm	

Source 7 Own elaboration (2024).

The period between 1994 and 2023 shows significant variability in rainfall, with the year 2009 registering the historical maximum. The seasonal distribution of rainfall presents a clear pattern: the months from December to April are the driest, while the rainy season is concentrated from July to September. When analyzing the period in subsections, it is observed that from 1994 to 2002, rainfall was below 1200 mm per year. Subsequently, from 2003 to 2015, there was an increase in rainfall, generally exceeding 1200 mm, except in 2005 and 2012. However, from 2016 onwards, a new downward trend has been observed, with values below 1200 mm per year.

On the other hand, storage data showed a downward trend in recent years, going from an all-time high of 4403.18 in 2015 to a low of 2029.20 units in 2023. Although the average for the period 1994-2023 is 3732.46 units, clear seasonality is observed, with lower levels in July and higher levels between October and January. It is interesting to note that the years with storage values below 3500 units (2006, 2009, 2013, 2021, 2022, and 2023) coincide with periods of lower rainfall, suggesting a possible correlation between both factors.

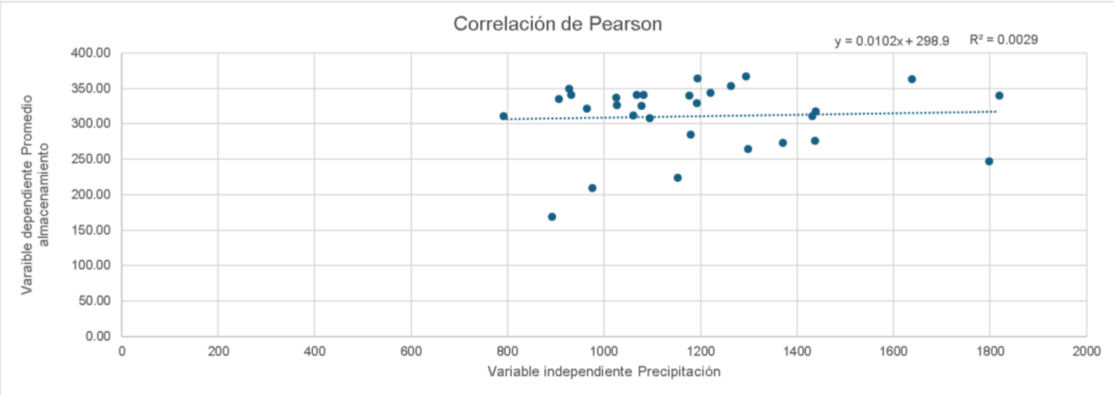

Figure 10 Storage vs. precipitation correlation 1994-2023. Source 8 Own elaboration (2024).

Analysis of water withdrawal data between 1994 and 2023 reveals a clear inverse relationship between the amount of water withdrawn and precipitation. The year 1996 stands out as the year with the highest extraction (129.72 million cubic meters), probably due to the lack of rainfall that year, which was the second driest of the period. In contrast, the years 2009 and 2010, the rainiest, presented the lowest extractions, with a minimum in 2013 (48.6 million cubic meters). The months with the highest rainfall were concentrated between June and October, especially in July, August, and September 2010. Throughout the period studied, the average extraction was 74.56 million cubic meters.

5. Conclusion

The analysis of the Balsas River basin, and in particular the municipality of Valle de Bravo, highlights the region's ecological, tourism, and water importance. Its natural environment, characterized by mountains and coniferous forests, contributes to its significance as a conservation area and tourist destination. However, pressure on its water resources represents a significant challenge.

The study of storage levels at the Miguel Alemán Dam between 1994 and 2023 reveals considerable fluctuations, influenced by variations in rainfall patterns, population growth, and water management practices. Four key periods are identified: a stable average level (1994–2004), a moderate decline (2005–2013), a recovery phase (2013–2019), and a subsequent dramatic decline coinciding with the COVID-19 pandemic.

Likewise, water extraction from the Valle de Bravo reservoir has shown significant variations over time, with peaks in 1995, 2004, 2011, 2016, and 2019. However, an inverse relationship is observed between the amount of water extracted and the amount received, suggesting that drier years have required greater water extraction, while in rainier years, demand has been lower.

The analysis of precipitation for the period 1994-2023 shows three distinct phases: a period of average precipitation (1994-2005), a period of high precipitation (2006-2018), and a period of low precipitation (2018-2023). The seasonal distribution of rainfall confirms a concentration in the months of July to September, while the period from December to April is the driest.

The findings highlight the complexity of the water crisis at the Miguel Alemán Dam and the need to address multiple factors to mitigate the problem and ensure a sustainable water supply for the region. The Miguel Alemán Dam has experienced a significant reduction in its water storage levels, particularly since the COVID-19 pandemic, registering only 29.3% of its capacity in March 2024.

The decrease in rainfall has negatively affected water levels; in addition, the intensive use of water for the Cutzamala System, which supplies Mexico City, has contributed to the reduction in water levels in the dam. The proliferation of private infrastructure such as dams, cisterns, and ponds has diverted the flow of water that would normally feed the dam.

Population growth and the expansion of services and commerce in the Amanalco-Tiloxtoc basin have increased the demand for water. Furthermore, excessive logging, erosion, and land-use changes have contributed to the deterioration of the natural environment, affecting the dam's recharge capacity.

Another critical problem is the eutrophication of the Valle de Bravo Dam, caused by high concentrations of nitrogen, phosphorus, and organic matter. The main sources of pollution include untreated wastewater, direct discharges from unregulated residential areas, agricultural fertilizer runoff, and fish farm waste.

The balance between the decrease in water storage and the reduction in rainfall is evident, suggesting the need for sustainable water resource management strategies. The growing demand for water, driven by population growth and commercial development in the region, makes it urgent to adopt water conservation and efficient use policies, as well as to improve collection and storage infrastructure.

Valle de Bravo faces significant challenges in water management. Conserving water resources is essential to ensuring the sustainability of its ecosystem, tourist appeal, and the well-being of its population. Implementing climate change mitigation and adaptation measures, alongside proper water planning, will be critical to maintaining a balance between development and conservation in the region. Furthermore, improving water management practices, regulating uncontrolled construction, and protecting the natural environment are imperative for ensuring the long-term sustainability of water resources.

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