Analysis of risk scenarios from gravitational movements caused by the overexploitation of the Toluca Valley Aquifer, State of Mexico

Analyse des scénarios de risques dus aux mouvements gravitationnels causés par la surexploitation de l'aquifère de la Vallée de Toluca, État du Mexique

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ABSTRACT: The objective of this study is to analyze risk scenarios associated with gravitational processes caused by the overexploitation of the Toluca Valley Aquifer in the State of Mexico, using automated cartographic analysis. The hypothesis suggests that the overexploitation of the aquifer is closely related to population growth and the expansion of metropolitan areas in recent years, which increases the demand for water for agricultural, industrial, and personal use. This phenomenon is reflected on the land surface through sinking, subsidence, and cracking in the metropolitan area. Through the collection and analysis of cartographic data, priority areas are identified at the local level and within Basic Geostatistical Areas (AGEB), in order to implement structural and non-structural measures to mitigate risks related to civil protection and aquifer conservation.
KEY WORDS: Risk scenarios, overexploitation, aquifer, gravitational motions, cartographic analysis.

RÉSUMÉ : L'objectif de cette étude est d'analyser les scénarios de risque associés aux processus gravitationnels causés par la surexploitation de l'aquifère de la vallée de Toluca dans l'État de Mexico, en utilisant une analyse cartographique automatisée. L'hypothèse suggère que la surexploitation de l'aquifère est étroitement liée à la croissance démographique et à l'expansion des zones métropolitaines ces dernières années, ce qui augmente la demande en eau pour des usages agricoles, industriels et personnels. Ce phénomène se reflète à la surface terrestre par des affaissements, des subsidences et des fissures dans la zone métropolitaine. Grâce à la collecte et à l'analyse de données cartographiques, des zones prioritaires sont identifiées au niveau local et dans les zones géostatistiques de base (AGEB), afin de mettre en place des mesures structurelles et non structurelles pour atténuer les risques liés à la protection civile et à la conservation de l'aquifère.

MOTS CLÉS: Scénarios de risque, surexploitation , aquifère, mouvements gravitationnels, analyse cartographique.

1. Introduction

In Mexico, the extraction of groundwater from aquifers has become a common practice due to the population growth experienced in recent years. This phenomenon has led to water management problems, evidenced by water scarcity in human settlements. As a result, a decline in the piezometric level is observed, leading to a tendency toward the overexploitation of underground water resources. One of the most overexploited basins in Mexico is the Upper Lerma River Basin, located in the central and northwest region of the State of Mexico, in the Toluca and Ixtlahuaca-Atlacomulco Valleys, covering an area of 5,354 km² (CONAGUA, 2023). This basin includes the Toluca Valley Aquifer, which spans 33 municipalities in the State of Mexico, of which only 23 fully encompass its territory and 10 covers a smaller portion, with a physical extent of 2,738 km²(INEGI, 2022).

Population growth in these municipalities has led to rapid urbanization, which affects recharge areas and green spaces essential for water infiltration, resulting in an increased demand for services such as water supply for domestic, industrial, and agricultural use. This has caused an ecological imbalance between the underground and surface phases of the hydrological cycle, reflected on the land surface through the presence of geological processes associated with gravitational movements, known as "geological risks" (Sandoval, 2011).

Several studies have addressed the effects of aquifer overexploitation, highlighting research by authors such as Quiroz (2020) and Pulido (2001), who point out the continuous decline in piezometric or groundwater levels as one of the main problems resulting from overexploitation. These effects include desertification, increased energy costs for water extraction, and the appearance of subsidence, sinking, and cracking zones.

The objective of this study is to diagnose the risk scenarios associated with gravitational processes caused by the overexploitation of the Toluca Valley Aquifer. To do so, automated cartographic analysis will be employed to propose measures aimed at the protection, conservation, and sustainable management of the aquifer. This approach will be broken down into three levels of analysis:

Characterize the risk areas associated with gravitational processes within the physical and socioeconomic context of the region.

Develop diagnostic mapping that identifies and locates risk zones derived from gravitational processes.

Propose mitigation measures to reduce local disaster risks caused by gravitational movements, through the protection and conservation of the Toluca Valley Aquifer.

We start from the premise that gravitational processes, such as subsidence, and cracking, have manifested themselves more frequently in metropolitan areas as a result of population growth. This increase in population generates a greater water demand, which in turn triggers the overexploitation of the aquifer and amplifies the effects of these geological processes.

2. Study area

The Toluca Valley Aquifer (TVA), as shown in figure 1, is located in the State of Mexico within the following UTM coordinates: minimum X 394027.285, maximum X 470670.391, minimum Y

2103433.323, and maximum Y 2169065.730. It is situated in the Upper Lerma River Basin, to the south of the Mexican Plateau, within the physiographic province of the Trans-Mexican Volcanic Belt. The topography of the area exhibits elevations ranging from 2,600 m a.s.l to 4,680 m a.s.l.

The aquifer area is bounded to the north by the Atlacomulco-Ixtlahuaca Aquifer, to the south by the Cerro de Tenango, to the southwest by the Nevado de Toluca Volcano, to the east by the Sierra de las Cruces, and to the southeast by Monte Alto, covering an approximate area of 2,738 km². This region includes all or part of 22 municipalities, with a total population of 2,552,633 inhabitants, according to the 2020 Population and Housing Census conducted by INEGI (National Institute of Statistics and Geography).

Regarding climatic conditions, the study area is classified, according to the modified Köppen system by Garcia, E. (1981), as a temperate subhumid climate with summer rainfall, and winter precipitation less than 5 mm. In the Sierra de las Cruces and Cerro de la Corona area, the climate is classified as subhumid semi-cold with summer rainfall (C (E) (w 2) (w)), with winter precipitation varying between 5 mm and 10.2 mm. Meanwhile, in the Nevado de Toluca area, the climate is characterized as cold high-altitude (E (T) H). The temperature in the study area ranges from 12°C to 13°C, with a precipitation regime varying between 1,000 mm and 1,500 mm annually.

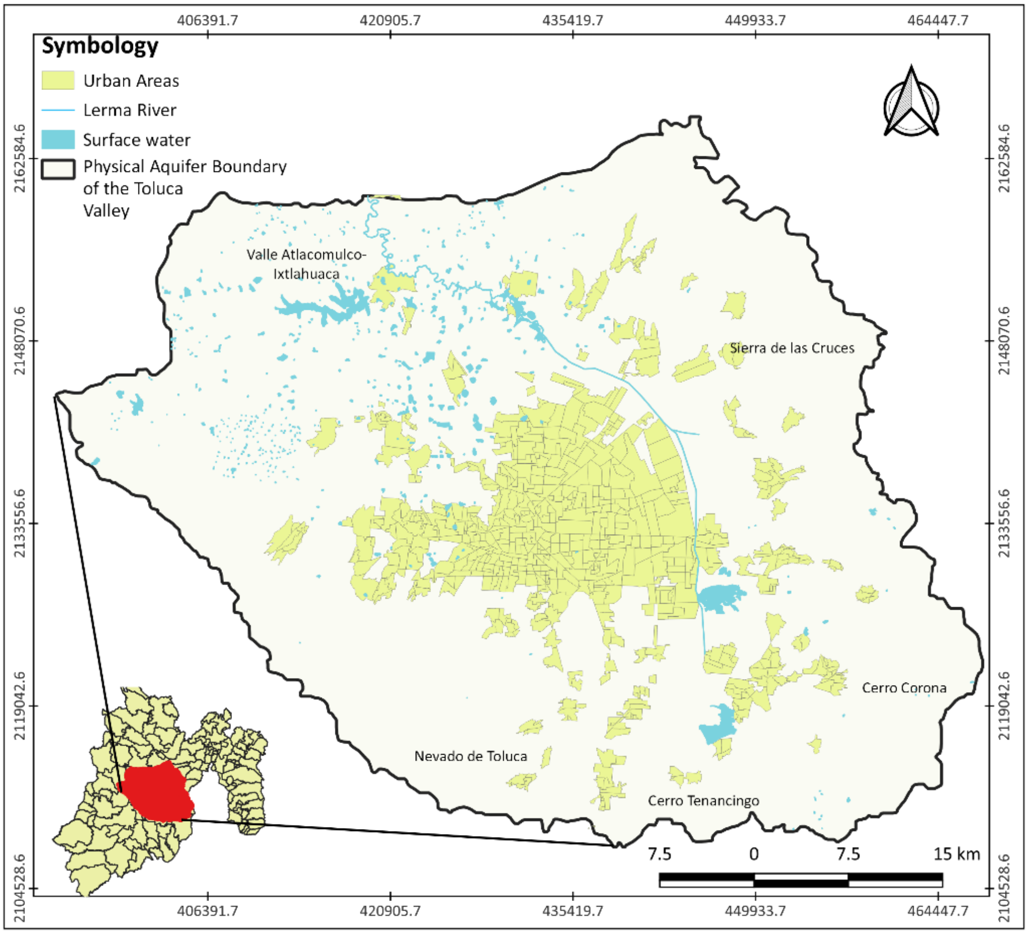

Figure 1 Map of Aquifer Location of the Toluca Valley (Self-made).

3. Methods

According to the National Center for Disaster Prevention (CENAPRED), although the current cartographic representation contains relevant information, the updating of risk mapping to a more specific level remains a challenge. In this context, the methodological analysis employed in this study was structured in three phases to develop a project that would allow for the generation of more updated and accurate mapping. This methodological approach enabled the detailed and modified representation of the three gravitational geological risks present in the Toluca Valley Aquifer, providing a valuable tool for decision-making regarding the management and protection of water resources.

3.1 Phase 1: Searching and Gathering Information

The first methodological phase consisted of the search and collection of relevant information for the study of the three geological phenomena of interest: sinkholes, subsidence, and cracking, within the study area. Information was gathered from various reliable sources, including the National Commission for the Knowledge and Use of Biodiversity (CONABIO), the National Water Commission (CONAGUA), the National Center for Disaster Prevention (CENAPRED), the Faculty of Geography of the Autonomous University of the State of Mexico (UAEMEX), the National Institute of Statistics and Geography (INEGI), the Inter-American Institute of Technology and Water Sciences (IITCA), the Institute for Mining and Geological Studies of the State of Mexico (IFOMEGEM), as well as publications in books, scientific journals, and specialized articles. Additionally, supplementary sources of information such as newspaper articles and fieldwork conducted in the region were incorporated.

3.2 Phase 2: Analysis and filtering of information, creation of databases

The second phase of the methodology focused on the analysis and filtering of the collected information, as well as the creation of structured databases. The analysis included a temporal and spatial assessment of the data, validating its quality and consistency. It was identified that some of the government data sources, although useful, were not available at the scale required for this study. Therefore, it was necessary to develop new databases for the three geological phenomena (sinkholes, subsidence, and cracking). During this phase, the collected data were compared to avoid duplication, ensuring that the temporal and spatial information was as up-to-date as possible. Furthermore, the most recent data were incorporated into the digitization and development of geographic layers.

3.3 Phase 3: Digitization of information for sinkholes, subsidence, and cracking

The third phase involved the digitization of the information obtained for each of the three geological processes: sinkholes, subsidence, and cracking. The digitization was carried out based on the information collected and the databases developed in the previous phase. For each of the three processes, an individual digitization process was performed, which included a comparison with additional information sources obtained from government commissions. Moreover, a data filtering process was conducted to eliminate irrelevant information, ensuring the accuracy of the data.

The digitization of the data included the creation of geographic layers using the software programs QGIS and ArcMap, which are essential tools for Geographic Information System (GIS) analysis. Through this process, the foundation was laid for the development of the mapping that supports the analysis of risks from gravitational processes, to propose measures for the protection, conservation, and management of the Toluca Valley Aquifer, as well as ensuring the safety of the population that depends on this resource.

3.4 Methodology for mapping sinkhole

The methodology used to develop the geospatial layers associated with sinkholes in the study area was based on an exhaustive collection of information from various sources. Among the key institutions in documenting these phenomena is the National Center for Disaster Prevention (CENAPRED), which provides cartographic information related to sinkholes and civil protection. However, when comparing the methodological approaches of CENAPRED with the standards found in the scientific literature, a significant discrepancy was identified in the representation of sinkholes. While CENAPRED presents sinkholes as affected areas, specialized literature suggests that these should be represented as point events for more precise and detailed localization.

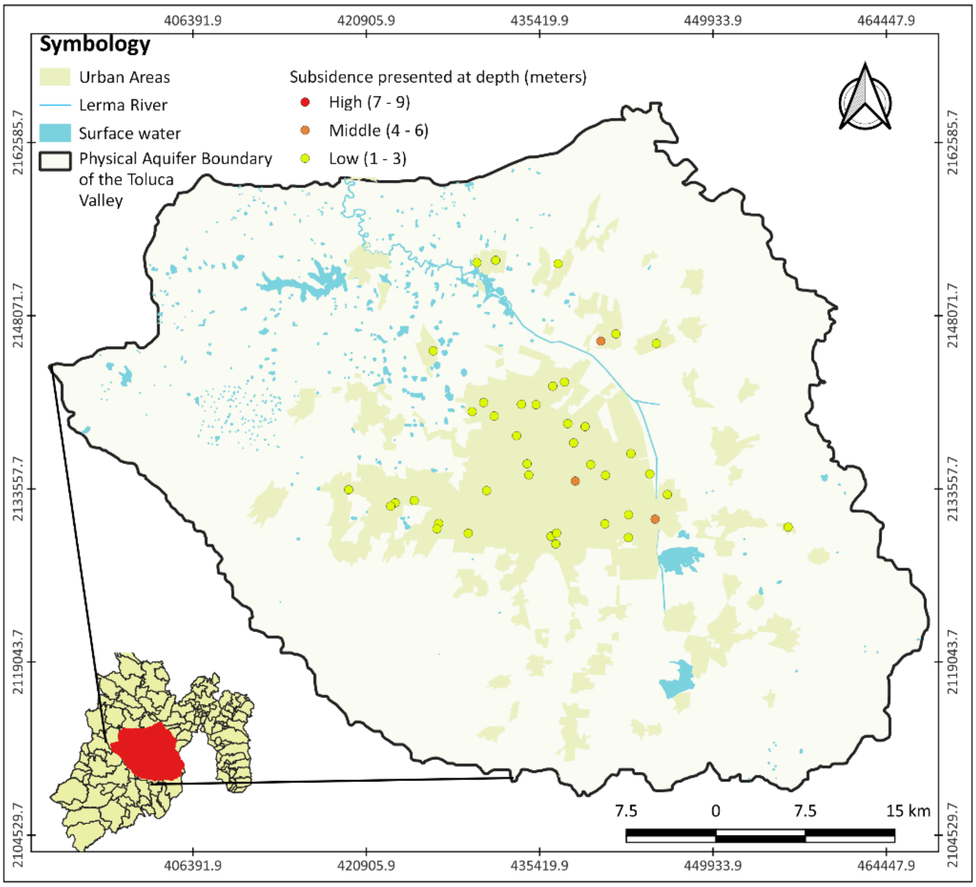

Figure 2 Subsidence Map (meters) Aquifer of the Toluca Valley (Own elaboration).

Due to this methodological difference, it was decided to discard the cartographic information provided by CENAPRED, which represented certain municipalities as "sunken" without specifying the exact locations of the phenomena within those municipalities. Instead, a new cartographic layer of "Sinkholes" was created, which was developed from fieldwork conducted over 8 months. During this time, direct field surveys and monitoring were carried out, allowing for the accurate identification and recording of areas affected by sinkholes in the study region.

The new cartographic layer precisely reflects the location of the sinkholes, enhancing the spatial resolution of the data and allowing for a more detailed analysis of the geological phenomena. The results obtained from this fieldwork phase are presented in figure 2, where the distribution and magnitude of the sinkholes in the study area are illustrated, providing a key tool for risk assessment and decision-making in aquifer management.

3.5 Methodology for Subsidence Mapping

The methodology employed for the generation of the subsidence cartographic layer in the study area was primarily based on the digitization of satellite images obtained from the National Institute of Statistics and Geography (INEGI), corresponding to the year 2018. This ensures that the most up-to-date satellite images available were used for the analysis. The processing of these images was carried out using Synthetic Aperture Radar (SAR) interferometry techniques, applying open-source software.

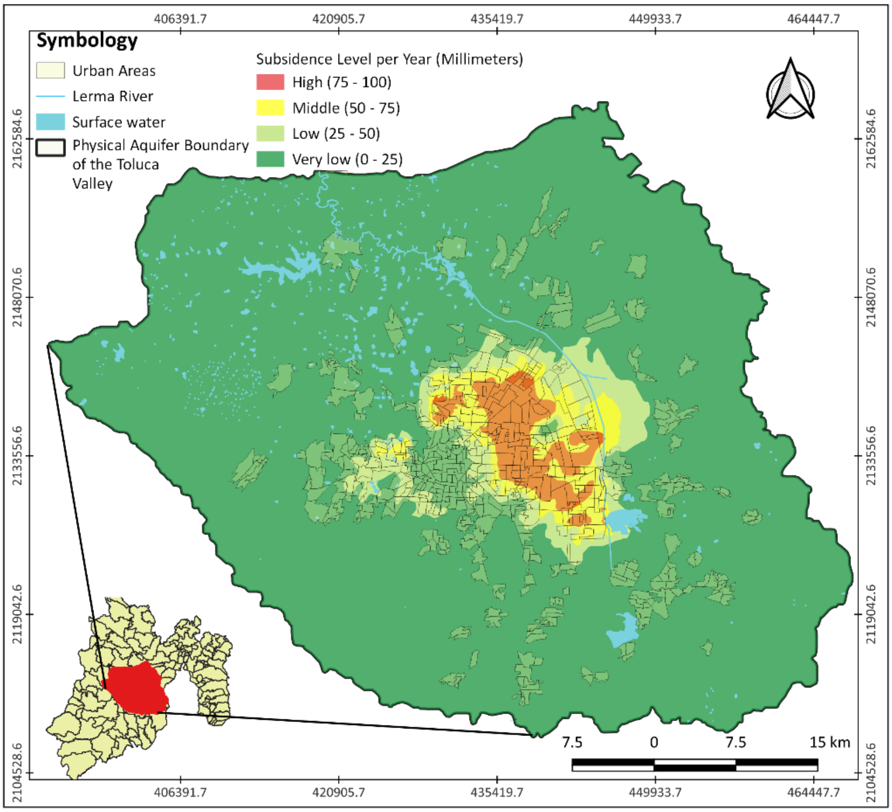

Figure 3 Subsidence Map (millimeters) AVT, (INEGI 2019).

Initially, the Sentinel Application Platform (SNAP), developed by the European Space Agency (ESA), was used for the preliminary stages of image processing and interferogram calculation. Subsequently, the Persistent Scatterers Interferometry (PSI) technique was implemented using the StaMPS program. During this process, other open-source software tools such as GDAL (Geospatial

Data Abstraction Library) were also employed, along with auxiliary utilities to perform additional specific calculations necessary for the analysis.

As a result of this interferometric process, a raster image was obtained, which was then processed and analyzed using QGIS software. The digitization of this image was carried out following the criterion of measuring subsidence in millimeters, allowing for the conversion of the raster representation into geospatial polygons. This conversion led to the creation of the subsidence map for the Toluca Valley Aquifer, which is presented in figure 3.

3.6 Methodology for mapping cracks

The methodology employed for the development of the cracking cartographic layer was primarily based on the thorough search and collection of available information from various institutional and scientific sources, following an approach similar to that used for the sinkhole and subsidence processes. In this case, the digitization of geospatial data related to cracking was carried out through the analysis of official sources, which provide information on the geological phenomena affecting the region.

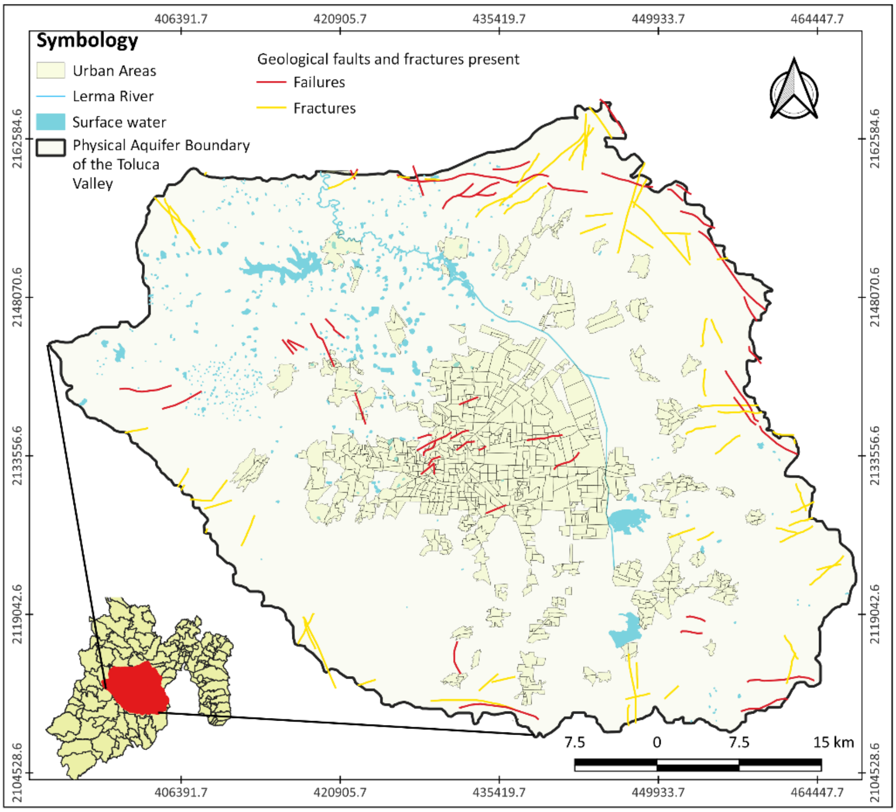

Figure 4 Map of Faults and Fractures Aquifer of the Toluca Valley (Own elaboration).

It is noteworthy that in the study area, cracking phenomena are divided into two main categories: geological faults and fractures, each with distinct geological characteristics and causes. For data collection, institutional portals such as the National Institute of Statistics and Geography (INEGI) and the National Center for Disaster Prevention (CENAPRED) were consulted, which provided crucial background information for the characterization of these phenomena. The collection of this information was not limited to geospatial data but also included an extensive literature review that complemented the analysis of the geological processes present in the area.

As a result of this data collection and digitization, a cartographic layer was created that represents the spatial distribution of cracking in the Toluca Valley Aquifer. The results obtained are presented in detail in figure 4.

4. Presentation of results and discussion

Risk analysis is a fundamental tool in the evaluation of geological phenomena in the study area, specifically within the Toluca Valley Aquifer. This aquifer is a strategic system, and its overexploitation process has induced the manifestation of geological phenomena associated with gravitational forces, such as sinkholes, subsidence, and cracking. The occurrence of these phenomena is directly correlated with the overexploitation of the water resource, which, in turn, is influenced by multiple socio-economic and environmental factors.

Among the key determining factors of this process are population growth, industrial expansion, excessive water consumption, and non-compliance with land use regulations established in territorial planning frameworks. These factors have created an imbalance in the hydrological system of the area, and their influence has been observed in a diachronic manner over time. However, the precise identification of the underlying causality remains a fundamental aspect for the formulation of effective mitigation strategies and the sustainable management of the aquifer.

4.1 Influencing factors in gravitational processes

4.1.1 Overexploitation

The term overexploitation refers to the excessive extraction, use, or exploitation of a natural resource. According to the National Water Commission (CONAGUA, 2023), overexploitation of groundwater is defined as "the condition in which, for an extended period, the average extraction of groundwater from an aquifer exceeds or approaches its average recharge."

The Toluca Valley Aquifer (TVA) is among the 106 overexploited aquifers out of the 653 registered in the national territory, as indicated in the Water Atlas published by CONAGUA (2018). Despite its considerable groundwater potential, this aquifer has been subject to intensive extraction through a series of wells belonging to the Lerma system, which supply both Mexico City and the Toluca Valley. This exploitation has led to a significant reduction in its recharge capacity. According to CONAGUA (2023), the drop in the water table level, as well as the decline in piezometric levels, has resulted in the appearance of surface cracks and the formation of areas of subsidence and sinking.

In Table 1, which presents the groundwater balance, a progressive increase in extraction over time is observed, mainly driven by the growing water demand in the region.

Table 1 Groundwater balance results Values in millions of m3 per year.

Entries	*1970*	*1992*	*1996*	*2000*
Underground entrances (Nevado)			94.5	94.608
Underground entrances (Crossings)			63.0	63.072
Total, of underground entrances		299.0	157.5	157.68
Natural vertical recharge		81.0	98.2	177.806

Induced natural recharge			0.8	1.273
Sums	342.1	380.0	256.5	336.76
Permanent performance				283.149
OUTPUTS				
Underground exits	2.0	2.0	0.0	0.0
Extraction	353.9	327.0	327.4	422.344
Evapotranspiration		10.0	14.7	0.0
Natural discharge including Rivers, Springs				53.611
Sums	355.9	339.0	342.1	475.955
STORAGE EXCHANGE	-13.8	41.0	-85.5	-85.584
Storage coefficient			0.045	0.045
Coefficient of infiltration			0.067	I1 = 0.067 I2 = 0.02

Source: CONAGUA 2023

As previously noted, in the mid-20th century, rapid population growth, coupled with the limited availability of high-quality surface water and increasing local demands, driven by climatic, hydrogeological, environmental, socioeconomic, and political factors, led to a significant increase in the intensive extraction of water resources (Llamas & Custodio, 2002).

4.1.2 Population Growth

In the last four decades, population growth has been most prominent in the Toluca Valley Metropolitan Area, which has recorded one of the highest population growth rates at the state level. This phenomenon has created significant challenges in the formulation of public policies and territorial planning and zoning. The issue is not only attributed to the increase in population volume but also to substantial changes in the structural parameters of the population. According to statistical data provided by INEGI (2024), Toluca stands out as one of the municipalities with the highest population density, with a total of 910,608 inhabitants, accounting for 36.63% of the population in the Toluca Valley metropolitan area.

Additionally, the municipalities of Almoloya de Juárez, Calimaya, Metepec, and San Mateo Atenco have experienced population increases of over 20,000 inhabitants during the last decade. On the other hand, Lerma and Zinacantepec have recorded increases of more than 30,000 inhabitants in the same period. According to the data presented in Table 2, Metepec ranks as the second most populated municipality in the area, with a population of 242,307 inhabitants.

This significant population increase has led to a greater demand for water resources in the region. Meanwhile, the availability of high-quality surface water has decreased, leading to an increase in the extraction of groundwater. According to the UNAM (2018), 1,000 million cubic meters of water are extracted annually, while the estimated natural recharge is only 500 million cubic meters. This mismatch between extraction and recharge contributes to a hydrological imbalance in the aquifer, which has in turn led to geological phenomena such as subsidence, surface cracking, and sinking in various urban areas.

Table 2 Total population of the municipalities that make up the Toluca Valley Aquifer.

	Municipality	1990	1995	2000	2005	2010	2020
1.	**Almoloya de Juárez**	84,147	96,662	110,591	126,163	147,653	174,587
2.	**Almoloya del Río**	6,777	7,729	8,873	8,939	10,886	12,694
3.	**Atizapán**	5,339	7,147	8,172	8,909	10,299	12,984
4.	**Calimaya**	24,906	31,902	35,196	38,770	47,033	68,489
5.	**Capulhuac**	21,258	25,900	28,808	30,838	34,101	36,921
6.	**Chapultepec**	3,863	5,163	5,735	6,581	9,676	12,772
7.	**Joquicingo**	9,011	12,412	15,086	13,825	12,840	15,428
8.	**Lerma**	66,912	81,192	99,870	105,578	134,799	170,327
9.	**Metepec**	140,268	178,096	194,463	206,005	214,162	242,307
10.	**Mexicaltzingo**	7,248	8,662	9,225	10,161	11,712	13,807
11.	**Ocoyoacac**	37,395	43,670	49,643	54,224	61,805	72,103
12.	**Otzolotepec**	40,407	49,670	57,583	67,611	78,146	88,783
13.	**Rayón**	7,026	8,300	9,024	10,953	12,748	15,972
14.	**San Antonio la Isla**	7,321	9,118	10,321	11,313	22,152	31,962
15.	**San Mateo Atenco**	41,926	54,089	59,647	66,740	72,579	97,418
16.	**Temoaya**	49,427	60,851	69,306	77,714	90,010	105,766
17.	**Tenango del Valle**	45,952	54,789	65,119	68,669	77,965	90,518
18.	**Texcalyacac**	2,961	3,744	3,997	4,514	5,111	5,736
19.	**Tianguistenco**	42,448	51,149	58,381	64,365	70,682	84,259
20.	**Toluca**	487,612	564,476	666,596	747,515	819,561	910,608
21.	**Xalatlaco**	14,047	17,601	19,182	20,002	26,865	30,687
22.	**Xonacatlán**	28,837	36,141	41,402	45,247	46,331	54,633
23.	**Zinacantepec**	83,197	105,566	121,850	136,167	167,759	203,872
	Total	**1,258,285**	**1,514,029**	**1,748,070**	**1,930,803**	**2,184,875**	**2,552,633**

Source: INEGI 2024

4.1.3 Water Availability Period 2023

Water Availability is understood as the total amount of water that can be used in a region for various activities, such as domestic consumption, irrigation, and industrial use. According to CONAGUA (2023), the availability of groundwater is defined as the volume of water that can be extracted from an aquifer without compromising its recharge capacity and without jeopardizing its long-term sustainability.

For the calculation of groundwater availability, the Official Mexican Standard NOM-011-CONAGUA-2015 is used, which establishes the criteria and procedures for determining the average annual availability of national waters. This standard applies to both surface and groundwater, and it is expressed through the following formula:

$$\mathbf{DMA = R - DNC - VEAS}$$

Where:

- **DMA**: Average annual groundwater availability in an aquifer
- **R**: Total average annual recharge
- **DNC**: Committed natural discharge
- **VEAS**: Volume of groundwater extraction

Below, the values corresponding to each of the parameters used in the calculation of groundwater availability for the Toluca Valley Aquifer (AVT) are presented, according to the most recent data provided by CONAGUA (2023).

Total Average Annual Recharge (R)

Total average annual recharge refers to the total volume of water entering the aquifer, including both natural and induced recharge. According to CONAGUA (2023), the total average annual recharge of the Toluca Valley Aquifer is 336.8 hm^3/year, indicating that, in 2010, the groundwater level in the aquifer was approximately 50 meters deep.

Committed Natural Discharge (DNC)

Committed natural discharge refers to the volumes of water from springs and the base flows of rivers that are fed by the aquifer, which are used under concessions or water rights for surface water use. According to CONAGUA (2023), the committed natural discharge of the AVT is 53.6 hm^3/year. This volume of water is crucial for supplying various activities, such as agriculture and human consumption, and must be managed sustainably to avoid negative effects on surrounding hydrogeological units.

Volume of Groundwater Extraction (VEAS)

The volume of groundwater extraction corresponds to the total amount of water extracted annually from the aquifer, both from formal concessions and unauthorized extractions authorized through technical studies. According to the Public Registry of Water Rights (REPDA), the annual volume of groundwater extraction in the Toluca Valley Aquifer is 411.92 hm^3/year (CONAGUA, 2023).

Average Annual Groundwater Availability (DMA)

The average annual groundwater availability is calculated by subtracting the total average annual recharge, the committed natural discharge, and the volume of groundwater extraction, using the formula provided above:

$$\mathbf{DMA = R - DNC - VEAS}$$

Substituting the corresponding values:

$$\mathbf{DMA = 336.8 - 53.6 - 411.915560}$$

The result obtained for the average annual availability of groundwater is:

$$\mathbf{DMA = -128.715560\ hm^3\ /2023}.$$

This negative value indicates that the Toluca Valley Aquifer is in a condition of water deficit, reflecting overexploitation of the aquifer. This phenomenon can be attributed to various causes, such as population growth, industrial expansion, excessive water consumption, and violations of land use regulations. Overexploitation has led to negative effects such as a decrease in piezometric levels, resulting in the appearance of sinkholes, subsidence, and cracks on the surface of the soil (CONAGUA, 2023).

According to data provided by CONAGUA (2023), it has been observed that the groundwater level in the aquifer has declined at an approximate rate of 2 meters per year since 2011, currently reaching a depth of between 70 and 75 meters.

The factors contributing to the overexploitation of the aquifer, together with the manifestation of geological phenomena such as sinkholes, subsidence, and cracks, were evaluated in the structural vulnerability analysis of the study area. In this context, the areas affected by these geological processes were identified and delineated, specifying the zones with signs of damage and the degree of impact. Additionally, the particular conditions of these areas were characterized, and preventive and corrective measures were established, aimed at mitigating impacts and strengthening structural resilience in the most vulnerable areas.

4.2 Structural vulnerability to subsidence

The structural vulnerability derived from sinkholes in the Toluca Valley Aquifer, based on data collected in this region, shows a total of forty-two sinkhole records. These are categorized into three levels, depending on the depth of the sinkholes, ranging from 1 m to 9 m. This analysis allows for focusing attention on the most affected areas, to implement effective mitigation measures.

The structural vulnerability analysis regarding sinkholes has identified several localities and Basic Geo-statistical Areas (AGEB) that require special attention from a civil protection perspective. These areas should be prioritized due to the intensity of the geological process and its impact on infrastructure. The results of this analysis are illustrated in figure 5, and constant monitoring is recommended to assess the evolution of the phenomenon.

It is also crucial to consider the characteristics of the soil in the affected areas. In particular, Feozem soils, which prevail in the affected zones, are porous, dark-colored soils rich in organic matter. These soils are typically used intensively, but they present limitations during periodic droughts, as well as a high susceptibility to wind and water erosion, exacerbating vulnerability. The continuous extraction of water has led to a decrease in the groundwater level, which contributes to the consolidation of underlying materials and creates unevenness on the surface. This phenomenon has intensified the presence of sinkholes in the identified AGEBs and localities, emphasizing the need for immediate corrective measures to prevent further structural damage.

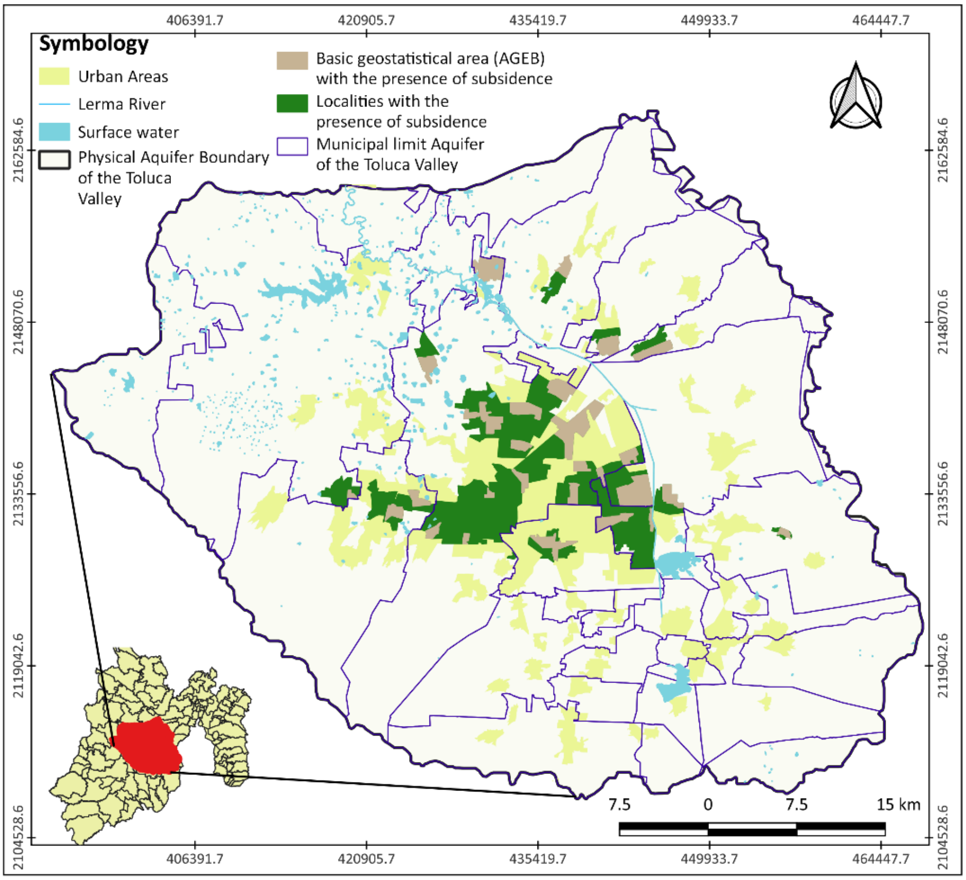

Figure 5 Map of localities and AGEB with the presence of subsidence in the Toluca Valley Aquifer (own elaboration).

4.2 Structural vulnerability to subsidence

The structural vulnerability associated with the subsidence phenomenon in the Toluca Valley Aquifer (AVT), as illustrated in Figure 8, is quantified in millimeters per year and classified into four ranges: 0 to 25 mm/year, 25 to 50 mm/year, 50 to 75 mm/year, and 75 to 100 mm/year. This phenomenon affects eight municipalities either partially or completely, with specific localities identified that require prioritization in decision-making at the governmental level.

Localities experiencing subsidence in the range of 50 to 100 mm/year exhibit moderate structural vulnerability. According to the structural typology defined by INEGI, the buildings in these areas primarily consist of social interest housing, both single-family and multi-family, as well as middle-class single-family homes. From an engineering perspective, these types of housing have a medium vulnerability to differential settlement due to the materials used in their construction. However, in areas where subsidence exceeds 100 mm/year, structural vulnerability increases to high levels, leading to the manifestation of structural faults such as unevenness in concrete floors and tilting of the structures of public buildings.

According to the data presented in figure 6, a total of 256 localities exhibit subsidence processes. Of these, 170 localities are considered high priority, as they fall within the 50 to 100 mm/year subsidence range. This finding underscores the urgent need to implement corrective and preventive measures in the affected areas to mitigate structural impacts and ensure the safety of infrastructures.

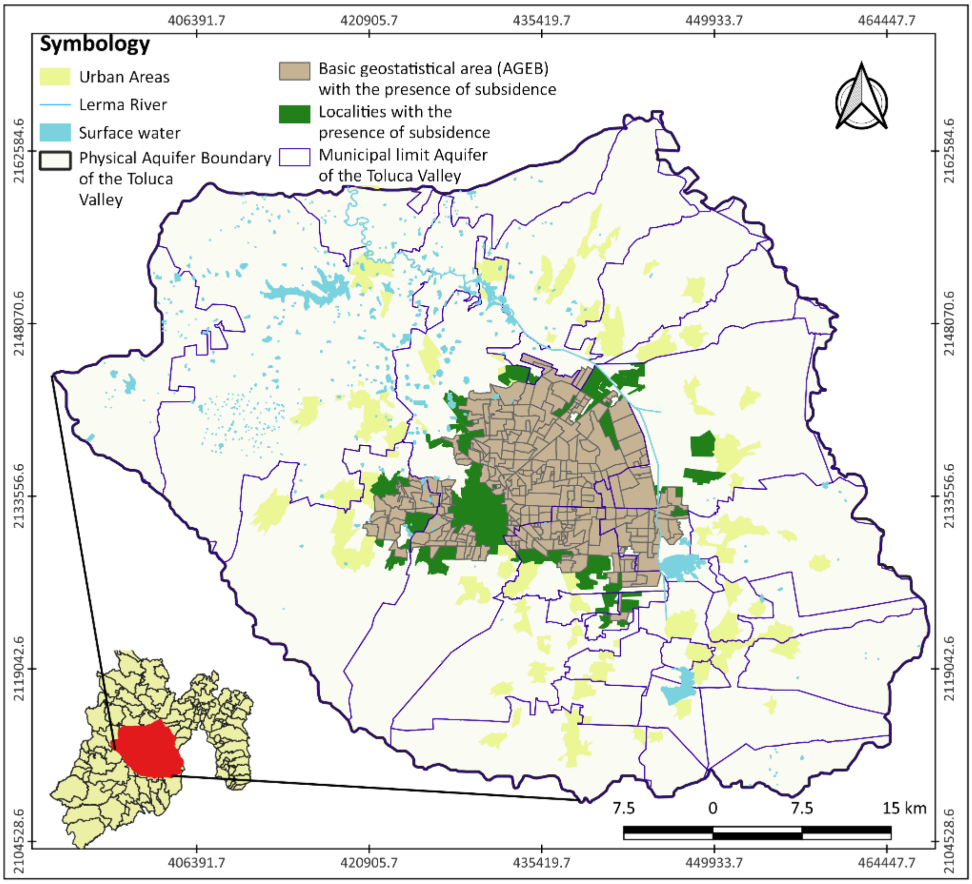

Figure 6 Map of Localities and AGEBs with Presence of Subsidence in the Aquifer of the Toluca Valley (own elaboration).

4.3 Structural vulnerability to cracking

The structural vulnerability associated with cracking in the Toluca Valley Aquifer (AVT), according to the data collected, reveals a total of 116 incidents of cracking, which are distributed between 50 faults and 63 fractures. These geological events are located in 14 municipalities within the AVT area, as detailed in figure 7. In light of these findings, it is crucial for the competent authorities, particularly those in civil protection, to implement appropriate strategies to mitigate the risks derived from these geological phenomena.

According to the structural typology provided by INEGI, it has been identified that in the affected geographic areas (AGEBs), social interest housing predominates, including both single-family and multi-family homes, as well as middle-class single-family homes. In terms of structural engineering, these types of housing present low vulnerability to differential settlement due to the materials used in their construction. However, the increasing incidence of cracking, resulting from the overexploitation of the aquifer, has significantly raised the structural vulnerability, increasing it to high levels in the affected areas.

The appearance of cracks in key structural elements, such as load-bearing walls, concrete floors, and partition walls made of concrete and drywall, has led to the manifestation of evident structural faults. This geological phenomenon, due to its intensification in recent years, has become of considerable importance. Therefore, the identification, monitoring, and evaluation of cracking should be considered priorities, given its potential impact on the stability and safety of infrastructures in the region.

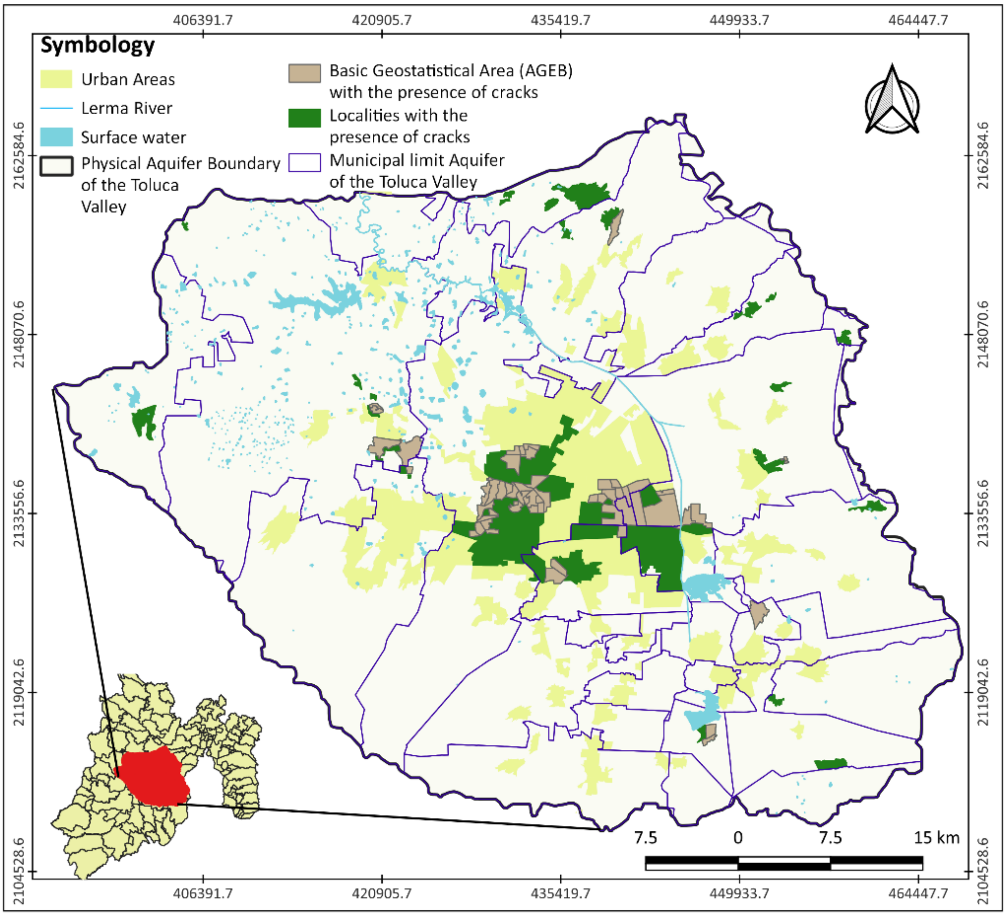

Figure 7 Map of Localities and AGEBs with Presence of Cracks in the Toluca Valley Aquifer (own elaboration).

4.4 Measures for Risk Reduction, Protection, and Conservation of the Toluca Valley Aquifer

The risk reduction measures are based on a thorough analysis of the three geological processes identified in the study area, namely: subsidence, sinking, and cracking. These measures consider both the social impacts and the effects on the natural environment, specifically the Toluca Valley Aquifer. The purpose of these measures is to mitigate the risks associated with the overexploitation of water resources by implementing processes and controls aimed at reducing the impact of these geological phenomena. The proposed actions are as follows:

1. **Development of Thematic Cartography**: The creation of detailed cartography is proposed to identify and classify areas with higher susceptibility to the aforementioned geological risks, in order to facilitate risk management.
2. **Structural Inspection and Verification**: It is suggested to carry out structural assessments of buildings and houses to identify possible variations in cracking and differential settlement. This action will allow for early warnings to residents and ensure the structural integrity of the buildings.
3. **Determination of Preventive and Corrective Measures:** The formulation of preventive and corrective measures in civil protection is recommended, aimed at reducing geological risks. This would include the implementation of emergency intervention strategies and the planning of actions to mitigate the impact of future events.
4. **Continuous Geotechnical and Geological Monitoring**: The implementation of a geotechnical and geological monitoring system in areas affected by cracking, subsidence, and sinking is suggested, to assess the evolution of these phenomena and anticipate possible increases in risk.
5. **Development of Standards and Construction Codes Adapted to Geotechnical Conditions**: The creation and updating of regulations and construction codes that consider the specific geotechnical conditions of the State of Mexico are proposed, to ensure the structural safety of buildings in areas prone to these geological phenomena.
6. **Proposals for Structural Adaptations**: The implementation of structural adaptations in homes and buildings is recommended, which would help withstand adverse geological conditions, reducing the impact of subsidence, sinking, and cracking phenomena.
7. **Establishment of Prevention and Early Warning Programs**: The creation of prevention and early warning programs is proposed, which would consider the vulnerability and marginalization indices of localities and Basic Geo-statistical Areas (AGEBs), allowing for a more effective response to risk situations.

Regarding the protection and conservation of the Toluca Valley Aquifer, the following measures are proposed:

1. **Inventory and Control of Polluting Activities**: An exhaustive inventory of polluting activities, including industrial, agricultural, and urban sources, is recommended, to identify pollution sources and develop specific measures to mitigate their effects on the aquifer.
2. **Development of Environmental Impact Statements**: The implementation of environmental impact studies in the areas surrounding the aquifer is suggested, as well as the adoption of protective measures for recharge zones of the aquifer, to ensure its preservation.
3. **Update of Regulations on Water Resource Exploitation and Use**: The review and update of regulations related to the exploitation and use of water resources in the region are proposed, in order to promote sustainable groundwater management.
4. **Development of Cartography for Water Recharge Zones**: The creation of specific cartography to identify water recharge zones, as well as potential future recharge areas, is recommended, to implement conservation and protection measures in these critical spaces.

5. Conclusion

The analysis conducted on the structural vulnerability and geological risks in the Toluca Valley Aquifer (AVT) reveals a complex interaction between the phenomena of sinking, subsidence, and cracking, all of which are closely linked to the overexploitation of the water resource. The results indicate that the geological alterations derived from excessive groundwater extraction have significant impacts both on urban infrastructure and the stability of surrounding ecosystems, especially in water recharge zones.

The process of evaluating and monitoring these phenomena, along with the establishment of preventive and corrective measures, is essential to mitigate associated risks. The proposed actions, including the development of geotechnical cartography, the implementation of geological monitoring programs, and the updating of construction regulations, are fundamental to reducing structural vulnerability and ensuring the sustainability of the aquifer in the long term.

Integral water resource management, coupled with a rigorous focus on the protection of recharge zones, is imperative to avoid the continued overexploitation of the aquifer and the exacerbation of geological phenomena. Efforts in public policy, territorial planning, and environmental regulations need to be strengthened to ensure sustainable coexistence between human activities and the conservation of water resources in the region. Therefore, the situation of the Toluca Valley Aquifer requires immediate attention and a multidisciplinary approach that addresses both geological risks and water management policies, ensuring the protection of infrastructure, the environment, and the resilience of affected communities. The following measures are proposed for implementation:

1. **Continuous Monitoring of Water Extraction Areas:** It is essential to implement a constant monitoring system for water extraction zones to assess the evolution of the water table levels and prevent overexploitation. This monitoring should include periodic measurements of extracted volumes, water quality, and changes in aquifer levels.
2. **Development of a Comprehensive Database on Water Use**: A centralized database is proposed to record the water use by various entities (companies, organizations, etc.), detailing consumption volumes and the type of use (industrial, agricultural, urban). This will allow for more effective tracking of consumption and its impact on water resources.
3. **Relocation of Houses in Critical Water Recharge Zones**: Relocation policies should be implemented for houses located in critical water recharge zones. This measure aims to reduce pressure on recharge areas and mitigate the negative effects of urbanization on underground resources.
4. **Optimization of Artificial Recharge with Treated Wastewater**: The artificial recharge of aquifers using treated wastewater should be improved as a strategy to increase the availability of groundwater. This measure must be implemented with strict quality controls to avoid negative health impacts on the aquifer.
5. **Strengthening Coordination with Civil Protection Authorities**: Efficient and continuous communication with the relevant authorities in civil protection, fire departments, and public safety should be established to adequately manage emergencies arising from geological risks (sinking, subsidence, cracking).
6. **Development of a Database of Affected Buildings**: It is essential to develop a geospatial database that includes all buildings affected by sinking, subsidence, and cracking phenomena. This database should include detailed records and visual documentation (such as a photographic album) to observe the evolution of damages over time.
7. **Implementation of a Comprehensive Geological Risk Monitoring Program**: A monitoring program for sinking, subsidence, and cracking should be established, incorporating

technologies such as topography to assess terrain altimetric changes, and electrical resistivity tomography to map changes in the geological structure of the affected zones.

8. **Continuous Monitoring of Affected Geo-statistical Basic Areas (AGEB):** Detailed follow-up on the Basic Geo-statistical Areas (AGEB) affected by geological phenomena should be conducted. Additionally, periodic assessment of the structural and geotechnical conditions of these areas should be performed to determine their vulnerability and plan necessary interventions.

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