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Articles

Barriers to the transition towards a circular economy in the sustainable management of groundwater in Mexico

Barreras para la transición hacia una economía circular en la gestión sostenible de las aguas subterráneas en México

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Abstract

We analyze gaps in groundwater management in Mexico from a circular economy perspective, emphasizing its relevance to environmental and social sustainability through indicators such as household water availability, contribution, and consumption. Using data mining, descriptive statistics and an exploratory linear regression model, the study analyzes indicators of availability, contribution and consumption of water in households, as well as the determinants of groundwater deficits in the hydrological-administrative regions of Mexico. The findings reveal inefficiencies and inequities in resource use. Additionally, exploratory econometric results show that groundwater deficits cannot be explained solely by hydrological availability or to population growth, suggesting the importance of structural and institutional factors. It is concluded that these challenges require moving towards a circular economy approach that ensures sustainable and equitable use of water, in line with Sustainable Development Goal 6.

Keywords: groundwater, water resources management, sustainable development, water consumption, data analysis, Mexico.

Resumen

Analizamos las deficiencias en la gestión del agua subterránea en México desde una perspectiva de economía circular, destacando su relevancia para la sostenibilidad ambiental y social mediante indicadores como la disponibilidad, la contribución y el consumo de agua en los hogares.



Mediante minería de datos, estadística descriptiva y un modelo exploratorio de regresión lineal, el estudio analiza indicadores de disponibilidad, contribución y consumo de agua en los hogares, así como los determinantes de los déficits de agua subterránea en las regiones hidrológico-administrativas de México. Los hallazgos revelan ineficiencias e inequidades en el uso del recurso. Además, los resultados econométricos exploratorios muestran que los déficits de agua subterránea no pueden explicarse únicamente por la disponibilidad hidrológica o al crecimiento poblacional, lo que sugiere la importancia de factores estructurales e institucionales. Se concluye que estos desafíos requieren avanzar hacia un enfoque de economía circular que garantice un uso sostenible y equitativo del agua, en consonancia con el Objetivo de Desarrollo Sostenible 6.

Palabras clave: agua subterránea, gestión de los recursos hídricos, desarrollo sostenible, consumo de agua, análisis de datos, México.

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1. Introduction

The global need for water has increased sixfold in the last century, and the world's population is growing by nearly 80 million people annually. By 2050, 90% of people will live in developing countries, in regions where sanitation and sustainable access to drinking water are lacking, a 55% increase in global water demand was projected for the period between



2000 and 2050 (UNESCO, 2010; OECD, 2012). Millions of people do not have access to improved sources and many others lack sanitation facilities (UN-Water, 2021; United Nations, 2010). More than 97% of the fresh water available in the world is located underground. Its availability depends on factors such as climate, geology and topology of the terrain, which would be reflected in the recharge and flow of water, as well as porosity and permeability (Jakeman et al., 2016; Macías González & Del Arenal Capetillo, 2007). Given the increasing scarcity of water in many parts of the world, it is imperative that groundwater be valued and managed carefully and sustainably according to the United Nations (UN-WATER & UNESCO, 2022).

The Circular Economy of Water (CEW) reuses, regenerates and reduces water consumption instead of extracting, using and disposing, it involves four stages throughout the hydrological cycle: rethinking, decreasing, optimising, retaining (ARUP et al., 2019; Morseletto et al., 2022). The CEW aligns with the United Nations Sustainable Development Goals (SDGs 6, 12, and 13) by promoting water reuse and efficiency, with data collection as a step for accurate assessment (UN-Water, 2021). Implement circular economy in efficient water management methods to obtain treated water or clean water, which can be used in industry, agriculture and other non-potable uses, reducing the demand for the resource suitable for human consumption, better responding to scarcity, equitable distribution and quality control (Hlavínek et al., 2023; Lima et al., 2025). Water management involves government institutions, water users, and other stakeholders; therefore, governance plays a fundamental role in ensuring equitable and sustainable access (Jakeman et al., 2016).

International evidence that efficient CEW implementation relies on context-specific strategies such as drip irrigation and wastewater treatment, which enable reuse, energy recovery, and green job creation, with demonstrated benefits in countries like India (Rasul et al., 2021; Saravia Matus, Gil Sevilla, Sarmanto, et al., 2022; Van der Kooij et al., 2013; World Bank, 2021). However, CEW adoption faces economic and regulatory barriers, including insufficient incentives and weak institutional frameworks, making impact assessment and strong social and institutional support essential for sustainable implementation (Ait-Mouheb et al., 2020, 2022; Azeb et al., 2020; Lountain et al., 2024). Evidence also shows that willingness to pay for groundwater improvements depends on uncertainty, reinforcing the need for better data, monitoring, and policy design, alongside strategies such as crop adjustments, demand management, and equitable tariff systems that promote efficient use without compromising financial sustainability (Brouwer & Neverre, 2020; Chávez et al., 2006; Neverre et al., 2022; SEMARNAT & CONAGUA, 2016).

At the same time, water inequality and scarcity disproportionately affect vulnerable populations, disrupting livelihoods, health, and social inclusion, which underscores the importance of resilient and inclusive governance frameworks informed by international experiences (Hartwig et al., 2022; Lund Schlamovitz & Becker, 2021; Parry, 2024). Since the 1990s, global governance reforms and circular economy initiatives have provided relevant lessons—though Mexico remains underrepresented—while international economic dynamics have intensified pressures on water resources through export-oriented agricultural models (Bjornlund & Bjornlund, 2025; Centre for Economic Development, Transport and the Environment (CDET), & SWECO, 2020; OECD, 2015). Addressing these

challenges requires strengthened governance, coordinated decision-making, and a balanced mix of incentives and regulatory instruments aligned with the Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), to advance equitable, efficient, and sustainable water management (Schulz et al., 2024; Venot & Molle, 2008).

Groundwater is a strategic resource in Mexico, where agriculture represents the largest water-consuming sector and several hydrological-administrative regions already exhibit groundwater deficits due to extraction levels exceeding natural recharge (Diario Oficial de la Federación, 2020; IMCO, 2023a; IMCO, 2023b). This situation reflects increasing pressure on aquifers and highlights the importance of improving groundwater governance and promoting circular economy strategies that enhance efficiency and sustainability. However, the circular water economy plays a limited role in policy, reflecting governance and implementation gaps; this study therefore examines how groundwater management can be reframed under a circular economy approach to support more equitable and resilient policies.

2. Material and methods

2.1. Data sources

This research was based on three main data sources and analyzed at the level of Mexico's 13 Hydrological-Administrative Regions (Regiones Hidrológico-Administrativas, RHA), the territorial units used for water resources planning and management in the country.

First, the 2020 and 2024 National Household Income and Expenditure Survey (Encuesta Nacional de Ingresos y Gastos de los Hogares, ENIGH), prepared by the National Institute of Geography and Statistics (Instituto Nacional de Geografía y Estadística, INEGI), which provides data on household heads, including variables related to water availability (frequency of water supply in the dwelling, l/s) and water distribution (type of potable water source available to the household).

Second, the Agreement updating the average annual availability of groundwater, which is part of Mexico's hydrological-administrative regions (Diario Oficial de la Federación, 2020), which reports indicators such as average annual recharge (the volume of water naturally replenishing aquifers) and committed natural discharge (the volume required to sustain ecosystems and surface water bodies), both expressed in million cubic meters per year (Mm^3/year).

Third, the groundwater quality database from the National Water Commission (Comisión Nacional del Agua, 2022), that includes classifications of water quality based on parameters such as fecal coliforms (microbiological contamination; values ranging from <1.1 to $>10,000$ MPN/100 mL), nitrate nitrogen (nutrient contamination; values ranging from ≤ 5 to >11 mg/L), and lead concentrations (heavy metal contamination; threshold value of 0.01 mg/L), used to classify groundwater quality.

2.2. Analytical methods y Geographical framework

For this research, we employed data mining as the primary analytical technique. The extraction of information from large datasets, known as data mining, has been widely applied in diverse fields of research,

particularly in information analysis and decision-making. Living in an information society facilitates the automatic collection of vast amounts of data on individuals, organizations, and institutions. The availability of this data for secondary analysis—such as the application of learning models and the identification of behavioral patterns—is valuable for policymakers, planners, marketing analysts, researchers, and other professionals (Ghaljahi et al., 2018; Hajian et al., 2014; Lauwo, 2018; Petreski et al., 2014). This approach enables the identification of recurrent patterns and disparities in water use, distribution, and allocation between male- and female-headed households in both rural and urban settings.

The methodological process followed in this study consisted of several stages. First, we obtained the 2020 National Household Income and Expenditure Survey (ENIGH) in .sav format and converted it to Excel. Data were organized using the variable folioviv, a unique household identifier assigned by INEGI, which includes the federal entity, municipality, and corresponding geographic areas. This variable served as the key to link data across different ENIGH tables. In addition, we used the variable ubicageo, which identifies the geographic location of the household, to delimit our variables of interest.

Second, a new column was created in the database to assign each household to its respective watershed. To achieve this, we cross-referenced ENIGH data with the hydrological basin codes provided by the National Water Commission (CONAGUA), which correspond to state and municipal identifiers. Using the Excel VLOOKUP function, we matched each record with its watershed label.

Third, the database was analyzed in IBM SPSS Statistics 23. All data were weighted using the expansion factor provided by ENIGH (Datos → Weight cases → Expansion factor), ensuring representativeness at the

national and state levels. Specific filters were then applied according to the variables under study, and the outputs were exported to Excel for further tabulation, percentage calculations, and graphical representation.

Additionally, an exploratory linear regression model was estimated using standard econometric procedures to assess the relationship between groundwater deficit, effective water availability, and population across hydrological basins.

Finally, the geographical framework for the analysis was based on Mexico's hydrological-administrative basins. Figure 1 illustrates their distribution across the country, which provided the spatial reference for interpreting disparities in water access and management.



Figure 1. Hydrological basins in México. Data source: CONAGUA 2024

3. Results

3.1. Groundwater availability and regional disparities

The Agreement on the Update of Average Annual Availability of Groundwater (Diario Oficial de la Federación, 2020) reveals how the Mexican government seeks to promote efficient water resource management in the 653 officially recognized aquifers. However, our analysis shows that eleven of the thirteen river basins have recharge deficits compared to demand, especially in the VI Río Bravo, VII Cuencas Centrales del Norte, and VIII Lerma-Santiago-Pacífico basins. This raises the question of whether these measures truly address current challenges in terms of sustainability, equitable access, and groundwater governance in the country's different regions.

Overall, the average groundwater contribution to the basins is 41%, which reflects a significant but uneven dependence on this resource across the country. The basins with the largest population are the VIII Lerma-Santiago-Pacífico with 25,649,083 people, the XIII Aguas del Valle de México with 23,815,128, and the VI Río Bravo with 13,295,533. In contrast, the VII Cuencas Centrales del Norte, the III Pacífico Norte, and the II Noroeste have the smallest populations (see Figure 2). The average population per basin is 9,680,262, but the concentration in certain regions places additional pressure on groundwater reserves. In highly populated basins, the challenge is not only the volume extracted but also the efficiency of distribution, water quality, and infrastructure, which complicates the adoption of circular economy measures. Conversely, in sparsely populated regions, governance and investment constraints may hinder sustainable management.

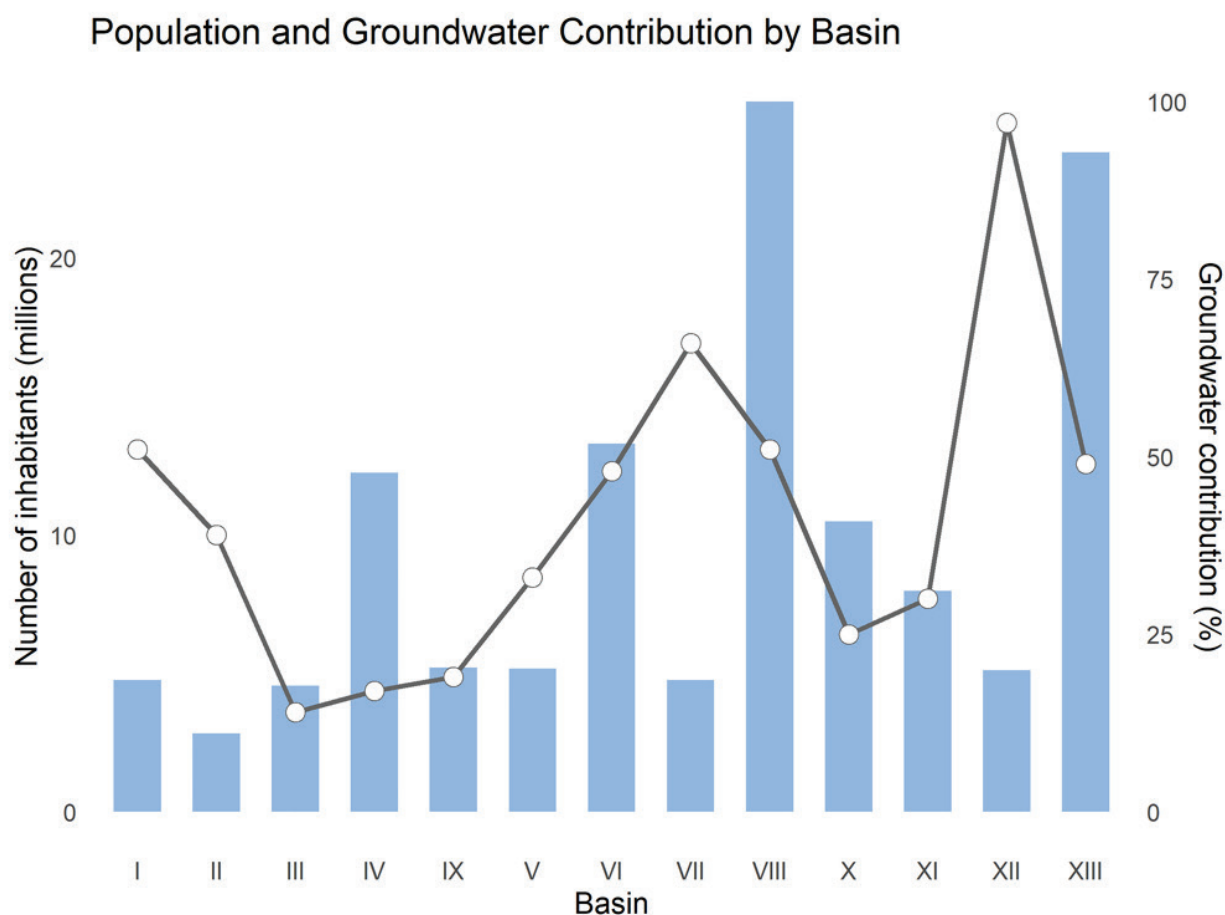


Figure 2. Population and Groundwater Contribution. Data source: CONAGUA 2024 from the National Survey of Household Income and Expenditure (ENIGH) 2020, INEGI and Diario Oficial de la Federación DOF Agreement updating the average annual availability of groundwater 2020.

The highest water consumption is found in the VIII Lerma-Santiago-Pacífico basins with 15,292 hm³/year (the term hm³/year refers to cubic hectometers per year, a unit that expresses large volumes of water, where 1 hm³ is equivalent to one million cubic meters), 30% more than

the following basins: IV Balsas and III Pacífico Norte. Those with the lowest consumption are: VII Cuencas Centrales del Norte, XI Frontera Sur, and V Pacífico Sur. On average, there is 6,533 hm³/year, a quantity that challenges the CEW (see Table 1). Continuing with the analysis of the information in Table 1, it is observed that the largest contribution of groundwater is located in the XII Península de Yucatán basin, where 96.6% of the water consumed comes from groundwater, followed by the VII Cuencas Centrales del Norte with 65.7% and the VIII Lerma-Santiago-Pacífico with 51.40%. The lowest contribution to the water supply comes from the IX Golfo Norte basin with 18.5%, IV Balsas with 17% and III Pacífico Norte with 13.7%. The average supply to the country is 41.39% which comes from groundwater.

Table 1. Statistics on Mexico's watersheds

Basin		Number of habitants in 2020 (According to INEGI)	Water consumption (hm ³ /year)
I	Península de Baja California	4,766,488	3,949
II	Noroeste	2,833,584	6,715
III	Pacífico Norte	4,555,601	10,731
IV	Balsas	12,240,831	10,784
V	Pacífico Sur	5,168,465	1,539
VI	Río Bravo	13,295,533	9,513
VII	Cuencas Centrales del Norte	4,755,573	3,801
VIII	Lerma-Santiago-Pacífico	25,649,083	15,292
IX	Golfo Norte	5,200,192	5,899
X	Golfo Centro	10,482,417	5,449
XI	Frontera Sur	7,973,261	2,337
XII	Península de Yucatán	5,107,246	4,149
XIII	Aguas del Valle de México	23,815,128	4,771
		125,843,402 Total number of habitants in 2020	84,929 total water consumption in cubic hectometers. Information taken from: Diario Oficial de la Federación (DOF) Agreement updating the average annual availability of groundwater 2020.

Source: Own elaboration based on data from the National Survey of Household Income and Expenditure (ENIGH) 2020, INEGI and Diario Oficial de la Federación (DOF) Agreement updating the average annual availability of groundwater 2020.

These figures shows the unequal distribution and use of groundwater across the country. While high consumption in the Lerma-Santiago-Pacific basin reflects the pressure of population, industrial, and agricultural activities, regions such as the Yucatán Peninsula face a different challenge: their overwhelming dependence on groundwater (96.6%) exposes them to risks of overexploitation and contamination. In contrast, basins with a low share of groundwater rely more on surface sources, which are highly vulnerable to seasonal variability and climate change. This imbalance the structural difficulties in moving toward a circular water economy, as strategies must be tailored to the specific challenges of each hydrological region.

A clear example of these dynamics is the Yucatán Peninsula, where groundwater accounts for almost 100% of the water supply for human consumption and agriculture. However, this region faces significant threats stemming from its highly permeable geology, the absence of surface rivers, and increasing population and industrial growth. Aquifer contamination is exacerbated by the dumping of waste into cenotes, wells, and ground fissures, the lack of wastewater treatment, and the expansion of industries such as the pork industry (Chávez Guzmán, 2021). Additionally, infrastructure projects such as the Mayan Train negatively impact the quantity and quality of water resources in the region (Rendón Molina et al., 2022).

Beyond this case, there is substantial regional variability in water consumption per capita across Mexico's watersheds. For example, the Noroeste II and Pacífico Norte III basins report the highest annual consumption, reflecting the influence of arid climates and agricultural water demands, whereas the Pacífico Sur V and Aguas del Valle de México

XIII basins have the lowest per capita consumption, partly due to higher population density and limited water availability. These contrasts underline the profound inequalities in water use and observes the challenges of promoting sustainable and equitable groundwater governance across the country.

If we analyze the frequency with which Mexican households receive water, as reported by ENIGH, clear disparities emerge across basins, although the survey does not distinguish between groundwater and surface water sources. The highest proportion of daily water supply is observed in II Noreste, III Pacífico Norte, VI Río Bravo, and XII Península de Yucatán (see Figure 3), whereas IV Balsas and V Pacífico Sur have very low daily supply percentages. Basins with the largest proportion of households receiving water every three days include IV Balsas, V Pacífico Sur VI Río Bravo, X Golfo Centro, and XI Frontera Norte. Notably, the V Pacífico Sur basin has a high share of households with sporadic water supply.

Figure 3 shows that the V Pacífico Norte basin, encompassing Guerrero and Oaxaca, exhibits the greatest disparities in water supply frequency. This pattern reflects not only geographic factors such as topography and precipitation variability, but also differences in infrastructure development, urbanization processes, investment levels, and the institutional capacity of water utilities to ensure reliable service provision (Jakeman et al., 2016; Lund Schlamovitz & Becker, 2021). The IV Balsas basin also shows substantial variability across multiple states, including Michoacán, Jalisco, Puebla, Oaxaca, Guerrero, Estado de México, Morelos, and Tlaxcala. These patterns underscore regional inequities in water access and show that water allocation does not always correspond to population needs or aquifer availability.

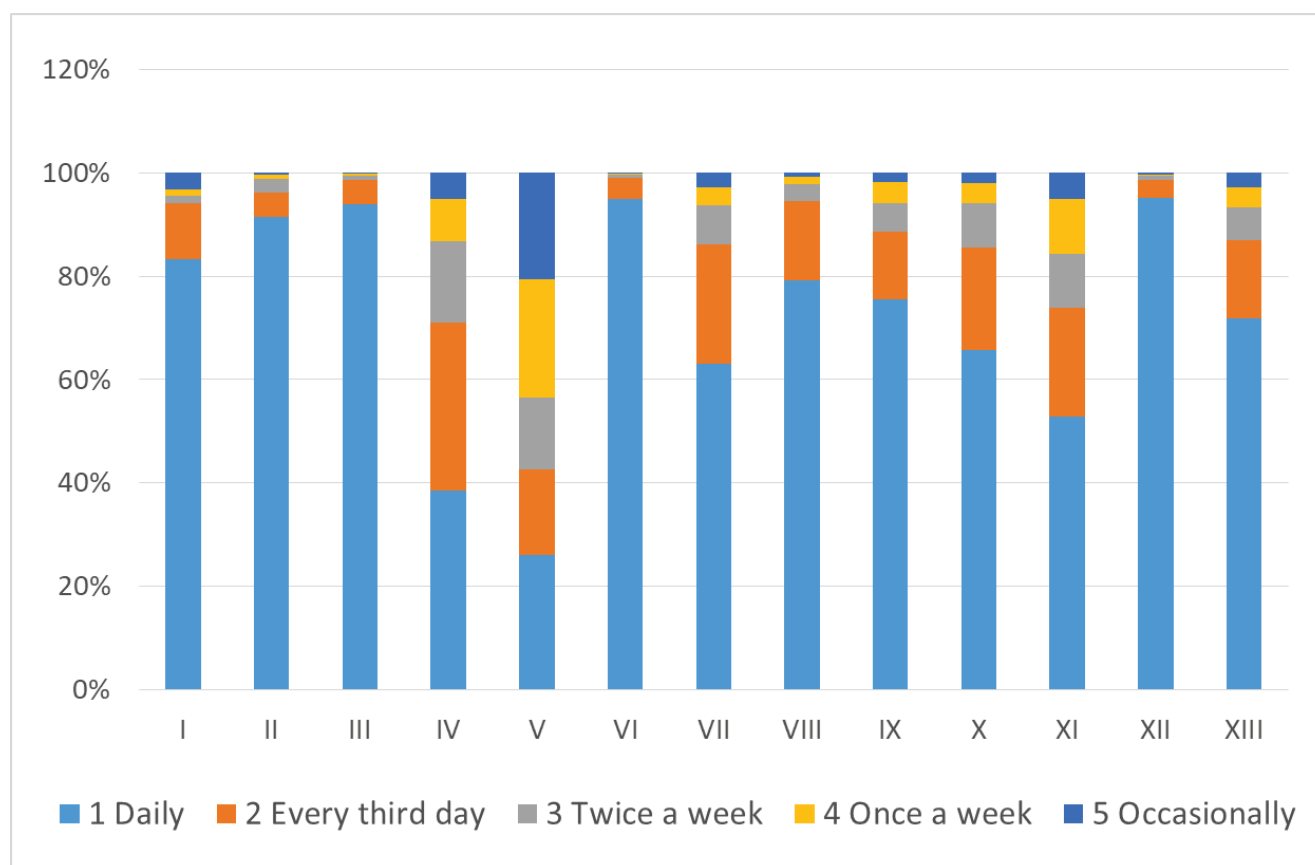


Figure 3. Population and Groundwater Contribution. Data source: CONAGUA 2024 from the National Survey of Household Income and Expenditure (ENIGH) 2020

From a circular economy perspective, these disparities indicate opportunities for improving water-use efficiency, implementing rainwater harvesting, wastewater reuse, and sustainable allocation strategies tailored to each basin. Addressing these gaps is essential to achieving Sustainable Development Goals (SDG) 6 and 12, ensuring equitable, reliable, and environmentally sustainable water access. Moreover, incorporating social dimensions, including gender equity, is crucial since water scarcity disproportionately affects women and vulnerable

communities, who are often responsible for domestic water collection (Aureli & Brelet, 2004; Saravia Matus, Gil Sevilla, Fernández, et al., 2022; Saravia Matus, Gil Sevilla, Sarmanto, et al., 2022; Sturzenegger & Dockweiler, 2019).

3.2. Groundwater management

The analysis of groundwater extraction in Mexico shows that the largest amounts of extracted water are found in Basins I (Península de Baja California), II (Noroeste), VII (Cuencas Centrales del Norte), VIII (Lerma-Santiago-Pacífico), and XIII (Aguas del Valle de México), see Table 2. Likewise, high extraction volumes are identified in areas with provisional suspension of free water supply and in those with rights registered in the Permanent National Registry, with Basin VI (Río Bravo) being particularly notable. Regarding the volume of water extraction still pending in the Public Registry of Water Rights, the highest percentages are observed in Basins I (Península de Baja California) and VI (Río Bravo). These patterns observe the institutional challenges of groundwater governance, as a portion of extraction is not yet fully registered in the Public Registry of Water Rights, meaning that actual withdrawals may exceed officially recorded volumes. This regulatory gap reflects the limited institutional capacity to monitor, enforce, and plan groundwater use, which in turn exacerbates regional overexploitation.

Table 2. Average annual groundwater availability by hydrological basin

Basin	Total average annual recharge	Required natural discharge	DMA: average annual groundwater availability	
			Positive	Deficit
I	1648	178	74	-601
V	1936	702	569	-61
XIII	2289	698	182	-837
VII	2460	170	300	-1049
III	3061	1224	173	-374
II	3207	316	264	-435
IX	4099	2386	571	-238
X	4599	2198	744	-75
IV	4871	2198	714	-69
VI	6370	1396	586	-4350
VIII	9832	2671	468	-1520
XI	22718	11412	10311	0
XII	25316	17342	3009	0
<i>Figures in millions of cubic meters per annum</i>				

Source: Own elaboration based on data from Diario Oficial de la Federación (DOF) Agreement updating the average annual availability of groundwater 2020.

This deficit is an important statistic, as it indicates that the demand for groundwater in that area is greater than the amount of water that is naturally replenished through recharge, which can lead to a decrease in the aquifer level. The greatest water deficits were observed in the VI Río

Bravo, VII Cuencas Centrales del Norte and VIII Lerma-Santiago-Pacífico basins, however, only two basins do not present a deficit, XI Frontera Sur and XII Península de Yucatan. This difference is associated with their comparatively higher groundwater availability, as shown in Table 2. However, the near absence of deficits in these regions should not obscure the broader national trend: the majority of Mexico's basins show unsustainable extraction patterns. From a sustainability perspective, this situation undermines progress toward SDG 6.4, which calls for substantially increasing water-use efficiency and ensuring sustainable withdrawals of freshwater. Previous studies have emphasized that effective groundwater management and the transition toward a circular water economy require robust governance frameworks, transparent allocation systems, and incentives that promote efficient water use and reuse (Jakeman et al., 2016; Venot & Molle, 2008; Morseletto et al., 2022; Schulz et al., 2024). In this context, groundwater management in Mexico remains a significant challenge for achieving long-term water security.

Looking at Mexico as a whole, the country has an average annual total recharge of 92,494 hm^3/year , which represents the volume of water that infiltrates the subsoil and maintains the long-term viability of aquifers. Recharge is fundamental for sustaining water availability and preserving the ecological integrity of groundwater-dependent ecosystems. However, the required natural discharge amounts to 42,892.7 hm^3/year , which is necessary to sustain aquatic ecosystems, wetlands, and surface water bodies. The resulting national water balance shows a deficit of -9,610.8 hm^3/year , revealing that extractions and commitments together exceed the natural recharge capacity of aquifers. This negative balance shows a pattern of overexploitation that not only

threatens aquifer health but also reduces the resilience of ecosystems and communities dependent on groundwater. In sustainability terms, this situation undermines the possibility of intergenerational equity, as current extraction levels compromise the future availability of this vital resource.

Thirty-eight percent of groundwater is allocated under concessions or assigned volumes, which at first glance suggests some level of planned management, 5.6% to areas under provisional suspension, 1.2% to pending registrations, and a negligible share to environmental reserves (Diario Oficial de la Federación, 2020). However, this figure is insufficient to guarantee sustainability unless complemented by broader indicators such as water-use efficiency, water quality, and compliance with environmental thresholds. Moreover, effective governance requires not only institutional enforcement but also community participation and monitoring mechanisms that ensure accountability in the allocation process (Jakeman et al., 2016; Lund Schlamovitz & Becker, 2021; Schulz et al., 2024). Within the framework of the Circular Economy for Water (CEW), analyzing patterns of groundwater recharge and discharge becomes central to promoting efficient and equitable resource management. Basins with higher consumption rates face severe risks of supply shortages, while those with lower pressures provide opportunities to pilot efficiency-oriented practices. Incorporating these indicators into urban planning, agricultural modernization, and industrial regulation would help address unsustainable extraction trends. In this sense, the national water balance clearly signals the urgency of adopting policies aligned with SDG 6 (Clean water and sanitation) and SDG 12 (Responsible consumption and production), emphasizing efficiency, conservation, and the preservation of groundwater-dependent ecosystems.

To assess the determinants of groundwater deficit across hydrological basins in Mexico, an exploratory linear regression model was estimated. The specification considers groundwater deficit as the dependent variable, while effective water availability (measured as the difference between recharge and natural discharge) and population are included as explanatory variables.

The estimated model is expressed as follows (Equation (1)):

$$Def_i = \beta_0 + \beta_1(R_i - D_i) + \beta_2Pop_i + \varepsilon_i \quad (1)$$

where:

Def_i = Groundwater deficit in basin i

R_i = Average annual total recharge

D_i = Required natural discharge

$(R_i - D_i)$ = Effective groundwater availability

Pop_i = Population in basin i

ε_i = Error term

Based on the estimation results, the empirical model can be written as (Equation (2)):

$$Def_i = -789.14 - 0.00499(R - D)_i + 7.13 \times 10^{-6}Pop_i \quad (2)$$

The regression results indicate a very low explanatory power of the model ($R^2 = 0.0019$; Adjusted $R^2 = -0.1976$), suggesting that the included variables explain virtually none of the variation in groundwater

deficits across basins. Additionally, the overall model is not statistically significant ($F = 0.0099$; $p\text{-value} = 0.9900$).

Individually, neither effective water availability nor population shows statistical significance ($p\text{-values}$ of 0.9677 and 0.8914, respectively). The estimated coefficients also exhibit very small magnitudes, indicating negligible marginal effects.

These results suggest that groundwater deficits in Mexico cannot be adequately explained by hydrological availability or demographic pressure alone. The absence of statistically significant relationships indicates that the dynamics of groundwater depletion are more complex and likely driven by structural, institutional, and management-related factors (Chávez et al., 2006; Jakeman et al., 2016; Morseletto et al., 2022; Schulz et al., 2024).

Figure 4 illustrates the distribution of groundwater quality conditions across Mexican basins using a traffic-light classification based on fecal coliforms, nitrate nitrogen, and lead concentrations. Green represents favorable water quality conditions, yellow indicates moderate levels requiring attention, and red indicates that at least one of the evaluated parameters exceeds the thresholds established for acceptable groundwater quality conditions. The results reveal a markedly heterogeneous pattern. Basins such as VII (63%) and IX (54%) exhibit a high proportion of critical conditions (red), indicating significant groundwater stress and potential risks for sustainability. In contrast, basins IV (69%), V (67%), and X (67%) are predominantly characterized by favorable conditions (green), suggesting relatively stable groundwater quality. Intermediate cases, such as II (52%) and VIII (54%), also show a majority of favorable conditions but with non-negligible shares of moderate and critical levels. Meanwhile, basins like XI display a more

balanced distribution across categories, reflecting transitional or mixed conditions. Overall, this variability observes that groundwater quality challenges in Mexico are not uniformly distributed, reinforcing the need for basin-specific management strategies that account for local environmental pressures, infrastructure, and governance capacity.

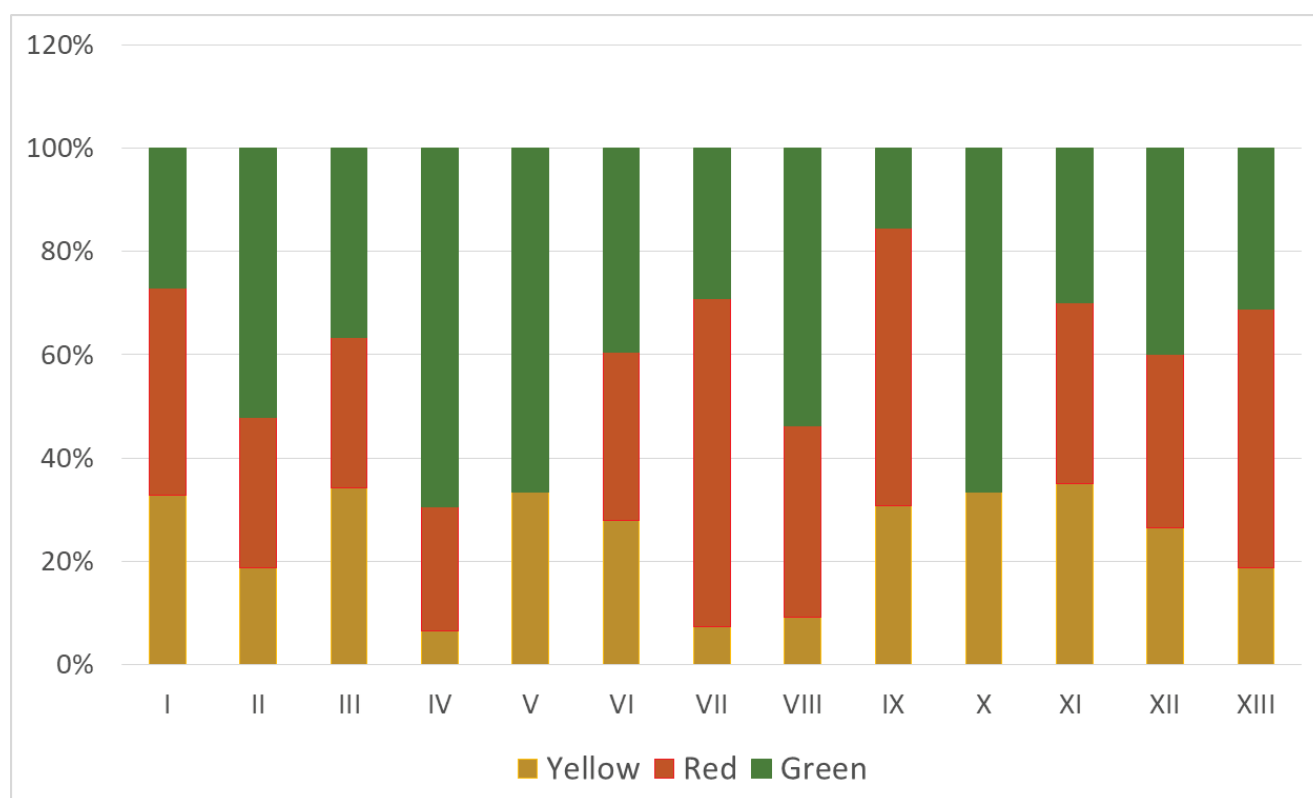


Figure 4. Groundwater quality indicator in Mexican basins

Taken together, these findings reveal that groundwater dynamics in Mexico are shaped by a complex interplay of extraction pressures, institutional limitations, and uneven territorial conditions. High levels of extraction and persistent deficits coexist with weak explanatory power from conventional variables such as water availability and population,

while the traffic light classification further confirms the heterogeneous distribution of groundwater quality across basins. This combination of results suggests that current approaches to groundwater management remain insufficient to capture the multidimensional nature of the problem. Rather than a purely hydrological or demographic issue, groundwater depletion emerges as a governance and management challenge, requiring integrated strategies that incorporate institutional capacity, monitoring systems, and circular economy principles to ensure sustainable and equitable water use.

3.3. Identification of information gaps

With a water circularity index of only 9% in 2019, Mexico faces a serious water security risk, making it urgent to strengthen its management and promote reuse in different sectors to mitigate environmental and economic deterioration (SEMARNAT, 2024). One of the main information gaps in these data is the lack of precision regarding the distribution of extracted water among the different use sectors. It is not specified how much of this water is intended for domestic consumption, how much is used by industry or agriculture, or what the criteria are for allocating these volumes. This omission makes it difficult to evaluate the efficiency of groundwater use and the implementation of sustainable management strategies, as the impact of groundwater overexploitation varies depending on its final destination (Chávez et al., 2006; Jakeman et al., 2016). Without this disaggregated information, it is difficult to design equitable and evidence-based public policies that allow for more equitable and efficient access to water resources.

Another limitation lies in the lack of systematic monitoring of aquifers. Data on recharge, extraction, and water quality are often outdated, incomplete, or inconsistent across regions. For instance, piezometric levels are not measured continuously in all aquifers, and many regions lack reliable data on pollutant concentrations beyond a few selected parameters (Chávez et al., 2006). This undermines the ability to forecast long-term trends and to design adaptive management policies. Furthermore, groundwater management involves multiple institutions and levels of government, while existing monitoring systems remain insufficient in key sectors such as agriculture, creating challenges for coordinated decision-making and sustainable water management (IMCO, 2023a).

The current water management system in Mexico does not promote a complete understanding of the natural groundwater cycle. This has had serious consequences, such as land subsidence, the disappearance of surface water sources, the impact on ecosystems, the imbalance in water bodies, and a significant impact on public health. Gradually and silently, the improper use of groundwater is harming the most vulnerable sectors of the population and causing irreversible damage to the quality of life of future generations (Cubas et al., 2017). In addition, the absence of transparent and disaggregated information hinders Mexico's progress toward the Sustainable Development Goals (SDGs), particularly Goal 6 (Clean water and sanitation) and Goal 12 (Responsible consumption and production), which call for integrated and equitable resource governance.

In the face of these challenges, the circular economy has gained increasing attention as an approach to improve water-use efficiency, promote water reuse, and reduce pressure on freshwater resources through the recovery and recirculation of water within production and

consumption systems (ARUP et al., 2019; Morsetto et al., 2022; Hlavínek et al., 2023). Strategies have been implemented in regions such as Europe, Latin America, the Middle East, and Asia to optimize water use, reduce waste, and promote reuse, all with the goal of minimizing pressure on water resources (ARUP et al., 2019; Morsetto et al., 2022; Saravia Matus et al., 2022; World Bank, 2021). The following paragraphs summarize selected international experiences in the application of circular economy principles in water management, identifying successful practices, barriers, and lessons learned that may be relevant to the Mexican context. For instance, countries such as Singapore and Israel have achieved significant improvements in water reuse and efficiency, with treated wastewater covering up to 30–40% of non-potable urban demand (Mekonnen & Hoekstra, 2016; OECD, 2020).

One of the main gaps in the circular economy for water management lies in the absence of clear and up-to-date regulations that promote the reuse of treated wastewater and aquifer recharge. Without a coherent legal framework, circular economy initiatives face administrative, technical, and financial obstacles, limiting their scalability. Insufficient investment in infrastructure exacerbates the problem, as the lack of treatment plants, rainwater harvesting systems, and smart irrigation technologies impedes the efficient use of water. Adequate monitoring and data transparency are also essential; without accessible, updated information on water quality, availability, and consumption, informed decision-making is hindered, and the impact of implemented strategies remains difficult to evaluate. Comprehensive policies that integrate legal, technical, and financial measures are necessary to address these persistent challenges.

The lack of stakeholder integration, particularly of local communities, further constrains the implementation of circular economy models. Gender and equity considerations are critical in groundwater management, as women and vulnerable groups are disproportionately affected by water scarcity. Women, for example, often bear primary responsibility for water collection and household usage, which impacts their time, access to economic opportunities, and overall well-being. Ignoring these social dimensions risks perpetuating existing inequalities rather than alleviating them. Circular water management policies must therefore adopt an inclusive approach, ensuring equitable access to water, active participation of women and marginalized groups in decision-making, and recognition of the specific needs of those most affected. This approach aligns directly with the Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 5 (Gender Equality), reinforcing the need for socially and environmentally sustainable water governance.

4. Discussion

The discussion of the results shows a persistent gap in knowledge and practice regarding the circular economy of water (CEW), particularly in the management of groundwater. While groundwater accounts for a substantial share of domestic and agricultural supply in Mexico, there is limited information on how resources are distributed across sectors such as agriculture, industry, and households, or on the criteria used to allocate water according to quality. Likewise, the management of wastewater remains opaque: it is often unclear whether effluents from these sectors are treated before disposal or reused, which hinders the transition

towards circular water strategies such as recycling, safe discharge, and aquifer recharge.

This limitation is also reflected in the empirical analysis, where the regression model showed no statistically significant relationship between groundwater deficit, water availability, and population, suggesting that current data and conventional variables are insufficient to explain the observed dynamics. This finding is consistent with previous studies suggesting that groundwater stress cannot be explained solely by hydrological variables, but is also shaped by governance arrangements, institutional capacity, and water allocation practices (Jakeman et al., 2016; OECD, 2015; Schulz et al., 2024).

One of the most critical challenges identified is the overexploitation of aquifers, which has already been documented in several basins and threatens to generate irreversible processes such as saline intrusion, diminishing water availability for human consumption and agriculture (IMCO, 2023a). These results support the argument of Brouwer and Neverre (2020) and Noémie et al. (2022), who emphasize that effective groundwater management requires reliable monitoring systems and better information to prevent long-term degradation and support sustainable decision-making. This overexploitation is compounded by uneven recharge rates and increasing pollutant loads, which put both ecosystem functioning and public health at risk. Sustainable groundwater management is therefore essential not only to guarantee future water access, but also to advance the commitments of SDG 6 on clean water and sanitation and SDG 12 on sustainable consumption and production, ensuring that groundwater is managed as a renewable but finite resource.

Water management in Mexico shows a marked dependence on groundwater sources, which provide close to half of the total demand for

household and agricultural use. This dependence reflects both the structural scarcity of surface water in several regions and the insufficient development of circular economy of water (CEW) strategies that could reduce extraction pressure. As shown in our results, some basins rely on groundwater for more than 90% of their supply—such as the Yucatán Peninsula—while others face severe recharge deficits, as in the case of the Valle de México and Río Bravo basins. These asymmetries emphasize that groundwater sustainability is not only a technical challenge but also a matter of territorial inequality, since overexploitation and poor quality disproportionately affect the most vulnerable populations and agricultural producers. Without effective CEW strategies, the long-term risks include depletion, saline water intrusion, and the deterioration of ecosystems that depend on groundwater flows.

Currently, approximately 40–41% of Mexico's water supply originates from its 653 officially recognized aquifers, while the remaining 60% comes from surface sources (IMCO, 2023b). This high and uneven reliance on aquifers underscores the urgency of implementing measures that integrate CEW principles—such as artificial recharge with treated water, reduction of urban leakages, reuse of wastewater, and the modernization of irrigation systems. Experiences from countries with similar levels of groundwater dependence, such as Spain and India, demonstrate that without such measures, aquifers face irreversible degradation processes that compromise food security, public health, and social stability. For Mexico, advancing in this direction is essential to align water management with sustainable development goals and to ensure resilience in the face of climate variability and demographic pressures.

According to Mexico's most recent water balance, the country receives an average of 1,449 cubic kilometers of precipitation per year,

of which nearly 70% evaporates and returns to the atmosphere through evapotranspiration. As a result, the effective natural water availability is reduced to approximately 451.6 cubic kilometers annually. Of this volume, around 80% becomes surface runoff, while the remainder infiltrates to recharge aquifers (SEMARNAT, 2022). This limited recharge is insufficient to offset extraction in several basins, particularly in regions such as the Valle de México and Lerma-Santiago-Pacífico, where water demand far exceeds natural replenishment. Conversely, in areas like the Yucatán Peninsula, highly permeable geology allows rapid infiltration but also increases vulnerability to contamination, showing that geographical and geological conditions are decisive in determining recharge potential and water security.

Beyond quantity, groundwater quality remains a challenge in Mexico, with contamination ranging from agricultural runoff to untreated urban and industrial wastewater. The traffic light classification system reveals basins in critical condition alongside others with more favorable profiles. This variability shows the need to integrate Circular Economy of Water (CEW) strategies, such as reuse, recharge, and efficiency measures, into regulatory frameworks to safeguard both water quality and long-term sustainability.

Effective groundwater management in Mexico requires governance structures capable of addressing contrasting regional conditions. Highly urbanized basins such as XIII (Aguas del Valle de México) face severe deficits and contamination, reflecting fragmented institutions and limited enforcement capacity. In contrast, regions like XII (Península de Yucatán), which depend almost entirely on groundwater, are vulnerable due to their karstic geology, increasing risks of contamination from wastewater, agriculture, and tourism expansion. These contrasting

dynamics show that groundwater challenges are both institutional and hydrogeological. Integrating Circular Economy of Water (CEW) strategies—such as reuse, artificial recharge, and demand management—together with inclusive governance models, is essential to balance environmental sustainability, social equity, and long-term water security.

5. Conclusions

Groundwater management in Mexico must be reoriented through the lens of circular economy principles in order to ensure long-term sustainability. Overexploitation of aquifers, a critical challenge across the country, not only compromises future water availability but also raises the economic and environmental costs of extraction and treatment. The circular economy provides a framework for minimizing waste, optimizing resource flows, and fostering systemic efficiency in water governance.

Strategies include the reuse of treated wastewater, the harvesting of rainwater, and the optimization of agricultural irrigation practices. These measures can significantly reduce pressure on aquifers, particularly in regions where agriculture remains the main consumer of water resources. Beyond improving efficiency, artificial recharge of aquifers with surplus rainfall or treated water has emerged as a promising alternative to mitigate shortages, reinforcing natural cycles and enhancing groundwater resilience.

Policy frameworks must therefore move beyond linear models of water consumption and embed circular practices that emphasize efficiency, reuse, and ecological balance. This involves not only regulatory innovation but also fostering awareness among industries, agricultural producers, and households about the shared responsibility of preserving

groundwater. The integration of circular economy principles into water policies can reduce demand in the most intensive sectors while also promoting equity and resilience.

Ultimately, adopting circular economy strategies in groundwater management is not an optional pathway but an imperative. By linking water governance with principles of resource recovery, waste minimization, and systemic efficiency, Mexico can safeguard groundwater availability for future generations while simultaneously advancing environmental sustainability and social well-being.

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7. Declaration of conflict of interest

The authors declare no conflict of interest.

8. Declaration of AI use

The authors used ChatGPT (OpenAI) exclusively for language editing and formatting purposes. All analyses, results, and interpretations were

conducted independently by the authors, who assume full responsibility for the content of the manuscript.

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