Managed Aquifer Recharge in Mexico: Proposals for an Improved Legal Framework and Public Policies

Abstract

In Mexico, groundwater availability has been decreasing, especially in arid and semiarid regions; this can be addressed by boosting aquifer recharge, known as managed aquifer recharge, with stormwater or treated wastewater. In this paper, we use qualitative approaches to analyse three managed aquifer recharge projects in the country and discuss related achievements, limitations, and lessons learned. We argue that the Law of Nations' Waters lacks precise rules for water storage and recovery of recharged water, making the planning of significant investments to implement these projects unlikely. We present legal, management, and financial proposals to improve the relevant legal water framework.

Keywords: Managed aquifer recharge, municipal governments, state governments, public policy, regulations, Mexico

Introduction

In Mexico, groundwater availability has been decreasing. One means to increase groundwater availability is by implementing artificial recharge projects. Managed aquifer recharge (MAR) refers to the diverse methods used to augment groundwater resources when available and recover the water from the same aquifer in the future when needed (Dillon, 2005; Khan et al., 2008).

This article examines the views of researchers and state and municipal water managers on operational MAR projects in three localities in Mexico. With this analysis, we contribute to the literature on MAR projects in Mexico and highlight the importance of collaboration among water managers at the federal, state, and municipal levels with researchers who are contributing meaningfully to several projects.

Managed aquifer recharge in Mexico: Legal and institutional frameworks

According to the National Water Commission (Comisión Nacional del Agua or CONAGUA), 100 of the most important aquifers are over-drafted (Cruz-Ayala & Megdal, 2020). Water stress increased significantly from 2008 to 2017 in the north of the country, with water stress above 80% in the North-Western region in 2015 (CONAGUA, 2018). Groundwater availability has diminished over the years due to over-abstraction (CONAGUA, 2012), threatening social and productive activities. MAR projects have been proposed to increase the water supply for human consumption and agricultural activities.

In Mexico, the Law of the Nation's Waters (hereafter, LAN) contains specific provisions for groundwater management. The LAN defines the role of CONAGUA as the federal agency responsible for water administration, setting national water policies, enforcing water regulations, and monitoring meteorological conditions (Akhmouch, 2012; DOF, 2004; Scott & Banister, 2008). It also reports on groundwater availability per aquifer (Diario Oficial de la Federación, DOF), which is used to set water allocation volumes (CONAGUA, 2017; OECD, 2015). In 2020, CONAGUA reported on the groundwater availability for 653 aquifers (DOF, 2020). In 157 aquifers, the extraction rate exceeded the natural recharge, while saline intrusion or high salt concentrations have been identified in 50 aquifers.

The federal government, through CONAGUA, provides technical assistance and authorizes financial infrastructure support to states and municipalities (Díaz-Cayeros et al., 2002). Municipal projects are submitted to CONAGUA, which approves projects after evaluating their feasibility.

CONAGUA has developed a centralized water policy and vision for groundwater management and aquifer recharge (Cruz-Ayala & Megdal, 2020). Such a centralized system has both advantages and disadvantages. An advantage is that there is only one institution and a single policy for the country (Carlisle & Gruby, 2019). Disadvantages are that the system is not flexible and does not incorporate learning from and adapting to local contexts. The centralized water policy has not been informed by consultation with state and local governments, water users, researchers, or civil society. Stakeholder participation could provide valuable knowledge that could influence policy and make individual and institutional goals more reachable (Marouf, 2007). Combining bottom-up and top-down consultation processes to include the views of as many groups as possible is recommended during policy

formulation (Rogers & Hall, 2003). Local perspectives can revamp federal policies to support MAR and improve water availability.

The Mexican Constitution prescribes explicit federal and municipal water management obligations, but not state obligations. However, state governments can support municipal governments when requested to do so (Briseño & Sánchez, 2018; Casiano-Flores et al., 2016; Akhmouch, 2012; DOF, 2004). Every state, including Mexico City, has an agency dedicated to water issues (Pineda, 2002), which functions as a bridge between CONAGUA and the municipal authorities. Financial support from the federal government for municipal water infrastructure is often disbursed into the state's accounts (Akhmouch, 2012; Díaz-Cayeros, 2002). There are several reasons for this arrangement. One is that state governments have terms of six years, compared to the three years for municipal governments, which helps infrastructure projects get completed. It can also resolve political differences that hinder collaboration among water managers at state and municipal levels (Díaz-Cayeros et al., 2002).

Municipal governments provide potable water, sanitation, wastewater treatment, and infrastructure related to these services (DOF, 2004; Scott & Banister, 2008; Wilder et al., 2020). Almost all municipal governments have water utilities and a fee structure to fund these services. This income is, however, insufficient for service provision, and financial support from federal or state governments is needed to build or maintain infrastructure (Briseño & Sánchez, 2018). Some water utilities have adequate financial and technical resources to meet their responsibilities, while others do not.

The LAN ordains that "the exploitation, use, or non-consumptive use of the nation's water resources should be carried out through a concession or *asignación* granted by the Federal Executive Branch or Basin Councils" (DOF, 2004; CONAGUA, 2012). *Asignación* is the legal term the Mexican legislation establishes for water appropriation to provide water services for urban or domestic purposes. Unlike concessions, *asignaciones* cannot be transferred to other users. The LAN prioritises a list when approving concessions and *asignaciones*; the first five uses listed in the LAN are 1. Domestic; 2. Urban-public; 3. Livestock; 4. Agriculture; 5. Aquaculture (Cruz-Ayala & Megdal, 2020; DOF, 2016).

The LAN does not include a MAR definition; it only refers to "artificial recharge" and requires a permit for artificial recharge activities (DOF, 2004). It does not specify the permit requirements or how MAR facilities would be monitored. There are two national

water quality standards for MAR in Mexico, NOM-015-CONAGUA-2007 (for recharge with stormwater) and NOM-015-CONAGUA-2007 (for recharge with treated wastewater). The LAN defines "wastewater" as a mixture of water resulting from various uses but does not define "treated wastewater." This lack of a legal definition for treated wastewater and its allocation creates uncertainty concerning water rights when used for recharge.

One aspect that can positively contribute to MAR efforts is making the technology widely available through demonstrative projects. For instance, the Managed Aquifer Recharge Solutions (MARSOL) project in Europe has financed MAR efforts and provided technical assistance in several European countries (European Union, 2017). Another example is the High Plains States Groundwater Demonstration Program Act enacted in 1984 by the Congress of the United States. Under this project, Federal agencies conducted studies in 17 states to identify appropriate sites for MAR projects (Rogers, 2009/2013).

The technical feasibility of MAR projects in Mexico has been extensively studied (e.g., Bonilla-Valverde et al., 2018; Cruz-Ayala & Megdal, 2020; González et al., 2015). However, only five states have implemented MAR projects on a large scale. Most of these projects are in semiarid regions with short rainy and prolonged dry seasons and are managed by local authorities (Cruz-Ayala & Megdal, 2020). Local agencies implementing these MAR projects are familiar with their operation; the experience of local authorities in implementing these MAR projects could provide valuable governance insights.

In this study, we evaluate three MAR facilities in Chihuahua, Mexico City (Iztapalapa), and Sonora and discuss relative achievements, limitations, and applicable regulations. We analyse the relevant legal framework for MAR and, incorporating the perspective of officials managing these three facilities, we present and examine some proposals to improve it.

Methodology

This qualitative study includes an in-depth review and analysis of legal and policy documents, academic literature, and consultancy reports in both English and Spanish. We also interviewed decision-makers, water managers, researchers experienced in MAR, and Non-governmental organizations representatives (see Table 1). Finally, we visited MAR facilities.

Table 1. Number of interviewees per sector (researchers, federal, state, and municipal water officials, NGOs, consultants)

Interviewees	Number
Researchers	8
CONAGUA (including IMTA)	7
State authorities	4
Municipal water managers	7
Non-governmental organizations	3
Consultants	2

The Human Subjects Protection Program of the University of Arizona reviewed and approved the study protocol (protocol number 1907776608). We identified interviewees from the literature review and previous research that one of the authors has conducted (Cruz-Ayala & Megdal, 2020). We also used snowball sampling to identify additional study participants.

Study sites

Based on previous research (Cruz-Ayala & Megdal, 2020), we identified three operational MAR study locations: San Luis Río Colorado (SLRC) city in Sonora; Chihuahua city in the state of Chihuahua; and Iztapalapa township in Mexico City. MAR facilities have been functioning for at least a decade in all three places (Fig. 1). Table 2 lists the main characteristics of each facility and the MAR methods employed.

San Luis Río Colorado is a municipality in Sonora, northwest Mexico, at the US border. SLRC depends on groundwater from the unconfined San Luis Rio Colorado aquifer. Based on data gathered in 2000, the water levels in wells of the San Luis Rio Colorado town ranged between 14-16 meters deep (UABC, n.d.). A city-government-initiated MAR project that uses treated wastewater (Hernández-Aguilar et al., 2017) has been operational since 2004. It was funded by the North American Development Bank and the municipal water agency. Chihuahua city is located in the central region of Chihuahua state. The MAR project, which uses stormwater, is situated in the unconfined Chihuahua-Sacramento aquifer (CONAGUA, 2020). The system where the MAR infrastructure is operating is, however, considered an isolated system, which is not connected with the Chihuahua-Sacramento aquifer (González-Núñez, 2014). During the operation of the MAR

system, the average groundwater level increased from 32 m in 1986 to 92 m in 2010 (Sánchez et al., 2021). The MAR project is led by the Autonomous University of the State of Chihuahua. The state and municipal water agencies provide financial support for its operation, and University researchers monitor the project.

Iztapalapa is the most populous township in Mexico City, and the groundwater is extracted from the Metropolitan Area of the semi-confined Mexico City aquifer. The dynamic groundwater levels vary between 15.74 and 187.7 meters deep (Ruiz, 2015). This aquifer has the highest water stress index in the country (CONAGUA, 2018). Inadequate drainage facilities cause frequent floods, and many neighbourhoods lack access to potable water. In late 2010, the local government started building percolation wells to reduce flooding. These wells have also helped increase aquifer recharge.

Table 2. Characteristics of the three study sites

	San Luis Río Colorado, Sonora	Chihuahua, Chihuahua	Iztapalapa, Mexico City
Management agency	Municipal agency	Municipal agency	Local water office
MAR objective	Aquifer recharge	Aquifer recharge	Aquifer recharge and flood control
Method	Soil aquifer treatment	Percolation tanks and recharge weirs	Percolation wells
Source of water	Treated wastewater	Stormwater	Stormwater
Funding agencies	North American Development Bank and municipal water agency	State and municipal water agency and Autonomous University of Chihuahua	Local government

Semi-structured interviews

We conducted 31 semi-structured interviews with relevant stakeholders (see Table 3). We gathered detailed information on stakeholders' experience in implementing MAR projects, the working relationship between researchers and water managers, and the opportunities and barriers faced when managing MAR facilities.

a

b

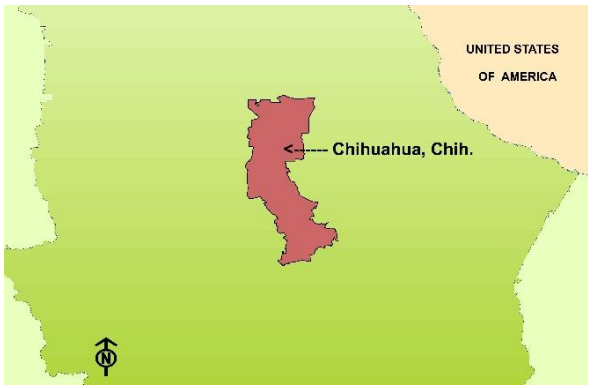

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Figure 1. Study sites: a. Mexico (country), b. San Luis Rio Colorado, Son. c. Chihuahua, Chih, d. Iztapalapa, Mexico City

Table 3. List of interviewees' organizations

	Sonora	Chihuahua	Mexico City
Federal agency	CONAGUA	CONAGUA	CONAGUA
State agencies	State water agency	State water agency	No state water agency.
Municipal agencies	Municipal water agencies in San Luis Río Colorado and Hermosillo	Municipal water agency	Urban services office, a water utility for Mexico City. Township governments.
Academic institutions	University of Sonora Autonomous University of Baja California	Autonomous University of Chihuahua	Mexican Institute of Water Technology, Metropolitan Autonomous University, National Autonomous University of Mexico
Non-governmental organizations and consultants	ProNatura	World Wildlife Fund	None

Rationale for the interviews

CONAGUA is responsible for water management, policy, and regulations and sets the national budget for water infrastructure, among other responsibilities (Akhmouch, 2012; DOF, 2004). The interviews included questions on the relationship CONAGUA had maintained with water agencies at the state and municipal levels about MAR efforts and whether CONAGUA has supported MAR facilities in the three study sites. In addition, we questioned whether the federal government has created programs to recharge aquifers in the northwest region of Mexico.

In Mexico, state governments build infrastructure for water resources at the state level. They have a closer relationship with CONAGUA than municipal authorities do and can negotiate financial support for municipalities (Díaz-Cayeros et al., 2002). Therefore, questions to officials at the state water agencies focused on whether they had authorized financial support for the MAR projects in their state and their role in creating managed aquifer recharge infrastructure. We also asked whether they had programs and financial resources to increase the urban water supply or to implement MAR projects in municipalities in their states.

Municipal governments have knowledge and experience in developing and running MAR facilities. Our questions focused on the challenges they have faced in maintaining these facilities and whether they had received technical and financial support from the

federal government to develop the MAR infrastructure. We also asked whether, through their experience, they had identified any legal barriers when operating MAR efforts and whether they had any proposals on how to improve regulations and policies.

Researchers from national and state universities have conducted research projects on MAR, so we interviewed them to determine whether they have shared project outcomes with water managers. Interviewees were also questioned about procedures for defining water allocations and whether regulations needed any revision.

A few NGOs are collaborating on aquifer recharge projects. In Sonora and Chihuahua, they have worked with water managers and researchers on MAR projects. Therefore, to obtain a broader perspective, we also interviewed NGO representatives. In SLRC, ProNatura has collaborated with the municipal water utility. ProNatura is an NGO working on restoring riparian ecosystems and water conservation in northwest Mexico. In Chihuahua, the World Wildlife Fund (WWF), an NGO working in the Chihuahuan Desert, has a project on integrated water management in the Conchos Basin. The WWF collaborates on MAR projects with researchers from the Autonomous University of Chihuahua. Our questions to ProNatura and the WWF representatives focused on their relationship with government agencies and the aquifer recharge projects these organizations had supported and implemented in the state.

Results

San Luis Rio Colorado and Hermosillo, Sonora

We present information on two MAR sites in Sonora, San Luis Rio Colorado, and Hermosillo. However, it should be noted that the proposed MAR project in Hermosillo has not been built. Hermosillo is a relevant example of the limited communication and working relationship between federal, state, and municipal water managers regarding MAR.

The San Luis Rio Colorado MAR facility was built in 2007 with the financial support of The North American Development Bank (NADB). The NADB can support communities within 100 km north or south of the US–Mexico border (NADB, 2020). Treated wastewater is recharged using the soil aquifer treatment method, where the soil provides additional treatment of the wastewater before it reaches the aquifer (Bonilla-

Valverde et al., 2018; Page et al., 2018). The recharge water infiltrates slowly into the aquifer via six lagoons (Hernández-Aguilar et al., 2017).

We interviewed municipal water managers who proposed the MAR project and managed it for ten years. They explained that the NADB representatives established that the wastewater treatment plant should include options to reuse or sell the treated wastewater for the project to be authorized. As a first option, municipal authorities considered selling the treated wastewater to farmers for agricultural use, but the price would have been higher than water pumped from local wells. A second possibility was to discharge the treated wastewater into the Delta of the Gulf of California. This could have helped maintain environmental services in the riparian ecosystem, and an NGO would have paid for the water.

The chosen option was to use the treated wastewater to recharge the SLRC aquifer as this would be less expensive than the two alternatives mentioned above. Researchers from the Autonomous University of Baja California and a former researcher at the Conservation Laboratory of the US Department of Agriculture in Phoenix, Arizona, advised the project manager to develop a pilot project.

The officials of the municipal office we interviewed mentioned they had faced technical and financial challenges. For instance, the municipality uses its funds to maintain the MAR facility because there is no specific MAR program. One of the main technical challenges was clogging, a common problem when a soil-aquifer-treatment method is used (Page et al., 2018). The problem was solved by scraping and removing sediments in each lagoon. In addition, a wetland was built to provide further treatment before sending the water to the basins to be recharged. ProNatura provided financial support to construct it and has functioned as a technical advisor in this regard.

Annually, 8.2 million cubic meters of water are being recharged (Hernández-Aguilar et al., 2018; Hernández-Aguilar et al., 2017). The recharged water meets federal water quality standards (NOM-001-SEMARNAT), except for iron, manganese, and chlorides, which are at the same levels as in the native water. According to the researchers interviewed, these higher levels are due to natural chemical reactions in the aquifer when the water is being infiltrated.

The San Luis Río Colorado MAR project is the most successful in Mexico. It has been operating for over a decade and maintains a monitoring system. One of the main concerns is the absence of regulations to define how the recharged water will be allocated;

for instance, whether the municipal government will get new *asignaciones* for public service based on the recharged water.

In Hermosillo, in 2014, CONAGUA sponsored a study to analyze the conditions of the Sonora River basin and the coastal aquifers, which are the water source for the city. Researchers from the Institute of Engineering of the National Autonomous University of Mexico conducted this study. A technical proposal was developed to build a MAR facility in Hermosillo to provide additional water to urban areas (Palma et al., 2015). This proposal included reducing the water supply for the irrigation district and reducing water losses by using more efficient equipment and building MAR facilities. The study models indicated that the best option to increase aquifer recharge would be to reduce the use of treated wastewater for irrigation and transfer this water to MAR facilities (Palma et al., 2015). This scenario would also include reducing the irrigated area, using less water, and growing a single crop yearly. Regarding this project, the interviewee from the State government mentioned that a managed aquifer recharge project would be the last option this agency might implement because they lack financial resources.

One of the topics mentioned in the interviews was the lack of clarity on how to get an aquifer recharge permit. An interviewee with long experience in water law and administrative affairs said that the LAN includes regulations on permits for discharging treated wastewater but not for using it for groundwater recharge. This lacuna in the Mexican legislation must be addressed, and clear rules must be created for investing in MAR.

Chihuahua city, Chihuahua

In the city of Chihuahua, water levels in some wells used for domestic water supply have been dropping. Because of this problem, a group of researchers from the Autonomous University of the State of Chihuahua, in collaboration with the local government, developed a pilot project to increase the recharge in the Chihuahua-Sacramento aquifer using gabions and wells, using stormwater as a recharge source (Cruz-Ayala & Megdal, 2020; González-Núñez, 2014; Silva-Hidalgo et al., 2017). The municipal government provided financial and human resources, and researchers from the university advised the government. The interviewees from the municipal government said that the collaboration with the researchers has been productive. This infrastructure has been functioning for at least ten years. Researchers monitor the wells to identify changes in the quantity and quality of the water. In

general, groundwater levels rose and stabilized in the first five years, with the water level rise being faster for wells closer to the MAR site than for wells further away.

In contrast, for the municipal government, "it is an option to increase water availability for inhabitants in the city of Chihuahua," and the results so far are promising. Several problems, however, need to be solved for the facility to operate over the long term. According to one municipal employee, "We need financial support to build monitoring wells and maintain the infrastructure." Another issue is that water rights for recharged water are insufficiently considered in the legislation. The municipal government needs assurance that the recharged or new water will not be allocated to other users.

The municipal government of Chihuahua has also participated with scholars from the National Autonomous University of Mexico on another MAR project. This project uses treated wastewater and aims to recharge the unallocated effluent (about 30 million cubic meters/year) currently discharged into the Chuvíscar River (Palma et al., 2018). CONAGUA funded this project. It was reported that the pilot project has been functioning for some years (Bonilla-Valverde et al., 2018), but it is still experimental. Some researchers and decision-makers do not support using treated wastewater as a source for recharge, with researchers saying that stormwater is a better source for aquifer recharge. However, decision-makers noted that all the available water supply options must be considered to replenish aquifers in the state. The WWF and the state government representatives said that creating a state hydrological plan is essential. This plan must include artificial recharge projects, payment for hydrological services, and the protection of natural recharge areas.

The WWF has developed a collaborative plan with the state and municipal governments to increase managed aquifer recharge projects. This plan includes conducting workshops to provide information on the advantages of MAR, evaluating sites for MAR using stormwater, and discussing the creation of specific committees with water users from rural and urban environments. The WWF has served as a bridge between researchers and the state water managers on MAR projects by, for example, helping to organize MAR workshops and conferences.

Iztapalapa township, Mexico City

The local government in Iztapalapa has begun constructing percolation wells to manage floods and reduce damage to houses and infrastructure. The wells have layers of

gravel and sand that function as filters, which are removed from time to time to eliminate silt and maintain the percolation.

Researchers at the Metropolitan Autonomous University collaborate with the local government to monitor recharge volumes and water quality. A monitoring well was installed within the university campus (Gómez-Reyes et al., 2010) to monitor the performance of the percolation wells continuously. Local water managers said that the relationship with researchers has been very productive and helped them communicate with the federal government. However, they pointed to the need to increase MAR research projects because local governments cannot handle experimental managed aquifer recharge projects and solve daily problems simultaneously. The local government's water managers presented a proposal to CONAGUA that includes potential sites for wells and asked for technical advice. Unfortunately, CONAGUA did not support this plan and did not provide them with financial or technical support. Researchers and local government representatives agree that long-term solutions to increase the city's water supply are needed.

As per the LAN, CONAGUA is responsible for the conservation and management of groundwater. Municipal agencies may extract this resource to provide water for public services (DOF, 2004). The interviewees from state and municipal agencies remarked that the aquifer recharge responsibility should be shared between the federal and local governments. Municipal governments have launched aquifer recharge efforts but need more financial and technical support from the federal authorities. Researchers and water managers remarked that specific policies and regulations are necessary to ensure the success of MAR. Their proposals can be summarized in two categories: creating incentives and defining water rights (Table 4).

Table 4. Proposals for public policies and regulations for MAR

Proposals	Sonora	Chihuahua	Mexico City
Incentives	● Fiscal incentives ● Water fees reduction or fees exemption for extraction of groundwater	● Groundwater banking to guarantee water entitlements (*asignaciones* and concessions)	● Increase public investment in MAR projects
Water rights / entitlements	● Users and enterprises that have invested in MAR projects should be entitled to the recharged water. ● Create a federal program to transfer water rights	● Users and private sector groups that have invested in MAR projects should be entitled to the recharged water	No specific proposals

Discussion

MAR projects would be more feasible with strong governance, institutional capacity, and support because inadequate institutional arrangements for MAR can lead to conflicts between water users ((Dillon et al., 2018; Ward & Dillon, 2012). Moreover, a key barrier to a broader implementation of MAR lies in the legal definition of ownership of the recharged water (Barreteau et al., 2016). As per the LAN, concessions, and *asignaciones* of assets under the Federation's public regime, in this case, water, do not create ownership of the resource (CONAGUA, 2012). According to the rules and conditions that federal laws establish regarding the concession deed, these entitlements grant the right to use, appropriate, or benefit from national resources without prejudice to third parties. Regarding *asignaciones*, the water rights are limited to using the water to provide public services, and this water right cannot be transferred to other users. The federal government retains ownership over any recharged stormwater or treated wastewater (CONAGUA, 2012). This means that the newly recharged water will be added to the available aquifer water volume and could be allocated to any user. This provision creates uncertainty for people interested in investing in aquifer recharge projects because CONAGUA could grant concessions or *asignaciones* to any new users who request them.

MAR facilities have been operating for decades in several countries (Dillon et al., 2018), but only a few of them, such as Australia, Spain, and the US, have specific MAR regulations (Bernat et al., 2020; Dillon et al., 2018; Ward & Dillon, 2011). In the US, two states have a regulatory framework to protect the rights of those recharging water. Colorado allows water rights to be conveyed by deed (Blomquist et al., 2001). Arizona has a system for

groundwater augmentation through recharge while protecting other water users and ensuring sufficient monitoring (Megdal, 2007).

In Mexico, state and municipal water managers propose that the LAN incorporate regulations to allocate recharged water and protect the rights of those who have created and are maintaining MAR infrastructure and are recharging treated wastewater. For instance, in Spain, the legislation establishes that "someone who wishes to reuse treated wastewater – including for aquifer recharge – may secure a right to do so through a contract with the holder of an administrative permit for the disposal of wastewater" (Burchi, 2014, p. 25). The interviewees argued that CONAGUA could define concessions and *asignaciones* of the recharged water according to the priority use established in the LAN (DOF, 2016). Ward & Dillon (2012) suggest that if a water user has a right over the water before it is recharged into an aquifer, the user should also have a right to recover it. Water rights holders want to engage in MAR because they expect to receive the full benefits –either water rights or financial incentives (Blomquist et al., 2001). In California, one of the objectives of the permitting process for underground aquifer recharge and storage was to help local agencies obtain water rights (Hanak & Stryjewski, 2012). Pienaar et al. (2021) examined the institutional and governance arrangements to implement groundwater protection measurements in South Africa. These authors suggest that reaching sustainable groundwater use is needed to support municipalities and the participation of local water users and other stakeholders. Considering these models, in Mexico, an option could be that if a state or municipal agency built and operated a MAR project, this agency might be the first to be granted a portion of the recharged volume in the form of *asignaciones*.

For water banking to work, there must be agreement on water use plans and infrastructure funding mechanisms and honoring water entitlements (Megdal et al., 2014; Villholth, 2021). In Arizona, entities that store water can legally recover that water (ADWR, 2021; Silber-Coats & Eden, 2017) in two ways: annual storage and recovery and long-term storage credits. In annual storage and recovery, entities that have recharged water may recover it in the same calendar year. As the water remains stored after the end of the calendar year, the Arizona Department of Water Resources calculates the amount that can be recovered and issues long-term storage credits. Owners may sell their long-term storage credits to other users (Bernat et al., 2020). In Colorado, entities receive credits for the water they recharge, and any water in excess of that may be transferred and sold (Blomquist et al.,

2001). Water managers from Sonora and Chihuahua suggested that similar schemes could be implemented in Mexico. Undoubtedly, federal regulations for water storage and recovery are needed in Mexico. State and municipal water managers should be consulted when these rules are developed.

Scholars have documented MAR examples in other Latin American countries, including Brazil, Chile, and Peru, but, like Mexico, these countries lack appropriate aquifer recharge regulations (Bonilla-Valverde et al., 2018; da Silva et al., 2019; Shubo et al., 2020). In Chile, the Water Code, and the Regulation on Groundwater Exploration and Exploitation Standards mention MAR as an option to address water scarcity in basins with a negative water balance (CSIRO, 2020; Donoso, 2006). However, water quality standards for recharged water have not been defined. In Perú, a large-scale aquifer recharge project has been running with positive results, but the national government has not enacted related regulations (Fernández et al., 2019). In Brazil, there are 26 laws regarding MAR at the federal and state levels. None include rules on recovering the recharged water (da Silva et al., 2019). In summary, as in Mexico, a comprehensive legal framework for MAR is needed in these Latin American countries.

Any new guidelines for MAR must include a transparent permitting system and water ownership rules (Fernández et al., 2020). The LAN permits the discharge (Article 3) and the recharge of treated wastewater (Article 90) (DOF, 2004) but does not outline the specific requirements to authorize a MAR facility using treated wastewater. Even though MAR facilities have been operating for at least a decade in Chihuahua, Mexico City (Iztapalapa), and Sonora, these facilities still lack official authorization and are considered pilot projects. The SLRC (Sonora) MAR facilities have permits from the Federal Ministry of the Environment and Natural Resources but no official authorizations from CONAGUA as MAR projects. The LAN does not mention how to obtain a permit to build a MAR facility, with one interviewee stating that "there are permits for water discharge but not for recharged water." While defining the guidelines for obtaining a permit to build MAR infrastructure could be considered a procedural issue, they are essential to creating a robust legal framework.

Incentives are needed to motivate the municipal and private sectors to store groundwater using MAR (Tuthill et al., 2018). In Mexico, the federal government defines the financial incentives for water conservation activities. The Federal Ministry of the

Environment and Natural Resources has implemented a Payment for Environmental Services program to maintain environmental services and protect natural aquifer recharge zones (Instituto Nacional de Ecología, 2005). Water managers in the state of Chihuahua suggested that the federal government could create a similar program for MAR. For instance, state water officials are exploring jointly with stakeholders a financing model with farmers and ranchers who rely on groundwater and how they can contribute a percentage of their profits to building aquifer recharge projects. Municipal governments might receive a payment per cubic meter of recharged water; this would help alleviate the economic impact on municipal authorities because their revenues cannot cover the operational cost of the MAR facilities.

Water managers and researchers also suggest that more incentives are needed for institutions to develop MAR projects. If a municipal or state water utility builds MAR facilities, fees for extracting groundwater could be reduced or exempted. The Federal Law on Duties and Taxes (Cámara de Diputados, 2021) sets the fees that municipal governments must pay for extracting groundwater. It also provides financial incentives for aquifer recharge: users "...do not have to pay the extraction fees if the water is recharged to its source. The water quality should comply with a certificate recognized by CONAGUA and all physical, chemical, and biological parameters listed in Article 225" (Cámara de Diputados, 2021, art. 224, para. V). Thus, a public or private agency that recharges water into the same aquifer where it was obtained can request this payment exception or reimbursement. Based on this legislation, the SLRC water agency has asked CONAGUA to reimburse it for payments already made, but the federal government has not agreed. The response is that the quality of the recharged water - the concentrations of three elements (iron, chloride, and manganese) are above the standard in the Federal Law on Duties and Taxes. In this case, these elements are not dangerous pollutants; they are merely associated with hard water (Fernández et al., 2020), which is very common in coastal regions. The interviewees suggest that the standards for the recharged water quality should be equal to the native water, except where the native water is contaminated. The interviewees believe that other tax incentives could be considered. More significant incentives would increase the participation of public and private investors interested in creating MAR facilities.

Subsidies are also required to establish MAR programs (Megdal & Dillon, 2015). In this sense, another proposal among water managers is for CONAGUA to subsidize MAR

projects, similar to the program for building and operating wastewater treatment plants, Programme for the Treatment of Wastewater, (CONAGUA, 2015; DOF, 2002). CONAGUA disburses federal funds to municipalities lacking wastewater treatment plants for their construction, operation, improvement, and monitoring. This financial support varies with the prevailing socio-economic conditions and can be up to 100 percent of the total amount needed (DOF, 2019). The 2019 Programme for the Treatment of Wastewater guidelines established that financial support would be greater if the water from the plants were reused (DOF, 2019). Interviewees suggest creating a similar plan for MAR projects. A federal program to support municipal or state water governments in building MAR facilities would draw the attention of other governments interested in this issue.

The most promising investors in aquifer recharge projects are medium- and large-scale farmers who grow high-value crops (Fernández & San Sebastián, 2021; Fernández et al., 2019; Rolf et al., 2019). Seventy percent of the groundwater in Mexico is used for agriculture (CONAGUA, 2018). However, the reuse of treated wastewater for irrigation is still insufficient - only 0.0004 percent of Mexican groundwater is saved using treated wastewater instead (de Anda-Sánchez, 2017). Researchers and municipal representatives indicated that farmers are essential in reducing groundwater extraction and increasing aquifer recharge to assist with the recovery of water levels in the aquifers. Farmers can reuse treated wastewater for irrigation, where appropriate. The pressure on groundwater will decrease with lowered water abstraction. The Sonoran interviewees emphasized that developing MAR projects using treated wastewater is possible. This option is viable if local farmers improve their irrigation systems and reduce their treated wastewater use, and the saved water is directed to MAR projects (Palma et al., 2018). More significant efforts to reuse treated wastewater in agriculture could help aquifers recover and boost MAR projects, as Gilabert-Alarcón et al. (2018) documented in a case in the State of Baja California. Rolf et al. (2019) recommend that the piloting of MAR is needed so that farmers can better understand the benefits and risks and develop the most suitable systems. Governments and farmers can achieve more optimum solutions by working together.

Partnerships are essential for the success of MAR projects. In Chihuahua and Sonora, NGOs facilitated the communication of technical information of MAR to municipal water managers and state officials. In SLRC, ProNatura has helped expand MAR facilities by building a wetland to improve the quality of the water to be infiltrated. In Chihuahua, the

collaboration between the WWF and the state has shed light on the importance of MAR projects as an option to increase water availability. These partnerships have helped create a long-term perspective for MAR, which helps maintain the continuity of MAR efforts even when new water managers take office. These outcomes are analogous to the findings Ahmed et al. (2021) described in Bangladesh; these authors analyzed the support NGOs provide to MAR system users and found that NGOs prioritize long-term collective actions more than day-to-day activities.

Conclusions

In Mexico, groundwater availability has decreased in the arid and semiarid regions, prompting efforts to increase aquifer recharge using stormwater or treated wastewater. Several MAR research projects, pilot projects, and facilities have been developed in Mexico over the past 30 years. A handful of municipal agencies have begun collaborating with researchers to improve the quantity and quality of recharged water. However, the lack of specific groundwater policies and recharge regulations for MAR projects hampers progress. In this study, we evaluate three MAR facilities in Chihuahua, Mexico City (Iztapalapa), and Sonora and discuss relative achievements, limitations, and applicable regulations. We analyse the relevant legal framework for MAR and, incorporating the perspective of officials managing these three facilities, we present and examine some proposals to improve it.

First, we found that the legal framework lacks clear and transparent permitting and ownership rules for water storage and the recovery of recharged water. Even though the three MAR facilities that we considered, have been operating for at least a decade, they still lack official authorization from CONAGUA as MAR projects and are considered pilot projects. This makes it difficult to plan future investments. The expansion of MAR projects has highlighted the need for a suitable legal framework. The LAN should be amended to incorporate ordinances for MAR. It should define the rights and allocation mechanisms for recharged water. Water allocation mechanisms could also consider the priority list already included in the LAN.

The successful implementation of MAR projects depends on proper financial support, the availability of accurate technical information, and stakeholder participation. A robust legal framework that addresses these aspects might increase MAR efforts in Mexico. Arizona in the

USA serves as an example where the development of legislation specifically for MAR, has ensured the successful launch and maintenance of MAR projects.

Partnerships are essential for the success of MAR projects. The recovery of over-abstracted aquifers, and MAR project development and management, should be a shared initiative between the federal, state, and municipal governments. CONAGUA has funding and administrative mechanisms to facilitate public investment in MAR projects. The municipal agencies that have developed and that manage the MAR projects in Chihuahua, Mexico City, and Sonora, are however operating with limited support from CONAGUA. They need financial and technical assistance from the federal government to ensure the adequate functioning of MAR facilities over the long term.

Stakeholders such as farmers are also key actors in aquifer recovery because they are entitled to high volumes of water. In the cities of Hermosillo and Chihuahua, a portion of the treated wastewater could be used for MAR, while the rest could be used to irrigate crops. One proposal is that farmers can reduce their groundwater extraction and instead irrigate with treated wastewater, if available to them. Authorities must however provide technical and financial support to make this possible, and specific public policies must be in place.

In two of the MAR examples, non-governmental organizations provided significant technical support and information. They functioned as a bridge between researchers and water officials to communicate scholarly findings and helped maintain and monitor MAR facilities. Additionally, non-governmental organizations have highlighted the importance of MAR for groundwater-dependent ecosystems.

In Mexico, political turnover every three years in municipal administrations is a major barrier to initiating long-term collaboration partnerships. State governments that have six-year political terms, can assist in managing MAR project finances to help complete infrastructure projects. The presence and support of non-governmental organizations can also help maintain MAR efforts beyond the time that authorities are in office.

If an unambiguous legal framework were created to manage MAR projects, MAR could be a strategy to recover groundwater levels in over-abstracted Mexican aquifers. Municipal and state water managers, NGOs, and independent researchers have extensive experience operating MAR facilities in the country, and their knowledge should be considered in creating public policy and MAR regulations. Broader participation can provide new sources of knowledge to inform and foster policy change. Furthermore, stakeholders are more likely to

adhere to regulations they have helped create and should therefore be consulted during their development.

Author contributions

MBCA: Conceptualization, Investigation, Methodology, Interviews, Writing - review & editing. CT, Co-writing the manuscript, review & editing.

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The authors have no interests to declare.

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