Inventory of managed aquifer recharge schemes in Latin America and the Caribbean

José Pablo Bonilla Valverde [1,2,*], Catalin Stefan [2], Adriana Palma Nava [3], Eduardo Bernardo da Silva [2] and Hugo Leonel Pivaral Vivar [2].

1 Instituto Costarricense de Acueductos y Alcantarillados, Costa Rica;
2 Department of Hydrosciences, Technische Universität Dresden, Germany;
3 Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico;
* Correspondence: jpbonilla@aya.go.cr; Tel.: +506-2242-5331 / Fax. +506-2242-5222

Bonilla Valverde, J.P., Stefan, C., Palma Nava, A., da Silva, E.B. and Pivaral Vivar, H.L. (2018). Inventory of managed aquifer recharge schemes in Latin America and the Caribbean. Sustain. Water Resour. Manag. 4(2) 163-178. https://doi.org/10.1007/s40899-018-0231-y This is the final accepted and corrected manuscript in author-provided format freely available at IAH-MAR web site https://recharge.iah.org with permission of Springer.

Abstract: Managed aquifer recharge (MAR) is being used worldwide as a tool to overcome distinct water management challenges. An analysis of MAR case studies from different countries in Latin America and the Caribbean (LAC) was carried out as part of a larger study focused on the compilation of a global inventory of MAR schemes which aims at providing guidance for the planning and implementation of new MAR projects. The MAR case studies were collected from freely available scientific publications. These were classified according to the specific MAR type developed, main objective and the source of the influent water. Most reported cases (>60%) were found in Brazil, followed by Mexico and Chile. The main MAR type reported in LAC is in-channel modification, which represents more than half of the reported MAR schemes and the main influent water used is river water and storm water (together accounting for >90%of cases). Approximately two thirds of the MAR cases in LAC were developed to maximize natural storage. Publication of freely available scientific reports on MAR in LAC is scarce, not due to lack of MAR projects, but rather suggests insufficient motivation in sharing experiences with the international scientific community. Nevertheless, MAR has been successfully implemented in at least ten LAC countries. For four of these, estimates of annual recharge volume are available; Mexico (156 Mm^3), Cuba (115 Mm^3), Peru (36 Mm^3) and Costa Rica (4 Mm^3), and a further 30 Mm^3 are crudely but conservatively calculated for the remaining LAC countries (mostly in Brazil) bringing the total to approximately 340 Mm^3. The application of MAR is expected to grow further as a sustainable and reliable tool to address challenges related to climate, population and economic changes..

Keywords: Managed aquifer recharge; Latin America and the Caribbean; Global inventory of MAR schemes; MAR per population index;

Abbreviations

EC: Electrical conductivity
EMBRAPA: Brazilian Agricultural Research Corporation
IGRAC: International Groundwater Resources Assessment Centre
IM: In-channel modifications
IMTA: Instituto Mexicano de Tecnología del Agua (Mexican Institute of Water Technology)
INTA: Instituto Nacional de Tecnología Agropecuaria (National Agricultural Technology Institute)
LAC: Latin America and the Caribbean
MAR: Managed aquifer recharge
MOP: Ministerio de Obras Públicas
UN: United Nations
UNSD: United Nations Statistics Division

1. Introduction

The Real Academia de la Lengua Española defines Latin America as the countries of America that were colonized by Latin speaking countries (Spain, Portugal or France) (ASALE, n.d.). According to the United Nations Statistics Division (UNSD) regional grouping Latin America and the Caribbean (LAC) is an intermediary region of the America continent (UN, **2017**). This grouping is based on six continents; where LAC is composed by the Caribbean, Central America and South America sub-regions. The United Nations division is used in this study.

In general, the LAC climate is classified as humid to very humid; however it has some arid and semi-arid regions (Guzmán-Arias and Calvo-Alvarado, **2013**; WWAP, **2017**). With 30% of the continental precipitation and one third of the global runoff (*ibid.*), the region as a whole has a large amount of water resources. Furthermore, the available water resources, such as reclaimed water from municipal treatment plants, offers an alternative source of water for reuse (WWAP, **2017**). According to Bixio *et al.* (**2005**), the majority of the municipal reclamation treatment plants in LAC reach a secondary treatment and the main use is direct irrigation of agricultural land. It is expected that the number of municipal reclamation treatment plants will increase with urban growth (WWAP, **2017**).

The LAC countries have a total area of >20 million square kilometres and an estimated population of >645 million inhabitants in 2017 (UN, **2017**), which represents 8.6% of the world population. Within LAC, the sub-region's population is concentrated in South America with almost two-thirds of LAC population (66%); the rest is composed of Central America with more than one-quarter (27%) and the Caribbean (7%) (UN, **2017**). Brazil is the largest country, representing almost 42% of the total area and with >32% of LAC population. Mexico is the second largest county regarding population (20%), and third regarding size.

The LAC population is concentrated in urban areas, representing 82% of the total population (Serebrisky, **2014**). Three cities in LAC are megacities (population >10 million inhabitants)—Mexico City, Sao Paulo and Buenos Aires; and two more are close to becoming megacities—Bogota and Lima (*ibid.*). In these five megacities already have a population >10 million inhabitants in the 1990s (Anton, 1993). In these five megacities, basic services such as water and sanitation are still unattended issues for lower economic classes (Serebrisky, **2014**).

A 14% increase in the LAC population is projected by 2030 and 24% by 2050 (UN, **2015**). Population growth triggers global change, which is defined as natural and anthropogenic influences on terrestrial climate and the hydrologic cycle (Green *et al.*, **2011**). Global change threatens the safe drinking water supply to the population as well as for agriculture, where water is a key component (Hanjra and Qureshi, **2010**). However, water demand is not restricted to drinking water supply in LAC. Almost half (46%) of the energy produced in the region comes from hydropower plants (Miralles-Wilhelm, **2014**). Additional major water users include industry and agriculture, with agriculture being almost entirely rainfed in the region (90% of the agriculture land) (*ibid.*). Thus, the trend is to depend more on groundwater for land irrigation as rain patterns are changing.

Salt water intrusion is another threat for the water resources in the region, as many of the biggest urban areas in LAC are located near the coast, *e.g.*, Buenos Aires, Cartagena, Havana, Kingston, Lima, Maracaibo, Montevideo, San Marta, Veracruz and most of the cities in Brazil and Guyana (Anton, **1993**). As these urban areas expand, the coastal aquifers where they are located become threatened by declining water levels and saline water intrusion. According to Anton (**1993**), saline water intrusion was reported along the coast of LAC in cities like Lima, Santa Marta, Coro, Rio Grande, Natal and Mar del Plata. These cities are not only threatened by overpumping of groundwater, but urbanization also reduces the recharge area of coastal aquifers.

Managed aquifer recharge (MAR) offers great potential to contribute to the prevention of saltwater intrusion and restoration of depleted groundwater, as well as other benefits (Gale, **2005**). MAR is defined as the intentional banking, recharge, storage and/or treatment of water in aquifers (Dillon, **2005**; Dillon et al., **2009**; Hannappel et al., **2014**); it has also been called artificial recharge, enhanced recharge, water banking and sustainable water storage (Dillon, **2005**). There are many human activities that increase the naturally occurring recharge to aquifers. Dillon *et al.* (**2009**) classified them as: unintentional, unmanaged and managed. In this classification system, MAR is done with the purpose of recovery of the water or for environmental benefit (*ibid.*).

According to Stefan and Ansems (**2017**), MAR is still regarded by some water resources managers as a rather costly and risky tool that is mostly applied in arid and semi-arid regions. This is due to their lack of easy access to information on successful MAR projects that are relevant to the characteristics of their locality. To address this, a global inventory of MAR schemes was created to raise awareness and improve the dissemination of results from MAR projects around the world (Stefan and Ansems, **2017**). A first compilation of MAR projects is found in the European MAR catalogue; this was elaborated by the DEMEAU project in order to demonstrated promising technologies that tackle emerging pollutants in water and waste water (Hannappel et al., **2014**; Sprenger et al., **2017**). They established a systematic and categorized database of the European MAR sites. A worldwide database of MAR projects was collected by the INOWAS Junior Research Group of TU Dresden. This database is known as the global inventory of MAR schemes (Stefan and Ansems, **2017**) and is accessible via the International Groundwater Resources Assessment Centre MAR Portal (IGRAC, **2015**).

A modification of the classification of the MAR techniques following Gale (**2005**), IGRAC (**2015a**), Sprenger et al (**2017**) and Stefan and Ansems (**2017**), is given in **Table 1**. This classification system is used for the collated MAR schemes from LAC. The main objectives of the MAR application as well as operational data were also recorded. The case studies for the global MAR inventory were collected from freely available scientific papers, reports, academic theses and published presentations that spread over 60 countries from all continents and with more than 1200 identified MAR projects (Stefan and Ansems **2017**).

Table 1. Classification of the MAR techniques modified from IGRAC (**2015a**)

	Main MAR technique	Specific MAR methods
Techniques referring primarily to getting water infiltrated	Spreading methods	infiltration ponds & basins
		flooding
		ditch, furrow, drains
		irrigation
	Induced bank filtration	river/lake bank filtration
		dune filtration
	Well, shaft and borehole recharge	Aquifer Storage and Recovery (ASR) / Aquifer Storage, Transfer and Recovery (ASTR)
		shallow well/ shaft/ pit infiltration
Techniques referring primarily to intercepting the water	In-channel modifications	recharge dams
		subsurface dams
		sand dams
		channel spreading
	Runoff harvesting	rooftop rainwater harvesting
		barriers, bunds and trenches

In the present paper, 144 case studies from nine countries of LAC region are analysed in detail. The main objective of this work is to synthesize the MAR experiences in LAC for a better comprehension of the existing developments and future outlook. Many of the MAR schemes in Latin America are published in local journals or internal reports, inhibiting the flow of information and likely constraining the spread of these techniques in the region. The aim of this work is not to discuss the implications of MAR in the regional water resources, but to bring to light and create awareness of available information of MAR in the region. The created data base is incorporated to the main data base which is published by IGRAC (2015).

2. Methods

The case studies were collected from freely available scientific papers, conference proceedings, internal reports and academic theses published in English, Spanish and Portuguese. Only fully implemented schemes were considered as case studies, small-scale investigations or test cases were not taken into consideration. Site selection for aquifer recharge and feasibility studies were also excluded, although there were several studies of this kind available for LAC (Bonilla et al., 2016; Cabrera Fajardo, 2014; MOP, 2014). Further selection criteria include the type of recharge, with only those schemes being considered that aim at purposely recharging the aquifer by means of various techniques (Dillon et al., 2009). Other types of anthropogenic recharge, either unintentional or unmanaged, were excluded from the LAC database. Some examples of unintentional recharge can be found in Brazil (Blackburn et al., 2002), Chile (Iriarte Díaz, 2003) and Mexico (Pastén-Zapata et al., 2014), while the El Mezquital/Tula Valley in Mexico represents a good example of unmanaged recharge (Kazner et al., 2012).

The information collected includes spatial and operational data. The spatial data refers to the country, the administrative unit, and the geographical coordinates of the MAR application. For some cases, a note is included in the data base reporting if the coordinates were explicitly mentioned in the reference, extracted from a map in the document, inferred from Google Maps or simply associated with the nearest geographical object (*e.g.* city, highway, etc.). The operational data includes the reported year of operation start and shut down, main and specific MAR technique, main and specific objectives, as well as the influent source of recharge and final use of the extracted water (Table 2). As one single MAR scheme may have several objectives, recharge sources and final uses, these are all recorded in the database however only the principal objective, influent source and final use are considered for the statistical analysis.

The main MAR technique follows the modified classification by IGRAC (IGRAC, 2015) (see **Table 1**). The main MAR objectives used in this work correspond to the categories proposed by Hannappel et al. (2014) for the European MAR catalogue: a) maximize natural storage, b) physical management of the aquifer, c) management of water distribution systems, d) water quality management, e) ecological benefits and f) other benefits. The maximization of natural storage refers to the enhancement of the aquifer storage capacity, while physical management of the aquifer refers to restoration of falling groundwater levels, reduction of land subsidence, prevention of saltwater intrusion, enhancing wellfield production, and hydraulic control of contaminant plumes (Hannappel et al., 2014).

The types of influent water considered in the present inventory include: a) brackish water, b) distilled water, c) groundwater, d) lake water, e) river water, f) storm water, g) tap water and h) treated wastewater. Four final uses are recognized in the inventory: a) agricultural, b) domestic, c) ecological and d) industrial.

Table 2. Collected information from the MAR projects

Geographical information	Operational data
Sub-region	Starting operation (year)
Country	Shut down since (year)
State / Prefecture / Province	Type of operation
County / District / Prefecture / Department	Main and specific MAR type
City	Main and specific objective
Latitude	Influent source
Longitude	Final use of extracted water

3. Results

In total, 144 MAR projects were collected from 71 publications and overlaid in **Figure 1** on the map of physical and economic water scarcity (Molden, 2007). **Table 3** presents the number of MAR projects reported per country and where they were published. The brackets contain the number of references when the correspondence is not one to one. For example, there are three case studies reported in one journal article For Argentina and the 44 case studies are reported in 18 journal articles for Brazil.

Table 3. MAR projects reported and the number of references

Country	**books**	**conference papers**	**journal articles**	**newspaper articles**	**presentations**	**reports**	**theses**	**Total MAR projects**
Argentina	1		3 (1)		2 (1)	2		**8 (5)**
Bolivia						3 (1)		**3 (1)**
Brazil	3 (2)	16 (9)	44 (18)			1	25 (10)	**89 (41)**
Chile			5 (2)		1	1	2	**9 (6)**
Colombia	3 (1)						2 (1)	**5 (2)**
Costa Rica			2 (1)					**2 (1)**
Cuba			4 (1)	2 (1)				**6 (2)**
Mexico		2 (1)	12 (6)		3 (1)	2		**19 (10)**
Peru		1	2					**3 (3)**
Total	**7 (4)**	**19 (11)**	**72 (31)**	**2 (1)**	**6 (3)**	**9 (7)**	**29 (13)**	**144 (71)**

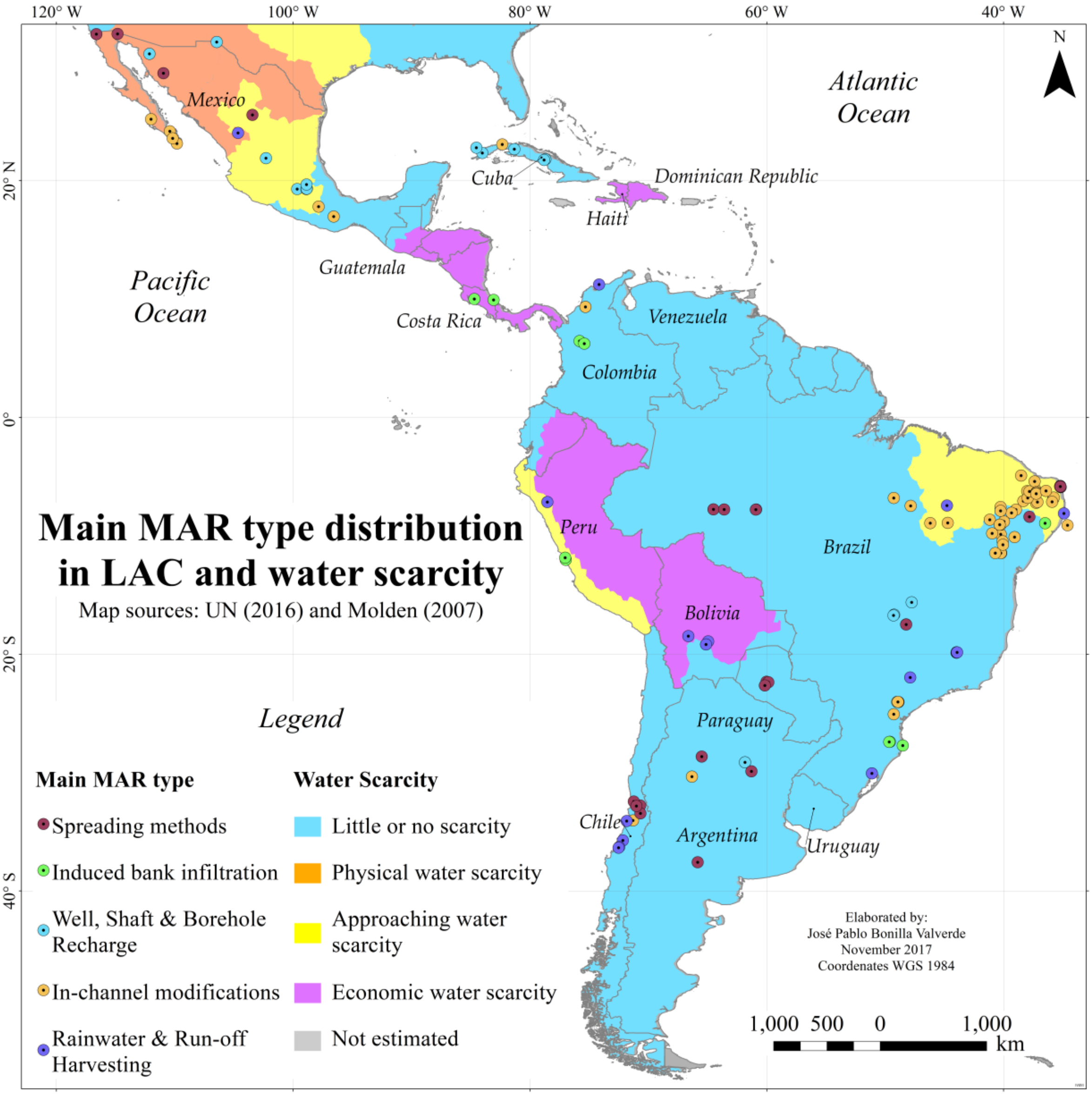

Figure 1. Spatial distribution of reported MAR type in LAC overlaying a map by Molden (2007) of physical and economic water scarcity

One report on Brazil describes >50,000 specific structures which are not represented in **Figure 1** because they are reported at state level, without coordinates. For more information on these structures see the description in section **"MAR schemes by country"** and the works of Barros (**2003**), Brito *et al.* (**1989**, **1997**), Silva (**2011**) and Silva *et al.* (Silva et al., 2007, 2009).

Regarding the total number of MAR projects in LAC, more than half of the surveyed case studies was reported in journal articles. Some of these journals are published in national languages (*e.g.* Spanish or Portuguese) and are only known locally, limiting thus the reach to an international audience. The same principle applies to the academic theses, which represent 20% of the sources that contained basic information for the case studies. The theses present a bigger challenge as most of them were not available online. In many cases only a reference to them was found and it was necessary to search for the full-text in the universities databases.

3.1. MAR schemes by country

The reported MAR schemes in Latin America are briefly presented by country, with a description of the most notable features encountered.

Argentina

Aquifer storage and recovery wells as well as infiltration ponds & basins are the main specific MAR techniques reported in Argentina and, in some cases, even a combination of both were used. Although most are distributed in the northern part of the country (**Figure 1**), all the areas share a common characteristic in the Provinces of La Rioja (Recalde, **2008**), Santa Fe (Basán Nickisch, **2011**) and La Pampa (Adema, **2015**), *i.e.*, the occurrence of a shallow unconfined aquifer with electrical conductivity (EC) values >1000 μS/cm. For this reason, the aquifer recharge and surface storage systems are implemented using rainwater to improve groundwater quality.

All case studies identified in Argentina were implemented and reported by the *Instituto Nacional de Tecnología Agropecuaria* (National Agricultural Technology Institute, INTA). INTA counts four MAR experimental sites in the Province of Santa Fe. Similar to the Paraguayan experience, rainwater is recharged into an aquifer with high EC to create a lens of fresh water which subsequently extracted by wells. The pumps are floating in these wells, extracting mainly the upper-most water which is composed mainly of the recharged rainwater and only little native groundwater.

Bolivia

In the case of Bolivia, the reported MAR technique involves infiltration trenches for runoff harvesting. These recharge schemes were installed in three rural communities in the Chuquisaca Department where the validation of methods for agricultural development was based on soil conservation and natural resources management. Infiltration trenches were constructed at the demonstration sites and operated for two years (Arteaga, 2003). Arteaga (2003) recorded that the infiltration trenches were accepted by the farmers in hill zones used for pasture rather than in agricultural plain lands and recommended this technique for forest plantations.

Brazil

Most MAR cases found in Brazil include in-channel modifications, specifically subsurface dams. According to Regueira *et al.* (2002), the first scheme was constructed in 1919 in a semi-arid region of the state of Paraíba. Almost all of the these cases were found in this region that occupies an area of about 900,000 km² (de Queiroz et al., 2006). They were implemented at different times over the last century as a policy of several governments, and have thrived particularly in the last two decades due to intensified public actions to eradicate hunger and poverty. The use of subsurface dams in the Brazilian semi-arid region is aimed at storing water for food production for poor families. Consequently, they could have enough to survive and also sell the surplus in local fairs and markets, increasing family incomes.

Programs such as "P1MC" (1 Million Cisterns) and "P1+2" (One Piece of Land and Two Types of Water) are examples of public policies that helped to make subsurface dams popular in Brazil. Furthermore, there are strong reasons to believe that the number of this type of in-channel modifications in Brazil is likely much larger than the amount reported in this paper, given that many references were found to other official programs concerning this type of MAR (at state and federal levels). Unfortunately, the access to the respective databases has not yet been possible.

The infiltration ponds and basins are the most frequent MAR types in Brazil. These types of spreading methods have been used in rural and urban areas but with completely different purposes. In rural areas they have been implemented to prevent soil erosion and to produce food, by planting in the area immediately around them (the Brazilians call these structures "barraginha"). In urban areas, they have been used as a drainage system component, especially in Natal, a city in the northeast of the country where soil characteristics are good for infiltration (Silva, **2011**). According to Landau *et al.* (**2013**), the Brazilian Agricultural Research Corporation (EMBRAPA) has supported the development of subsurface dams and the rural model of the infiltration basins. Between 1997 and

2013, >50,566 *barraginhas* were constructed; they were financially supported mainly by federal official programs, like the ones that boosted the use of subsurface dams in the same semi-arid region (*ibid.*).

An estimation of the recharged amount by a *barraginha* is presented by de Barros (**2003**) on an experimental area in Sete Lagoas, Minas Gerais. It is estimated that 80 m^3 of water was recharged to the groundwater after each precipitation event. The dimensions of these small infiltration ponds are 1.5–2.0 m deep and 16–20 m in diameter (de Barros, **2009**). The precipitation event that fills the *barraginhas* in this area occurs 10–15 times per year, resulting in a recharge up to 1200 m^3/year from a single *barraginha*.

Other types of MAR reported in Brazil are infiltration trenches which are implemented in urban areas to prevent floods. Belo Horizonte, the capital city of Minas Gerais state, seems to be leader in application of this type of runoff harvesting (Caputo et al., 2013). Almost all rooftop rainwater harvesting cases in Brazil correspond to pilot projects. The water which is collected and stored in cisterns, common in semi-arid areas, is used almost entirely for drinking purpose. Induced bank filtration is performed in the state of Santa Catarina. A leading research application of this kind of MAR is at Ituporanga, which provides water for pisciculture (Michelan, **2010**; Mondardo, **2009**; Soares, **2013**). Ditches and furrows have been used to give a final destination to the domestic effluent treated in a wastewater treatment plant named ETE Ponte Negra, in Natal-RN, a likely isolated case of soil aquifer treatment in Brazil (Ferreira, **2008**).

Only a few MAR projects reported information regarding the recharged amount of water by MAR techniques in Brazil. Induced bank filtration by a well installed on the bank of a lake was reported to produce up to 2.56 m^3/d in Ituporanga, a small city in the Santa Catarina state "to supply small animal production during drought periods" (Soares, **2009**). This well is currently not in use. Freitas and Nascimento (**2006**) have shown that a subsurface dam of 95 m wide and 1.5 m deep constructed in the rural area of Iguaba Grande, a small city in the state of Rio de Janeiro, allowed the use up to 32 m^3 of water per day from a well installed adjacent to the dam. This contrasts with the 5 m^3 that would be available without the subsurface dam.

Chile

The Chilean government by means of the *Ministerio de Obras Públicas* (Public Works Ministry, MOP) has investigated MAR opportunities since 2012. The first study identified focuses on the detailed analysis of two river basins—the Choapa River and Quilimarí River (MOP, **2012**), followed by a compilation of suitable studies and pilot projects (MOP, **2013**). All these efforts led to the formation of a guideline for MAR projects in Chile (MOP, **2014**), which also includes a good review on MAR cases in LAC and around the world. A detailed study of the technical possibilities for MAR in 18 river basins in the north and centre of Chile is presented by Cabrera (**2014**), where the legal and technical aspects are also discussed.

From the reported MAR schemes, the two main MAR techniques identified in Chile are infiltration ponds/basins and trenches. Two MAR schemes using infiltration ponds/basins are located close to the Aconcagua River (Tobar Espinoza, **2009**; Törey, **2014**) and several others are located in the La Ligua River and in the southern part of Santiago (Rengifo, n.d.). These are pilot projects implemented in the last five years mainly by MOP (Törey, **2014**).

The reported trenches are in the coastal side of the country, south-west of Santiago. The regions where these techniques are applied are: Región de O'Higgins, Región del Maule and Región del Bío-Bío. The trenches have been applied in combination with plantation of pines for two reasons, *i.e.*, to capture the humidity that comes from the ocean and to retain the rainwater longer and allow better infiltration. These trenches have been managed in cooperation with *Corporación Nacional Forestal* (National Forest Corporation) that looks for maximal efficiency of soil conservation and hydraulic advantages in the dry coastal and arid regions of Chile (Pizarro Tapia et al., **2008**).

Channel spreading was reported in the Peumo Valley, in the Cachapoal River. During the winter season the channel intercepts the runoff and it flows to the rechargeable areas in the valley. During summer, the infiltration from the channels keeps the groundwater level stable which contributes to good agricultural practices in the region (Arumí et al., **2009**).

When reported, the results from the Chilean MAR projects are expressed by a rise of the water table, as for the Peumo Valley (Arumí et al., **2009**), or biomass production (Pizarro Tapia et al., **2008**). Estimations on the achievable recharge are given by Törey (**2014**), but no paper or document mentions the actual quantity of recharge.

Colombia

Colombia has two reported case studies of induced bank filtration, although according to Jaramillo (**2015**) there is vast experience in this technique in Colombia that is not reported. This affirmation is also true for most of the LAC countries. Colombia has a methodological guideline for the environmental management of aquifers (Ministerio de Ambiente y Desarrollo Sostenible, **2014**), where MAR is taken into account. Two cases are presented—one in the Manzanares River in Santa Marta and the pilot project for the Morroa aquifer in Sucre (*ibid.*).

Two other cases are reported by Escobar *et al.* (**2011**), where two operational wells located in alluvial aquifers were identified in the Antioquia Department. Different experiments were conducted to determine the interaction between the river and the aquifer. The interaction was confirmed for both wells, by means of particle transport with the aid of field experimentation and computer simulations using MODFLOW.

Costa Rica

For Costa Rica, induced bank filtration was reported by Arias *et al.* (**2006**). The sites are in the alluvial aquifers of the Barranca and Banano Rivers, which are on the Pacific and Caribbean coasts, respectively. Both well fields are used for drinking water supply. River bank filtration accounts for more than one quarter of water supply of the Caribbean city of Limón—115 l/s out of 425 l/s (AyA, **2012**). This was also reported in Colombia by Jaramillo (2015), suggesting significant experience in induced bank filtration in Costa Rica, as well as all over the region; however, it has not been reported.

Cuba

The MAR schemes in Cuba have continued to be used to prevent saline water intrusion since the 1950's (González Báez, **1985**). A recharge dam and injection wells are reported for prevention of saline water intrusion in karstic aquifers with runoff water (González Báez **1974**, in MOP, **2014**). In 2016, two more injection wells were built in Cuba to also prevent saline water intrusion (Ulloa Trujillo, **2016**).

Mexico

A MAR inventory was developed to evaluate the current groundwater situation, MAR potential, challenges and targets (Palma **2014**). Mexico has some experience in MAR and water reuse but not in the context of comprehensive integrated groundwater management. There has been interest in MAR in Mexico since 1943, with a diversion constructed to move water off stream from the Magdalena River to flood fields and infiltrate it in the southern part of Mexico City.

The Mexican inventory represents the only systematic record of MAR projects in any LAC country to date. As part of the MAR inventory approach, technical sheets have been generated that summarize the main features of each MAR project (method, technique, water source, objective and recharged volume). Currently, the estimated total volume of active MAR projects is approximately 156 Mm^3 annually. MAR projects currently in development have a potential to recharge an additional 192 Mm^3 annually, using an approach to increase the storage and recovery at a reduced cost and in a sustainable manner. Additionally, the *Instituto Mexicano de Tecnología del Agua* (IMTA, Mexican Institute of Water Technology) compiled a book concerning MAR in Mexico, with national and international project descriptions and best practices (Escolero Fuentes *et al.*, **2017**).

The main purpose of MAR projects in Mexico is for groundwater storage and recovery, and to improve water supply resilience. Additional MAR objectives include the improvement of water quality, improving drainage and flood control (mainly with boreholes or "dry wells"), and to help control differential land surface subsidence due to chronic groundwater overexploitation in Mexico City.

Unlike many other countries, Mexico is among the few that has regulations for the development and implementation of MAR projects. Article 7 of the National Water Act (1992) identifies water-related matters considered in the public interest, including but not limited to protection, conservation and improvement of basins, aquifers, river beds, enclosed bodies of water, and other nationally owned water bodies, and restoring the hydrological balance between surface water and groundwater. In the National Water Law (LAN), there are two main Official Mexican Standards (*Normas Oficiales Mexicanas* (NOM)) that help to ensure appropriate MAR project approaches:

- NOM-014-CONAGUA-2007 - Requirements for artificial recharge of aquifers with treated wastewater (SEMARNAT, **2009a**), and
- NOM- 015-CONAGUA-2007 - Artificial infiltration of water into aquifers with rainwater harvesting (SEMARNAT, **2009b**).

Paraguay

Three cases from Paraguay are located in the Chaco region, in the cities of Filadelfia, Loma Plata and Neu-halbstadt (von Hoyer and Godoy, **2000**). They all have in common the MAR type (infiltration basins) as well as the main objective, *i.e.*, to improve the water quality of the unconfined aquifer which contains water with high salinity. The Filadelfia case is the best characterized, with the author reported the changes directly under and around one infiltration basin. Although this case is considered as single experience, 12 additional infiltration basins are represented in the map of von Hoyer and Godoy (**2000**). It is reported that these practices of aquifer recharge have been performed for many years in an empirical way by the indigenous people of the Chaco (Sosa, **1976**, in Godoy et al., **1994**).

In the Filadelfia case study the EC of the water in the aquifer without infiltration basins is 3000 μS/cm in the upper part [and up to 10,000 μS/cm for the first 4—5 m (Godoy et al., **1994**)] and it increases with depth to almost 30,000 μS/cm in the base of the aquifer. By means of a basin originally designed for the superficial storage of water (locally known as *"Tajamar"*), a fresh water lens is created in the aquifer with the recharged rainwater. Under and around the infiltration structure the EC was <1000 μS/cm for a depth of 7 m (*ibid.*). The recovery of this recharged water for productive use is not explicitly mentioned in the text. However, in the Argentinean cases, which are based on the Paraguayan experience, the recharge water is used for productive activities.

Peru

The MAR experience in Peru is concentrated in the alluvial quaternary deposits of the Rímac and Chillón Valleys that form the main aquifer used for the water supply of Lima (Quintana and Tovar, **2002**). By 2001, induced bank filtration and in-channel modifications were developed in the Rímac River, where 60 screens with a depth between 3.0 and 3.5 m and a width between 150 and 200 m were built along the river with a separation of 100 m between each. The water is recovered by 30 extraction wells for a total production of 1.6 m^3/s (*ibid*).

A similar approach was also used for the Chillón River—40 screens and 28 wells in 4 km with a depth between 2.5 m, and width between 70 and 250 m (Grados Chaw, **2014**). One runoff harvesting experience is also reported for Peru by Carhuapoma and Portugués (**1996**, in Pizarro Tapia *et al.* **2008**).

3.2. Comparison between countries

Qualitative information relating to sites could be compared among LAC countries, but there was insufficient data on recharge volumes to allow quantitative comparisons across the region. Hence the following analysis relates to the number of sites rather than the volume of recharge. The authors recognise they have aggregated information from projects with a wide range in scale, and this compilation reflects the accessible information rather than the totality of sites in LAC countries.

Therefore, these comparisons are presented as a preliminary perspective on MAR in LAC, and as an inducement to others to report more sites and hence allow a more accurate future picture.

Brazil (excluding hundreds of thousands of *barraghinas*) accounts for more almost two thirds (61%) of the total reported MAR case studies in LAC, followed by Mexico (12%), Chile (6%) and Argentina (5%). The other six countries represent <15% of the total cases. In-channel modifications are the most applied MAR technique reported in LAC (see **Figure 2**), covering almost half of the case studies (47%); the second most applied MAR technique is spreading methods (22%), followed by well, shaft and borehole recharge and runoff harvesting (both with 12%). Induced bank filtration is the least reported MAR technique in LAC.

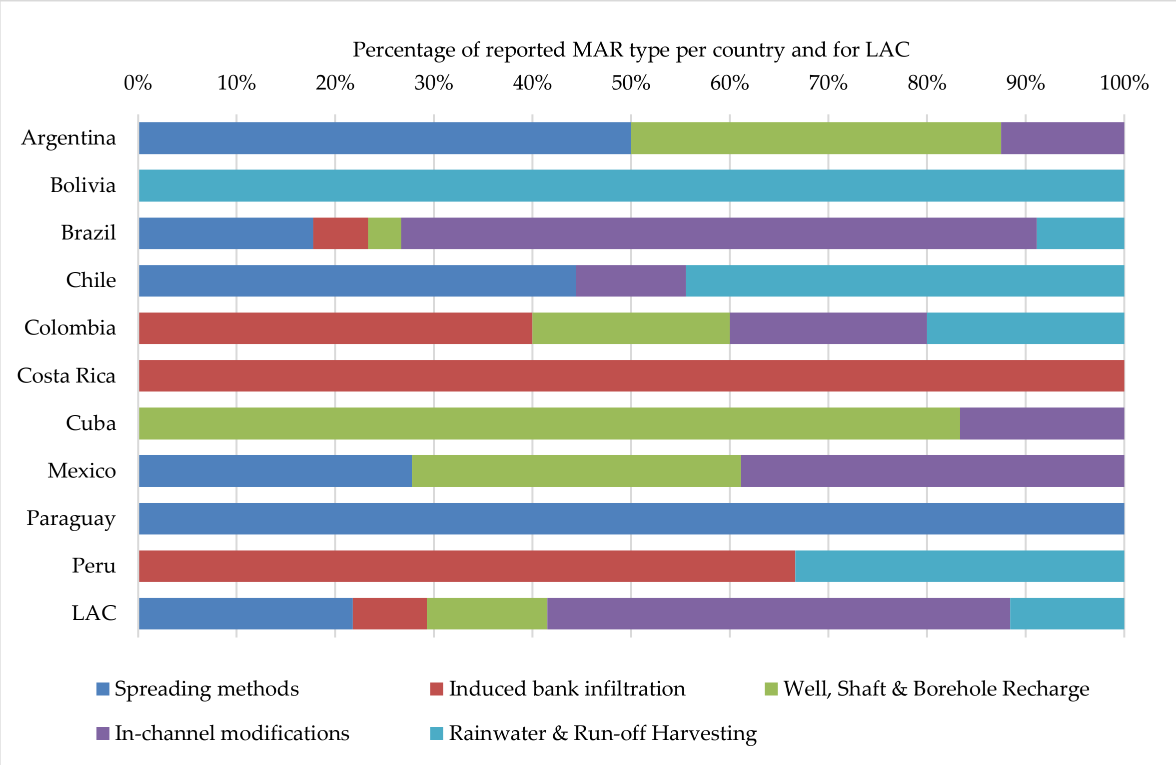

Figure 2. Reported MAR technique by country in LAC

Most of the reported MAR schemes are located in areas that either have physical water scarcity or are approaching this situation (Molden, **2007**) as in shown in **Figure 1**; *e.g.* in-channel modifications in the north of Brazil, induced bank filtration in Peru or the different MAR schemes in Mexico. Induced bank filtration and runoff harvesting can be also found in areas defined as with economic water scarcity. Argentina, Chile, Colombia and Paraguay are defined as having little or no water scarcity; however, in the Argentina and Paraguay cases, the quality of the available water resources in some areas where MAR techniques are being implemented is not good enough for agricultural uses.

Well, shaft and borehole recharge and spreading methods are the main MAR types reported for Argentina and Paraguay in areas that share a common characteristic, *e.i.*, the occurrence of a shallow unconfined aquifer with an EC of >1000 μS/cm (Basán Nickisch, **2011**; Godoy *et al.*, **1994**). For this reason, the aquifer recharge and surface storage system are implemented to improve the quality and quantity based on the distribution and management of rainwater. In Cuba, water runoff has been used to prevent saline water intrusion by a system of perforated wells in storm water channels since the 1950's (Gonzalez Baez, **1985**).

Induced bank filtration is the main reported MAR technology for Colombia, Costa Rica and Peru. This technique is used for urban water supply in Costa Rica and Peru. It is one of the water sources for the main coastal cities in the Pacific and Caribbean of Costa Rica (Arias et al. **2006**); and it is used for part of the capital city of Lima in Peru (Quintana and Tovar, **2002**). There is only case study in Bolivia, with runoff harvesting being reported mainly for agricultural proposes (Arteaga, **2003**). A special case is the Chilean experience, where there is no direct use of the water after recharge, but a biomass increase is reported in the plantations that used MAR techniques (Pizarro Tapia et al., **2008**).

Although any of the MAR project may have multiple benefits, only the main objective for each MAR scheme in LAC was recorded in the database. The main objective of the reported MAR schemes for LAC is to maximize the natural storage of the aquifers, accounting for more than half of the reported objectives (56%), followed by physical management of the aquifer (26%) and improvement of water quality (10%). The other reported objectives account for <8%. **Figure 3** shows the distribution of the MAR schemes objectives by country and for LAC. MAR schemes for the maximization of the natural storage are reported in all countries except Cuba, Paraguay and Peru. Ecological benefits are the least reported objective, identified only in Chile, Mexico and Peru.

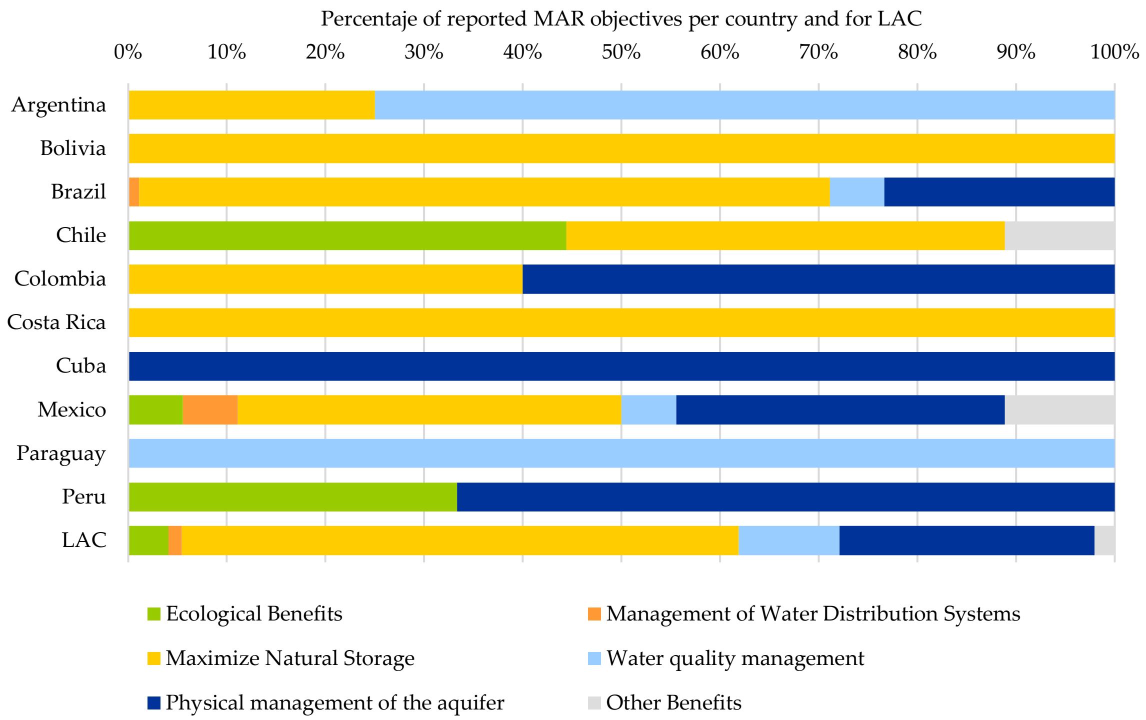

Figure 3. Reported main MAR scheme objective by country and for LAC

Bolivia, Costa Rica and Cuba have only one stated objective for all their reported MAR schemes. Bolivia and Costa Rica also have only one MAR type reported, *i.e.*, runoff harvesting and induced bank filtration respectively (see **Figure 2**). The final use of the MAR schemes in Bolivia is for agriculture and in Costa Rica is for water supply systems. In Cuba, both the reported MAR schemes are used for the same objective, *i.e.*, to stop or prevent saltwater intrusion.

Storm and river water are the main source of water for the MAR schemes in LAC, representing 48% and 45% respectively. Waste water accounts for one-quarter of the reported MAR schemes in Mexico. Brazil is the other country where waste water is also being reused via MAR. The distribution of the influent source of recharged water among LAC countries is given in **Figure 4**. The use of wastewater as a source of recharge is being used in these two countries that either have physical water scarcity or are approaching water scarcity (**Figure 1**).

The final use of the recharged water in LAC is shown in **Figure 5**. MAR is mostly applied in LAC to recover water for agricultural purposes (>50% of the case studies) followed by domestic and ecological uses. Industrial use of the recharged water is only reported in Colombia (Escobar Correa and others, **2011**; Jaramillo Uribe, **2015**).

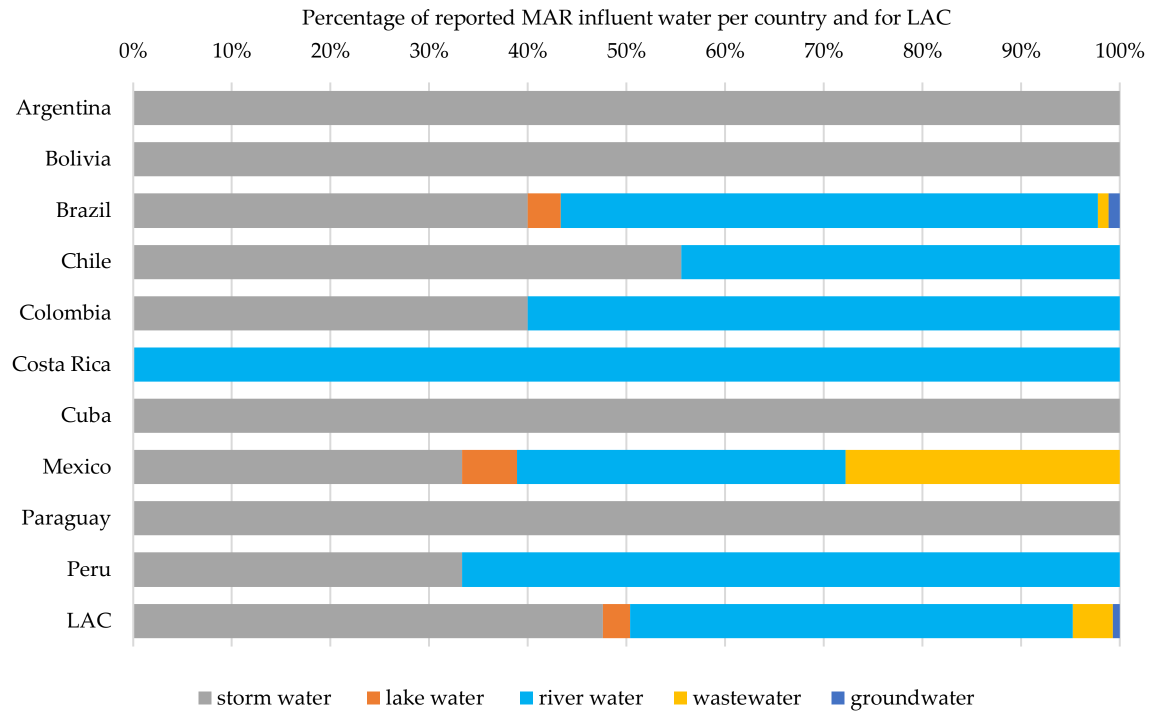

Figure 4. Reported main MAR scheme influent water by country in LAC

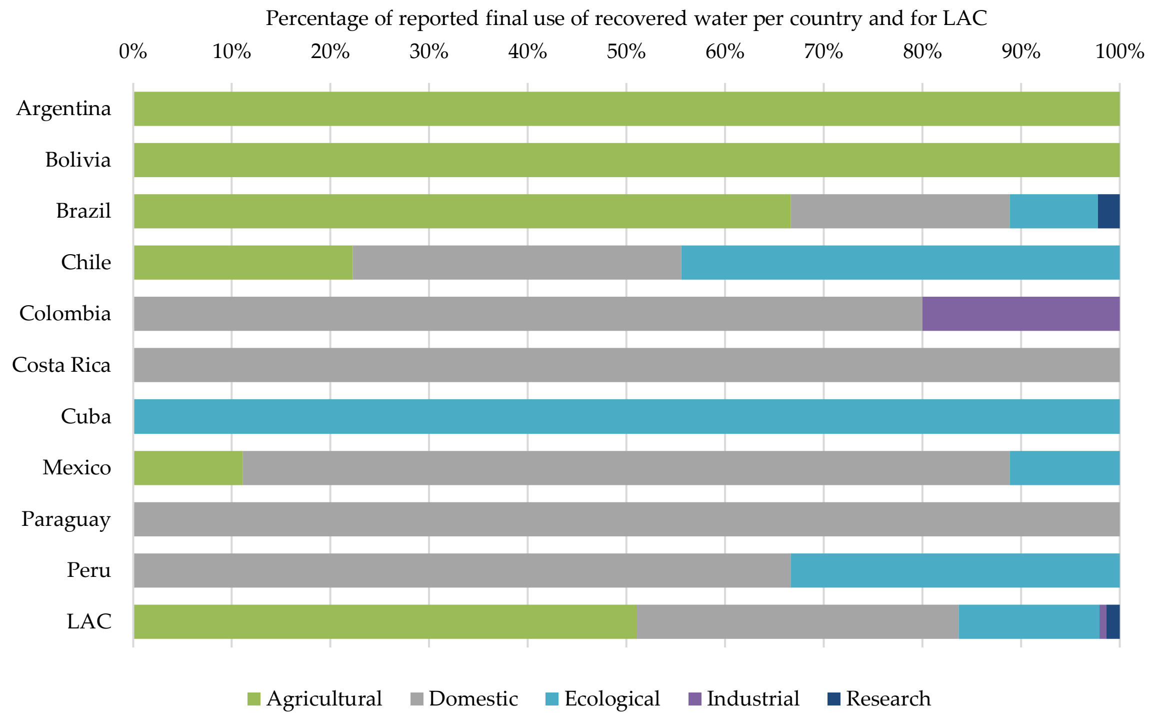

Figure 5. Reported final use of the recovered water by country in LAC

These statistics are strongly influenced by Brazil, where in-channel modifications account for 64% of the MAR cases. For the other nine LAC countries (without Brazil) the leading MAR techniques are spreading methods and well, shaft and borehole recharge with more than one quarter of the case studies (28% and 26%, respectively), followed by in-channel modifications representing 19% of the total reported MAR schemes. The main objective without Brazil is still to maximize the natural storage, but it represents only one-third (35%) of the reported cases, closely followed by the physical management of the aquifer (30%). The source for recharge percentages also changes with the exclusion of Brazil, but storm water (60%) and river water (30%) are still the main reported source of recharge. Without Brazil, the dominant final use of the recovered water is domestic.

A "*MAR per population index"* is proposed to facilitate the comparison between countries. This is calculated by dividing the reported MAR cases by the country population, *i.e.*, cases per million inhabitants. The total volume of recharged and recovered water would be an optimal index but the available information in this matter is scarce in the MAR projects reported in LAC and could only be estimated for Mexico (2.7 m^3 per capita). The "MAR per population index" (**Figure 6**) is a first effort to produce a common base to compare the application of MAR between countries. Cuba and Chile have the highest index in LAC, both >0.5. These are followed by Brazil, Paraguay and Costa Rica, all with an index >0.4. Brazil still appears as one of the main participants in the region in respect of application of MAR schemes, but other countries are now appearing when the population is taken into account. Bolivia, Costa Rica and Paraguay are among these countries, but they only have one reported MAR technique–runoff harvesting, induced bank filtration and spreading methods respectively. Note that **Figure 6** refers to the reporting of MAR cases, not to the relative magnitude nor importance of MAR in LAC countries.

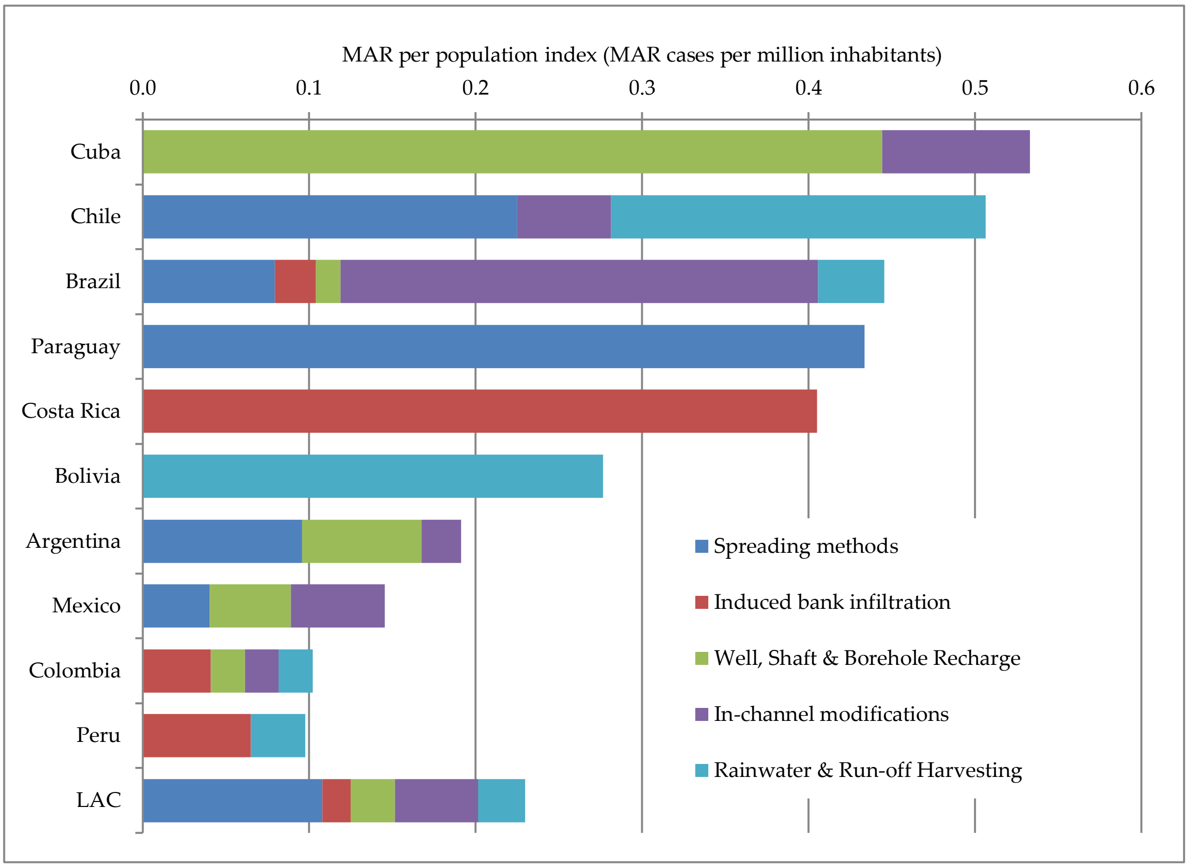

Figure 6. Reported MAR cases per population by country and by technique.

4. Discussion

For a better readability, the discussion is split into specific topics–a comparison with other regions of the world (the LAC MAR database in the global MAR inventory context), the freely available information on LAC MAR projects, MAR guidelines in various countries, and the opportunities for MAR in LAC.

4.1. LAC MAR database in relation to other regions

In this survey, almost 150 MAR case studies were identified in this survey in LAC, representing >12% of the current total global inventory of MAR schemes. This percentage is higher than the LAC population percentage of the world (9%). LAC is the fourth world region regarding the number of identified MAR projects according to the global inventory of MAR schemes (Stefan and Ansems, **2017**). LAC has little more than half of the MAR case studies identified for North America (USA and Canada), Asia or Europe.

The two main objectives among the MAR projects in LAC are to maximize natural storage of the aquifers and the physical management of the aquifers. These two objectives aim to augment the availability of water resources; the first by enhancing the aquifer storage capacity and the second by recovery of water levels, *i.e.*, retrieval of available water resources. These two objectives stand for >80% of the total main objective in LAC, in contrast with water quality management in Europe (Hannappel et al., **2014**).

Another difference between LAC and Europe regarding MAR is in the main MAR technique applied. While induced bank filtration is the main applied MAR technique in Europe, for LAC it is in-channel modifications. Induced bank filtration is mainly implemented for domestic use with the objective of water quality management in Europe. Even though these statistics are strongly influenced by Brazil, induced bank filtration is still the less reported MAR technique in LAC.

Agriculture is the main user of the recharged water in LAC, even though most of the regions agricultural lands are rainfed. Again, Brazil's contribution to the statistics is high. Domestic use is the main user of the recharged water in the other LAC countries. Industrial and research uses of the recharged water in LAC is seldom reported. Storm water is the main source of recharge with and without considering Brazil. This could relate to the humid climatic conditions of LAC, where water is not evenly distributed in time.

4.2. Availability of information and the scale of recharge projects

The scale of MAR schemes plays an important role in evaluating their impact on water resources. The database of reported MAR cases constitutes a first effort to identify local experience and lessons learned in the region, and to the assessment of MAR replication potential in LAC. As it has been presented in section "**MAR schemes by country**", the range of MAR activities in LAC goes from domestic rainwater harvesting in Bolivia, Brazil and Peru, to large scale recharge with recycle water in Mexico. The need to improve the way of reporting the results from the MAR schemes, not only for LAC, but for all the MAR cases in the Global MAR inventory, cannot be overemphasized.

Another challenge lies in the way the results of the MAR projects are reported. These varied from increase in the water table (Arumí *et al.*, **2009**; Landay *et al.*, **2013**; Quintana and Tovar, **2002**), biomass production (Pizarro Tapia et al., **2008**) to yearly extracted/injected volume.

The MAR projects with information regarding the yearly extracted/injected volume are given in

Table 4. To the best of our knowledge, there are only a couple of projects with information regarding the recharge quantity in the reported cases from Brazil; even though this country represents more than two thirds of the LAC database. Mexico is the country with detailed information on the recharged quantity regarding the MAR projects, mostly based in the review by Palma (2014).

Table 4. MAR projects with detailed information

Project name	Country	MAR type	Recharge volume (Mm^3/year)	References
Banano river	Costa Rica	IBF	3.6	AyA, **2012**
Dam and wells	Cuba	IM / SWBR	115	MOP, **2014**
San Luis Río Colorado	Mexico	SM	12	Palma, **2014**
Región Lagunera	Mexico	SM	50	Palma, **2014**
Valle de México	Mexico	SWBR	94	Palma, **2014**
Hermosillo	Mexico	SM	70	Palma, **2014**
Chillón river	Peru	IBF	36	Grados Chaw, **2014**
Total			311	

IBF induced bank filtration, *IM* in-channel modifications, *SM* spreading methods, *WSBR* well, shaft and borehole recharge

Table 4 shows that estimates of annual recharge volume are available in only four countries; Mexico (156 Mm^3), Cuba (115 Mm^3), Peru (36 Mm^3) and Costa Rica (4 Mm^3). Volumes are unknown in other LAC countries. A crudely calculated figure of 30 Mm^3 for Brazil's *barraginhas* would bring a conservative total for LAC countries to approximately 340 Mm^3.

4.3. MAR guidelines and regulation in LAC

Only a few countries in LAC have adopted integrated water resources management in their legislation (Guzmán-Arias and Calvo-Alvarado, **2013**), let alone specific legislation regarding MAR. Mexico has specific official standards related to MAR with treated wastewater (SEMARNAT, **2009a**) and rainfall harvesting (SEMARNAT, **2009b**). Both Colombia and Chile have guidelines regarding the implementation of MAR projects. To the best of our knowledge, Brazil has no guideline, legislation, nor standards regarding MAR; however, the government is directly involved in the construction of MAR facilities as a governmental policy with the P1MC and P1+2 programs (see **"Brazil**" subsection).

In general, legislation tends to be restrictive for reuse of reclaimed water, requiring treatment to make water quality suitable for the aquifer recharge and its existing beneficial uses and dependent ecosystems in the proximity. The legal framework should be flexible and water body-specific, as high-quality water may be required for non-potable uses *e.g.* taking into account soil-aquifer treatment techniques, aquifers remote from groundwater-dependent ecosystems and drinking water sources.

4.4. MAR outlook for LAC

The existence of guidelines and the incorporation of MAR in the legal framework encourage the application of these techniques in the countries where it is available. The governmental participation in Brazil is particularly promising; however, there is still a lack of dissemination of the results to an international audience, making it difficult to replicate or improve on these efforts in other LAC countries. Furthermore, there is no reliable estimate of the effectiveness and impact of MAR projects in most LAC countries.

It is expected that with global climate and population change, more water specialists will consider MAR as a viable solution for the water-related problems in the region. The Paraguayan MAR projects are good examples of the adaptation of local methods for water management while incorporating technical improvements. The same applies to the Argentinian MAR projects where the implementation of the floating pump allows for storing rain water in an aquifer that would otherwise be difficult to use due to groundwater quality.

Reclaimed water has been largely neglected as a source for MAR in LAC, with the exception of Mexico and Brazil. Reuse of reclaimed water offers an additional source for MAR, especially with the expected increase of the implementation of treatment plants in LAC. Direct use in irrigation is indeed reported (Bixio et al., 2005; WWAP, 2017), but users of this resource may be unaware that the water quality poses serious health risks. Reclaimed water recovered from a planned MAR scheme offers an additional barrier to prevent health hazards (Dillon and Jimenez **2008**).

Another promising application of MAR in LAC is the prevention of saline water intrusion, especially in large cities around the coast where it has already been reported. MAR has been applied for >50 years for this purpose in Cuba. Cuba's experience in karstic aquifers is not only valuable for LAC but for the rest of the world. For the coastal cities, direct use of the reclaimed water from municipal treatment plants involves cost of transportation to the irrigation areas. If used to recover or prevent salt water intrusion, the reclaimed water could present an excellent opportunity for reuse.

5. Conclusions

MAR technologies are reported as being applied in ten of the LAC countries. The percentage of reported MAR schemes in LAC regarding the Global MAR inventory (12%) is relatively similar to the percentage of the LAC global population (9%). Cuba and Chile are the countries with the highest MAR-per-population index in the region (>0.5 MAR cases reported per million inhabitants), followed by Brazil, Paraguay and Costa Rica.

The best estimate of total annual volume of MAR from reported sites is 340 Mm^3, where 311 Mm^3 have been reported and 30 Mm^3 are roughly estimated, considering the type and likely scale of project.

The concentration on only two types of MAR techniques (spreading methods and in-channel modifications) among the reported cases and the record of few attempts with other MAR types (in pilot projects) suggests that the other possibilities may have a future in the region.

This synthesis of the MAR schemes in LAC improves the dissemination of the local experiences in the region to an international audience. This will expand the comprehension of the opportunities and limitations of distinct MAR techniques in LAC and the world. The application of MAR is expected to increase in the coming years to overcome global change challenges in the region–three countries in LAC already have guidelines or regulation for MAR projects (Colombia, Chile and Mexico).

Acknowledgments: This work was partly funded by the Programa de Innovación y Capital Humano para la Competitividad (PINN) of Costa Rica through a fellowship grant provided to José Pablo Bonilla Valverde, by the German Academic Exchange Service (DAAD) through a fellowship grant provided to Eduardo Bernardo da Silva and Hugo Pivaral Vivar and by the German Federal Ministry of Education and Research through a research grant provided to the Junior Research Group INOWAS, project no. 01LN1311A. The authors will like to thank the reviewers and the editor for the suggestions made to improve the manuscript.

Author Contributions: Catalin Stefan conceived and designed the methodology and provided final corrections. José Pablo Bonilla Valverde collected and analysed the results and wrote the first draft of the paper. Eduardo Bernardo da Silva collected and analysed the data from Brazil and Hugo Leonel Pivaral Vivar collected and analysed the data from the rest of the Latin American countries. Adriana Palma collected and analysed the data from Mexico and provided feedback on the written manuscript.

Conflicts of Interest: The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

Adema, E.O., 2015. Manejo integral de aguas para uso ganadero en el semiárido-árido de La Pampa. Bol. Divulg. Téc. 42.

Anton, D.J., 1993. Thirsty Cities: Urban Environments and Water Supply in Latin America. International Development Research Centre (IDRC), Ottawa.

Arias Salguero, M., Losilla Penón, M., Arredondo Li, S., 2006. Estado del conocimiento del agua subterránea en Costa Rica. Bol. Geológico Min. 117, 63–73.

Arteaga, E., 2003. Prácticas de Conservación de Suelos y Aguas Validadas por el Proyecto Jalda, Estudios e Investigación.

Arumí, J.L., Rivera, D., Holzapfel, E., Boochs, P., Billib, M., Fernald, A., 2009. Effect of the irrigation canal network on surface and groundwater interractions in the lower valley oh the Cachapoal River, Chile. Chil. J. Agric. Res. 69, 12–20.

ASALE, R.-, n.d. Diccionario de la lengua española - Edición del Tricentenario [WWW Document]. Dicc. Leng. Esp. URL http://dle.rae.es/?id=Mz2oteK (accessed 2.29.16).

AyA, 2012. Informe final Ciudad de Limón. Instituto Costarricense de Acueductos y Alcantarillados, San José, Costa Rica.

Basán Nickisch, M.H., 2011. Una alternativa de manejo eficiente de los recursos hídricos para ganadería en el Norte de Santa Fe. Voces Ecos XIII.

Bixio, D., Heyder, B.D., Cikurel, H., Muston, M., Miska, V., Joksimovic, D., Schäfer, A.I., Ravazzini, A., Aharoni, A., Savic, D., Thoeye, C., 2005. Municipal wastewater reclamation: where do we stand? An overview of treatment technology and management practice. Water Sci. Technol. Water Supply 5, 77–85.

Bonilla, J., Blank, C., Roidt, M., Schneider, L., Stefan, C., 2016. Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods. Water 8, 391. https://doi.org/10.3390/w8090391

Brito, L.T. de L., Silva, A. de S., Maciel, J.L., Monteiro, M.A.R., 1989. Barragem subterrânea I: construção e manejo. Bol. Pesqui.

Brito, L.T. de L., Silva, D.A. da, Anjos, M.M. do R., Rego, M.M. do, 1997. Barragem subterrânea: um estudo de caso, in: Congresso Brasileiro de Engenharia Agricola 26. Presented at the Congresso Brasileiro de Engenharia Agricola, SBEA/UFPB, Campina Grande, Brazil.

Cabrera Fajardo, G., 2014. Análisis desde Arica hasta el Maule: ¿Dónde hay Condiciones para la Recarga Artificial de Acuíferos en Chile? Rev. Aidis Chile 47, 32–39.

Caputo, Ú.K., Moura, P.M., Oliveira, N., Aguiar, I., 2013. Trincheiras de infiltração instaladas em Belo Horizonte–Aspectos operacionais, in: Anais do XX Simpósio Brasileiro de Recursos Hídricos. Presented at the Simpósio Brasileiro de Recursos Hídricos, Bento Gonçalves, Brasil.

de Barros, L.C., 2009. Barraginhas: água de chuva para todos, 1st ed, ABC da agricultura familiar. Embrapa Informação Tecnológica, Brasília, DF.

de Barros, L.C., 2003. Micro-dams for rain water catchment and reclamation of degraded areas-a, b, c and d, mobilization phases, in: ABMAC. Presented at the Proceedings of the Eleventh International Conference on rain water catchment systems, Toxcoco, Mexico.

de Queiroz, L.P., Rapini, A., Giulietti, A.M., em Biodiversidade, P. de P., 2006. Towards greater knowledge of the Brazilian Semi-arid Biodiversity. Ministério da Ciência e Tecnologia.

Dillon, P., 2005. Future management of aquifer recharge. Hydrogeol. J. 13, 313–316. https://doi.org/10.1007/s10040-004-0413-6

Dillon, P., Pavelic, P., Page, D., Beringen, H., Ward, J., 2009. Managed Aquifer Recharge: An Introduction, Waterlines Report Series. National Water Commission.

Escobar Correa, R., others, 2011. Simulación numérica de riverbank filtration o filtración ribereña para su aplicación en tres municipios de Antioquia: Santa fe de Antioquia, Guarne y Nechí (Master thesis). Universidad Nacional de Colombia, Sede Medellín, Medellín.

Escolero Fuentes, O., Gutiérrez Ojeda, C., Mendoza Cázares, E.Y. (Eds.), 2017. Manejo de la recarga de acuiferos: un enfoque hacia Latinoamérica. Instituto Mexicano de Tecnología del Agua, Jiutepec, Morelos, México.

Ferreira, L.C. de A., 2008. Variação da qualidade da água do escoamento superficial de duas bacias de drenagem de Natal/RN - Brasil (Master thesis). UFRN - Universidade Federal do Rio Grande do Norte, Natal, Brazil.

Freitas, I.M. de, Nascimento, E.A. do, 2006. Simulação hidrogeológica de barragem subterrânea implantada na microbacia do Córrego Fundo, situada na região dos Lagos/RJ. Águas Subterrâneas 0.

Gale, I. (Ed.), 2005. Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas. UNESCO IHP, Paris, France.

Godoy V, E., Garcia S, D., Farina L, S., 1994. Recarga Artificial de Acuífero Freático en Filadelfia - Chaco Central Paraguayo. Presented at the VIII Congresso Brasileiro de Águas Subterrâneas, Sao Paolo, pp. 385–394.

Gonzalez Baez, A., 1985. ALIMENTACION ARTIFICIAL DE ACUIFEROS: c,HASTA DONDE SE JUSTIFICA EN LAS FORMACIONES CALCAREAS ALTAMEN·TE CARSIFICADAS? Volunt. Hidráulica 22, 14–26.

Grados Chaw, P.L., 2014. Recarga Artificial inducida en el Acuifero Local el Punchauca aprovechando los excedentes Hidricos del Rio Chillon. Presented at the XXXIV Congreso Interamericano de Ingeniría Sanitaria y Ambiental 2014, Monterrey, México.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., Treidel, H., Aureli, A., 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405, 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Guzmán-Arias, I., Calvo-Alvarado, J.C., 2013. Planificación del recurso hídrico en América Latina y el Caribe. Rev. Tecnol. En Marcha 26, 3–18. https://doi.org/10.18845/tm.v26i1.1117

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy 35, 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

Hannappel, S., Scheibler, F., Huber, A., Sprenger, C., 2014. Characterization of European Managed Aquifer Recharge (MAR) sites - Analysis (Project report No. M.11.1.).

IGRAC, 2015. MAR Techniques [WWW Document]. URL http://www.un-igrac.org/mar-techniques (accessed 11.9.15).

IGRAC, (International Groundwater Resource Assessment Centre), 2015. Global Inventory of managed aquifer recharge (MAR) schemes [WWW Document]. URL https://ggis.un-igrac.org/ggis-viewer/viewer/globalmar/public/default (accessed 11.9.15).

Iriarte-Diaz, S., 2003. Impact of urban recharge on long-term management of Santiago Norte aquifer, Santiago–Chile (Master thesis). University of Waterloo, Ontario.

Jaramillo Uribe, M., 2015. Evaluation of the potential of riverbank filtration in Colombia (Doctoral thesis). Universidad Nacional de Colombia-Sede Medellín.

Kazner, C., Wintgens, T., Dillon, P. (Eds.), 2012. Water Reclamation Technologies for Safe Managed Aquifer Recharge. IWA Publishing.

LANDAU, E.C., BARROS, L.C. de, RIBEIRO, P.E. de A., BARROS, I. de R., 2013. Abrangência geográfica do Projeto Barraginhas no Brasil.

Michelan, D.C. de G.S., 2010. Filtração em margem de rio precedendo a filtração lenta, para remoção de carbofurano, em tratamento de água para consumo humano (Doctor thesis). UFSC - Universidade Federal de Santa Catarina, Florianópolis, Brasil.

Ministerio de Ambiente y Desarrollo Sostenible, 2014. Guía Metodológica para la Formulación de Planes de Manejo Ambiental de Acuíferos. Bogota, Colombia.

Miralles-Wilhelm, F., 2014. Development and application of analytical tools in support of water-energy-food nexus planning in Latin America and the Caribbean. Water Energy, Water Monographies II, 76–85.

Molden, D., 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute (IWMI) and FAO, London: Earthscan, Colombo: International Water Management Institute.

Mondardo, R.I., 2009. Avaliação da filtração em margem como pré-tratamento à filtração direta descendente na remoção de células de cianobactérias e saxitoxinas (Doctor thesis). UFSC-Universidade Federal de Santa Catarina, Florianópolis, Brasil.

MOP, M. de O.P., 2014. Diagnóstico de metodología para la presentación y análisis de proyectos de recarga artificial de acuíferos.

MOP, M. de O.P., 2013. Análisis y Síntesis Preliminar de Iniciativas Sobre Recarga Artificial en Chile (Technical Report No. SDT No 344). División de Estudios y Planificación, Dirección General de Aguas, MOP, Santiago de Chile.

MOP, M. de O.P., 2012. Investigacíon recarga artificial de acuíferos cuencas del Río Choapa y Quilimarím región de Coquimbo (Executive Summary No. S.I.T. No292). AC INGENIEROS CONSULTORES LTDA., Santiago de Chile, Chile.

Palma Nava, A., 2014. Inventario de la recarga artificial en México. Presented at the XXIII Congreso Nacional de Hidráulica, Puerto Vallarta, Jalisco, México, October 15-17, 2014, Asociación Mexicana de Hidráulica (AMH), Jalisco, Mexico.

Pastén-Zapata, E., Ledesma-Ruiz, R., Harter, T., Ramírez, A.I., Mahlknecht, J., 2014. Assessment of sources and fate of nitrate in shallow groundwater of an agricultural area by using a multi-tracer approach. Sci. Total Environ. 470–471, 855–864. https://doi.org/10.1016/j.scitotenv.2013.10.043

Pizarro Tapia, R., Flores Villanelo, J.P., Sangüesa Pool, C., Martínez Araya, E., León Gutiérrez, L., 2008. Diseño hidrológico de zanjas de infiltración en el secano costero e interior de las regiones semiáridas de Chile. Bosque 29, 136–145.

Quintana, J., Tovar, J., 2002. Evaluación del acuífero de Lima (Perú) y medidas correctoras para contrarrestar la sobreexplotación. Bol. Geológico Min. 113, 303–312.

Recalde, D., 2008. CAPTACIÓN, ALMACENAMIENTO, DISTRIBUCIÓN DE AGUAS PLUVIAL Y RECARGA ARTIFICIAL DE ACUÍFEROS "NUESTRA SEÑORA DE FÁTIMA," Manejo

Sustentable de Los Recursos Naturales en La Región de Catamarca - La Rioja CATRI - 11. Catamarca, Argentina.
Regueira da Costa, M., Cirilo, A., others, 2002. [7] Avaliação do potencial de aproveitamento de reservatórios constituídos por barragens subterrâneas no semi-árido brasileiro. UFPE - Universidade Federal de Pernambuco.
Rengifo, P., n.d. Recarga artiticial de acuíferos en Chile: "Proyectos en ejecucíon en acuíferos de Aconcagua (DOH) y Santiago (SCM).
SEMARNAT, S. de medio ambiente y recursos naturales, 2009a. Norma Oficial Mexicana NOM-014-CONAGUA-2003, Requisitos para la recarga artificial de acuíferos con agua residual tratada.
SEMARNAT, S. de medio ambiente y recursos naturales, 2009b. Norma Oficial Mexicana NOM-015-CONAGUA-2007, Infiltración artificial de agua a los acuíferos.-Características y especificaciones de las obras y del agua.
Serebrisky, T., 2014. Mega-Cities & Infrastructure in Latin America: What its people think.
Silva, M.S.L. da, Mendonça, C.E.S., Anjos, J.B. dos, Honório, A.P.M., Silva, A. de S., Brito, L.T. de L., 2007. Barragem subterrânea : água para produção de alimentos, in: Potencialidades da água de chuva no semi-árido brasileiro. EMBRAPA-Semiárido, Petrolina, Brasil, pp. 119–137.
Silva, M.S.L. da, Neto, M.B. de O., Ferreira, G.B., Parahyba, R. da B.V., Cunha, T.J.F., Chaves, V.C., 2009. Caracterização do solo em barragens subterrâneas no Estado da Paraíba. Rev. Bras. Agroecol. 4.
Silva, S.T.B. da, 2011. Uso urbano não potável de água de lagoas do sistema de drenagem de Natal (Master thesis). UFRN - Universidade Federal do Rio Grande do Norte, Natal, Brazil.
Soares, M.B.D., 2013. Estudo da implantação em escala real da filtração em margem em lago de piscicultura extensiva para dessedentação animal (Master thesis). UFSC-Universidade Federal de Santa Catarina, Florianópolis, Brasil.
Soares, M.B.D., 2009. Estudo da implantação em escala real da filtração em margem em lago de piscicultura extensiva para dessedentação animal (Master). Universidade Federal de Santa Catarina, Florianópolis, Brasil.
Sprenger, C., Hartog, N., Hernández, M., Vilanova, E., Grützmacher, G., Scheibler, F., Hannappel, S., 2017. Inventory of Managed Aquifer Recharge sites in Europe - historical development, current situation and perspectives. Hydrogeol. J. 25, 1909–1922. https://doi.org/10.1007/s10040-017-1554-8
Stefan, C., Ansems, N., 2017. Web-based global inventory of managed aquifer recharge applications. Sustain. Water Resour. Manag. 1–10. https://doi.org/10.1007/s40899-017-0212-6
Stefan, C., Ansems, N., 2016. Web-GIS of global inventory of managed aquifer recharge applications, in: Proceedings of 9th International Symposium on Managed Aquifer Recharge (ISMAR9). Presented at the ISMAR9, June 20-24, 2016, Mexico City, Mexico.
Tobar Espinoza, E.A., 2009. Modelacion del egecto de la recarga artificial sobre la operación del dren Las Vegas. Universidad de Chile, Santiago de Chile.
Törey, S., 2014. EL LENTO CAMINO EN LA RECARGA ARTIFICIAL DE ACUÍFEROS. Rev. AIDIS 47, 27–31.
Ulloa Trujillo, L., 2016. Ciego de Ávila prioriza recarga del manto freático. Invasor - Periód. Digit. Ciego Ávila.
UN, U.N., 2017. Statistical Yearbook 2017 edition: Sixtieth issue. UNITED NATIONS PUBLICATION.

UN, U.N., 2015. World Population Prospects: The 2015 Revision.
von Hoyer, M., Godoy V, E., 2000. Methods for the Improvement of the Water Supply in the Chaco of Paraguay. Episodes 23, 29–31.
WWAP, U.N.W.W.A.P., 2017. Wastewater: The Untapped Resource, The United Nations World Water Development Report. UNESCO, Paris, France.