GROUNDWATER IN LATIN AMERICA AND THE CARIBBEAN

Policies and experiences for managing and preserving aquifers

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Abbreviations

ANA	National Water Authority of Peru
CAN	Andean Community Countries
CCB	Caribbean Group Countries
CID	Central America, Haiti, Mexico, Panama, and the Dominican Republic countries
CRC	Costa Rican Colón
CSC	Southern Cone Countries
EPS	Water and sanitation utilities in Peru
FCAS	Cooperation Fund for Water and Sanitation
GMMS	Groundwater Monitoring and Management Service
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LAC	Latin America and the Caribbean
MAR	Managed Aquifer Recharge
MINAE	Ministry of the Environment and Energy of Costa Rica
OFWAT	Water Services Regulation Authority (England and Wales)
PEN	Peruvian Sol
SAG	Guarani Aquifer System (by its Spanish acronym)
SDGs	Sustainable Development Goals
NbS	Nature-based Solutions
SAYTT	Yrendá-Toba-Tarijeño Aquifer System (by its Spanish acronym)
SUNASS	National Superintendence of Water and Sanitation Services of Peru
UGI	Urban Green Infrastructure
USA	United States of America
USD	USA Dollar

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Introduction

In the first quarter of 2017, Chile and Peru were hit by the *El Niño* phenomenon, which generated heavy rains and landslides. As a consequence, the turbidity level of rivers increased (Stip et al., 2019), which forced water utilities in Lima and Santiago to temporarily close their water treatment plants. Although there were interruptions in the provision of the service, water utilities were nonetheless able to continue thanks to their reserve wells, put in operation as part of their emergency plans. Groundwater played a crucial role in ensuring the water supply for millions of people in challenging circumstances.

Water is essential for socio-economic development, as it promotes health and prosperity in societies and, in turn, is a central element in the production of food, energy, and most industrial processes (Delgado et al., 2021). Groundwater, which accounts for 99% of the planet's freshwater (Shiklomanov and Rodda, 2003), is essential to meeting demand for this resource for its various uses. In Latin America and the Caribbean (LAC), about 30% of freshwater extracted comes from groundwater sources; however, some activities use it more intensively, such as industry, which supplies 50% of its demand with groundwater (UNESCO, 2022).

Groundwater is central to population supply, as it provides a source of water both regularly and in emergencies, thus contributing to the fulfillment of the first target (universal access) of the sixth Sustainable Development Goal (SDG). Its exploitation, however, must consider the fourth target of this same goal that requires countries to significantly improve their efficiency in the use of water resources, ensuring the sustainability of freshwater supply and extraction.

How important is groundwater for population supply in the region? In Mexico City, a city with more than 9 million inhabitants, 58% of the water distributed comes from groundwater sources. In addition, 100% of the water distributed to the population of some cities in Bolivia, Colombia, Costa Rica, Chile and Peru comes from groundwater sources, as identified in this study. In rural areas, groundwater may be the only viable technological solution, thanks to the low investment, operation and maintenance costs associated with it and to the wide geographic distribution of aquifers allowing for its extraction by disperse populations.

Groundwater also has unique characteristics, making it a strategic natural asset in climate change adaptation. Since an important component of groundwater comes from the infiltration of rainwater, it converts unstable climatological events into a relatively stable water supply source. Groundwater extraction enhances the resilience of water systems by guaranteeing a consistent water supply even in the face of extreme climate events, such as droughts or intense rains that increase turbidity in rivers (and make the utilization of surface water impossible). This use of groundwater is not recent, as infrastructure built more than 1400 years ago by pre-Inca cultures allowed the ancient inhabitants of the Peruvian Andes to deal with climate variability (Ochoa-Tocachi et al., 2019).

Because of their importance, we must protect groundwater resources from threats to their quality and future availability. Contamination of aquifers from various causes can nullify these sources of population supply, while excessive extraction can produce adverse results such as land subsidence and saline intrusion. Land subsidence can seriously affect cities not only by its impact in streets and roads, and thus in mobility, but also by putting pressure on water networks. This pressure causes breaks that increase physical water losses and can lead to flooding. Finally, overexploitation of aquifers also increases the vulnerability of cities to climate change, as it jeopardizes the future availability of the source and reduces resilience to extreme climate events.

This document has the following structure: the first chapter deals with the main hydrological and economic concepts to understand groundwater dynamics and the incentives surrounding its extraction. The second chapter develops the importance of groundwater resources for the LAC region. The third chapter reviews policy instruments for groundwater management, dividing them into demand management instruments and supply management instruments. The fourth chapter reviews case studies in the region, and the fifth chapter contains the conclusions of the document.

It should be mentioned that this monograph focuses on urban groundwater and its potential to supply residential and industrial demands. Due to its importance, agricultural use is mentioned in certain sections, considering the implications and interrelationships it has with the extraction of water for domestic and industrial consumption. However, it is necessary to continue expanding this analysis to understand the rivalry between the different uses of the resource as well as other factors that make the analysis more complex, such as the case of transboundary aquifers or the use of water markets[1] for the allocation of the resource between different uses, to mention a few.

[1] Sanchez and Eckstein (2017) can be reviewed for information on the challenges in managing transboundary aquifers in Mexico and the United States. For analysis of two case studies on water markets in the United States and Chile, Montginoul et al. (2016) can be reviewed.

1. Groundwater: theory and concepts

1.1.
Basic concepts

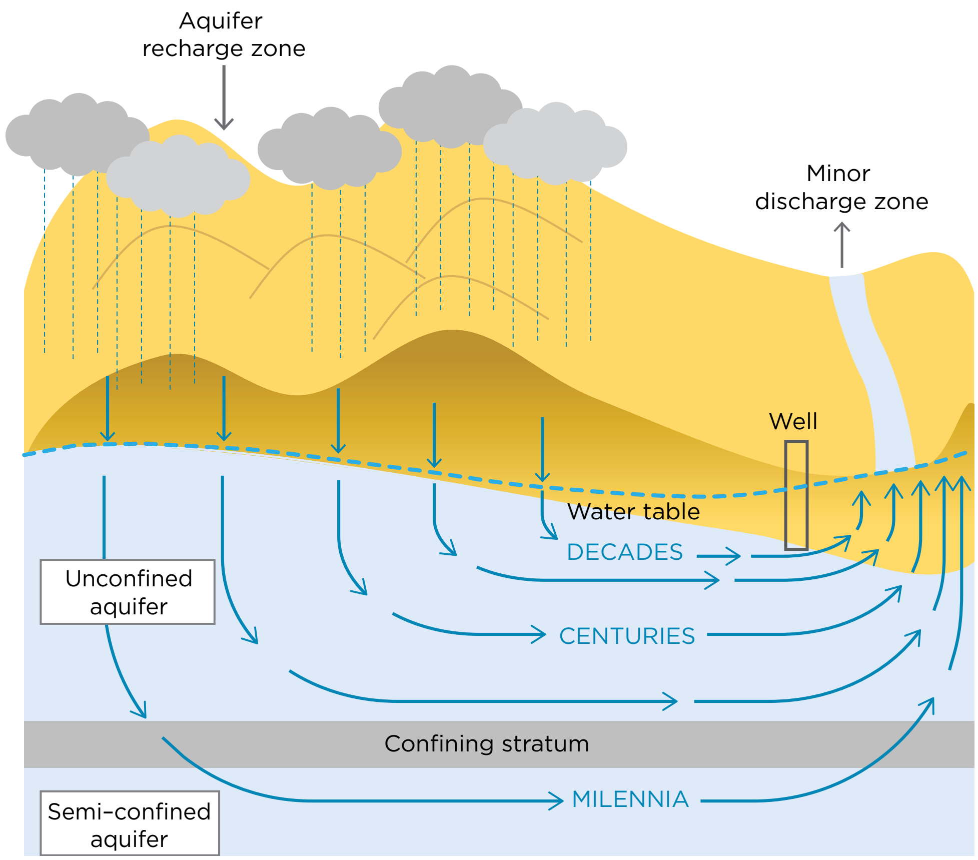
1.1.1. Groundwater and aquifers

Groundwater is the least visible manifestation of water resources. Aquifers are geological formations that store large quantities of water, characterized by recharge and discharge zones. **Aquifers** can be recharged directly by the infiltration of water from rainfall and from bodies of water such as rivers or lakes into the ground. Aquifers can also be artificially recharged by human activity. Discharge can be natural (such as groundwater upwelling through springs or its contribution to rivers) or human-induced through groundwater extraction using wells.

Groundwater moves through the subsurface at different rates from recharge zones to discharge zones, such as springs, wetlands, and coastal zones, among others. Thus, aquifers transform unstable recharge phenomena into a more stable water source (which may form over decades, centuries, or even millennia). As can be seen in **Illustration 1**, when aquifers are located beneath less permeable strata, the upper layers confine groundwater, making them **confined aquifers**. **Unconfined aquifers**, on the other hand, are those that can be easily accessed by human activity because they do not have low permeability layers that constrain them.

■ **ILLUSTRATION 1**

Confined and unconfined aquifer formation



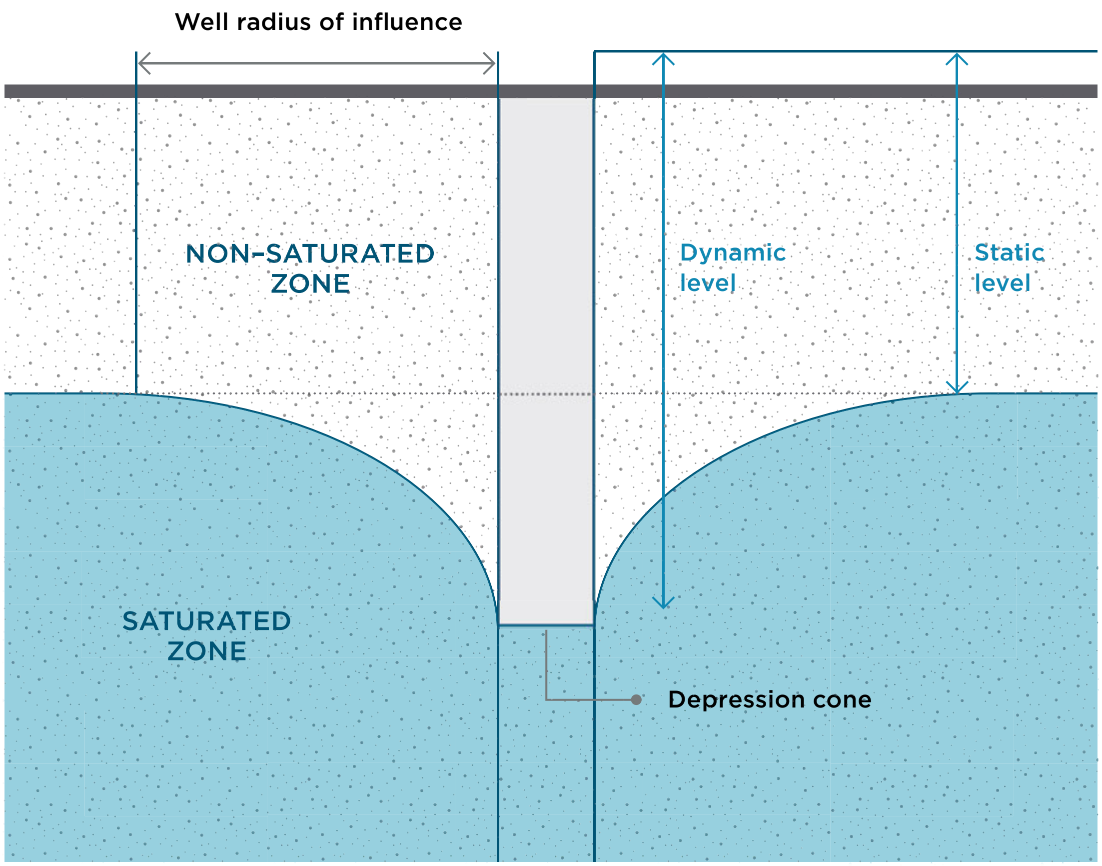
Source: Author's elaboration, based on Foster et al. (2010) and UNESCO (2022).

1.1.2. Water table: static level and dynamic level

The **water table** (also known as the phreatic surface) marks the level below which the ground is saturated (i.e., where the pores or fissures in the ground are filled with water). The **static level** corresponds to the position that the groundwater occupies under natural conditions; however, when a well is installed, it corresponds to the distance (measured in meters from the wellhead) when the pumping equipment is not in operation. The **dynamic level** is the position of the groundwater when the pumping equipment is operating. As the well begins pumping water, a drop in the hydraulic head known as a **cone of depression** is generated (see **Illustration 2**).

By definition, greater variability over time is expected in the dynamic level; while changes in the static level take longer and are indicative of the well's extraction intensity in the medium and long term. **Box 1** contains an analysis of the evolution of the static level of the wells operated by the water utility in Lima in the period 2011-2020.

ILLUSTRATION 2
The water table of a well



BOX 1

The evolution of groundwater levels in Metropolitan Lima (Peru) over the last 10 years

In 2020, 20% of the drinking water distributed by the water utility in Lima was produced using water extracted by more than 400 wells (Sedapal, 2021a). The second column of **Table 1** shows that there are data for a variable number of wells in the period analyzed.

We use static water levels because they allow us to observe trends over time. In contrast, dynamic water levels are usually more variable and considerably lower (Kinzelbach et al., 2022). The initial assessment of the average static level indicates the existence of a slightly increasing trend, meaning that the water table is progressively moving further from the surface, suggesting a retreat of the aquifer.

However, several factors influence the water tables level, such as topographic elevation and the historical pattern of well extraction, which causes the average static level to vary among the districts of Metropolitan Lima.

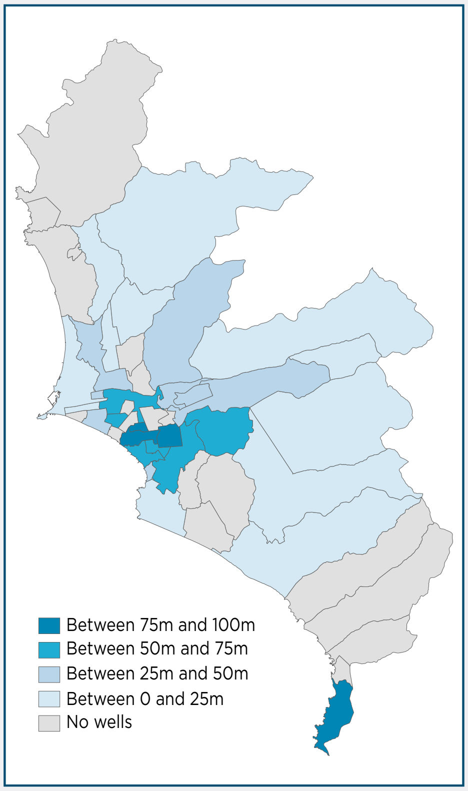
TABLE 1
Evolution of the average static water level of the wells in Metropolitan Lima (in meters)

YEAR	WELLS	AVERAGE
2011	407	25.96
2012	398	26.21
2013	412	26.15
2014	393	27.09
2015	378	26.69
2016	392	27.96
2017	390	27.99
2018	389	27.59
2019	423	28.54
2020	398	28.88

Source: Author's elaboration based on information submitted by Sedapal (2021b).

More in-depth analyses are performed at the district-level. **Illustration 3** shows the result of processing the information submitted by Sedapal on the static water level of its wells for the year 2020. As can be seen, there is a group of districts in central Lima whose wells have an average static level higher than 60 meters (Cercado de Lima, Santiago de Surco, Miraflores, Surquillo, San Isidro, San Borja and Lince). This group also includes wells located in the Pucusana beach district, located in the south of the region, whose wells in 2020 had an average static level of 78.9 meters.

ILLUSTRATION 3
Average static water level per district in 2020 (in meters)



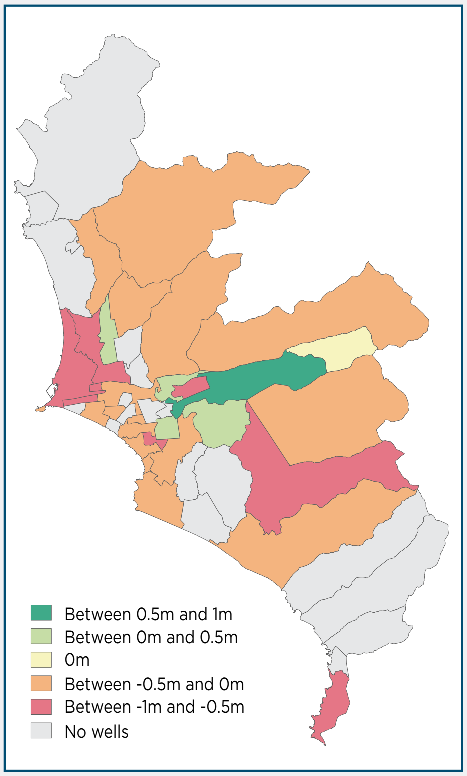
Source: Author's elaboration based on information submitted by Sedapal (2021b).

In a more detailed analysis (see **Illustration 4** and **5** and **Annex 1**), we see an increase in the static water level measured in meters (i.e., a decrease in the aquifer level) during the period 2011-2020 in most of the districts of Metropolitan Lima. Districts exhibiting a recovery in the aquifer level include Ate (0.7 meters average per year), San Borja and Los Olivos (0.3 meters average per year), El Agustino (0.2 meters average per year) and La Molina (0.1 meters average per year). The district of Chaclacayo exhibits a relatively stable static level during the period analyzed.

On the other hand, Carmen de la Legua is the district with the greatest retreat, in absolute terms, in the level of the groundwater table: the static level increased by 8.1 meters in the period 2011-2020; that is, an average of 0.9 meters per year or 35% of its 2011 level. Other noteworthy districts include Miraflores, Surquillo and Pucusana, which belong to the group of districts whose static levels are above 60 meters and which have reported average well level retreats of 0.5, 0.8 and 0.5 meters per year, respectively.

ILLUSTRATION 4

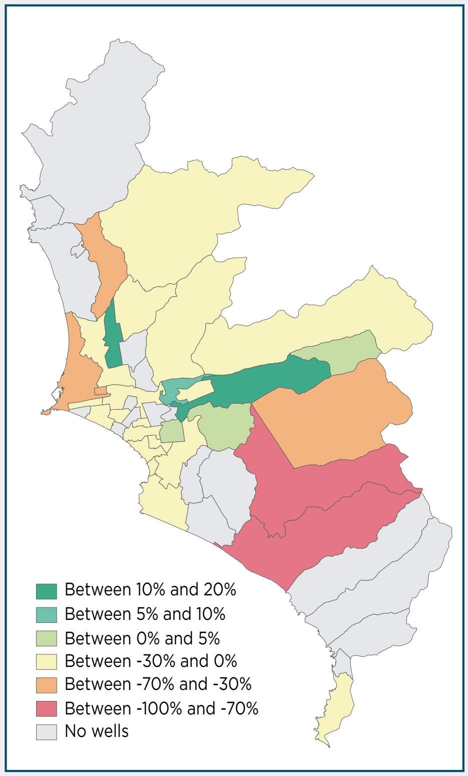
Average annual variation of the static water level between 2011 and 2020 (in meters)



Source: Author's elaboration based on information submitted by Sedapal (2021b).

ILLUSTRATION 5

Percentage change in static water level between 2011 and 2020 (%)



Source: Author's elaboration based on information submitted by Sedapal (2021b).

1.1.3. Advantages of using groundwater

Groundwater has the following advantages over surface water:

i) Lower treatment cost. Although there is a cost associated with its extraction, with some exceptions, groundwater requires less treatment (often only chlorination), so infrastructure investment and expenditure on water treatment chemicals are lower in the case of groundwater use.

ii) Spatial distribution. When provision is carried out by an operator, the deployment of wells throughout the city allows the operator to produce drinking water in locations closer to the users, thus reducing the costs of transporting drinking water and the associated physical losses of water. Similarly, groundwater is an important cost-effective technical option for water supply in rural areas. A phenomenon occurs in such rural contexts similar to that of "distributed generation" in electricity service, where the absence of economies of scale and density does not allow for network distribution. Aquifers are a source of distributed storage capacity (UNESCO, 2022). In both cases, the user becomes the producer of the service.

iii) Source stability. Groundwater sources are available at all times of the year, unlike surface sources whose availability is seasonal and depends on the time of the hydrological year, increasing during wet seasons and decreasing during dry seasons. This allows water utilities to make a conjunctive use of the sources—that is, an optimal and coordinated combination of surface and groundwater, both intra- and inter-annually. In that sense, the aquifer acts as a buffer to overcome fluctuations in water supply (WWAP, 2018). This characteristic also gives groundwater the potential to act as a reserve and ensure the resilience of the system in the face of extreme weather events. These benefits are part of the ecosystem services provided by aquifers (see **Box 2**).

BOX 2

Groundwater as a provider of ecosystem services

Good management of ecosystems, conserving them and ensuring their adequate use, is a necessary condition for guaranteeing the sustainable development of countries. According to the Millennium Ecosystem

Assessment (2003), **ecosystem services** are all those benefits that humans receive from ecosystems, divided into four types:

- **Provisioning services:** raw materials or products obtained by humans from ecosystems.
- **Regulating services:** benefits obtained from the regulation of physical, biological and chemical processes that take place in ecosystems.
- **Cultural services:** non-material benefits that people obtain from ecosystems through recreation, contemplation and cognitive development, among others.
- **Supporting services:** services necessary for the production of other ecosystem services (soil formation, nutrients, etc.).

Groundwater and the aquifers where it is stored provide different ecosystem services that humans take advantage of, which are summarized in the following Table.

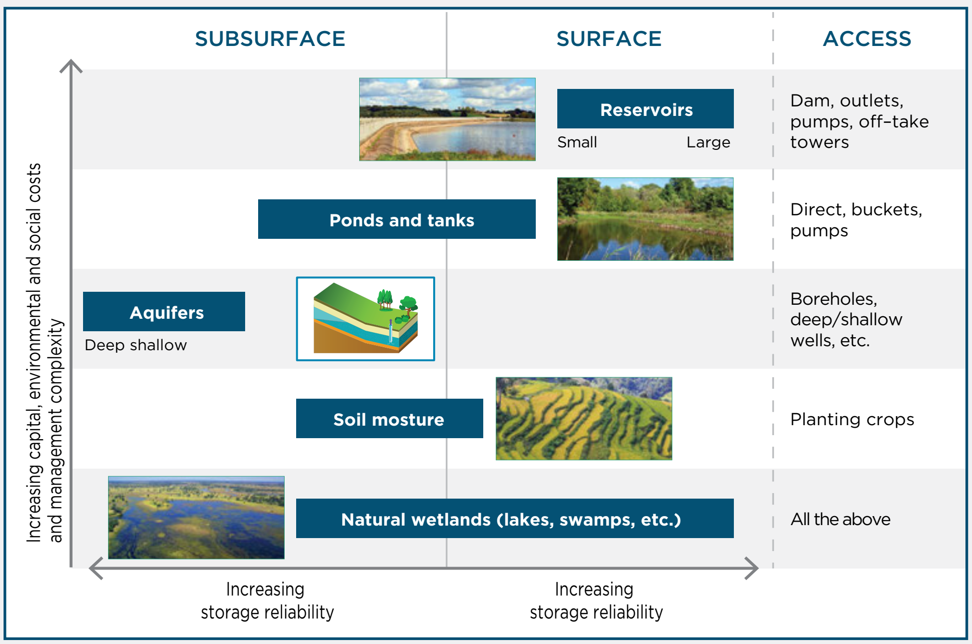
TABLE 2
Ecosystem services provided by aquifers and groundwater

TYPE OF SERVICE	ECOSYSTEM SERVICE
Provisioning	• Water for urban and rural human consumption • Water for irrigation of agricultural land and agricultural uses • Water for industry • Water for geothermal power generation
Regulating	• Water purification • Storage (buffering) between dry and wet seasons • Buffering against climate change effects (autonomy of surface sources) • Flood mitigation • Erosion reduction
Cultural	• Mineral water • Thermal waters
Supporting	• Springs • Maintenance of subsoil microbial organisms • Maintenance of phreatophyte plants • Maintenance of biodiversity, including animal species

Source: Author's elaboration, based on The Nature Conservancy (2022), Grieber and Avramov (2015) and van der Gun (2019).

Aquifers are one of many options for providing water storage. One can rather speak of a "water storage continuum." In other words, there is a wide spectrum of surface and sub-surface options, which should be considered when planning storage (see **Illustration 6**). For example, in LAC, the natural infrastructure of wetlands and paramos (located in the central and northern Andes, respectively) have a high water retention capacity due to their highly organic soils (Muñoz and Crisman, 2019). The optimal combination, including gray infrastructure and natural infrastructure, must consider the capital, environmental, and social costs, as well as the complexity in managing each alternative.

ILLUSTRATION 6
Water storage continuum



Source: WWAP – Unesco (2018).

1.1.4. Threats to groundwater

As per Wijnen et al. (2012), the unsustainable utilization of groundwater, driven by rapid population and economic growth, poses a dual threat to both its quantity and quality. The authors further classify these threats into three distinct categories:

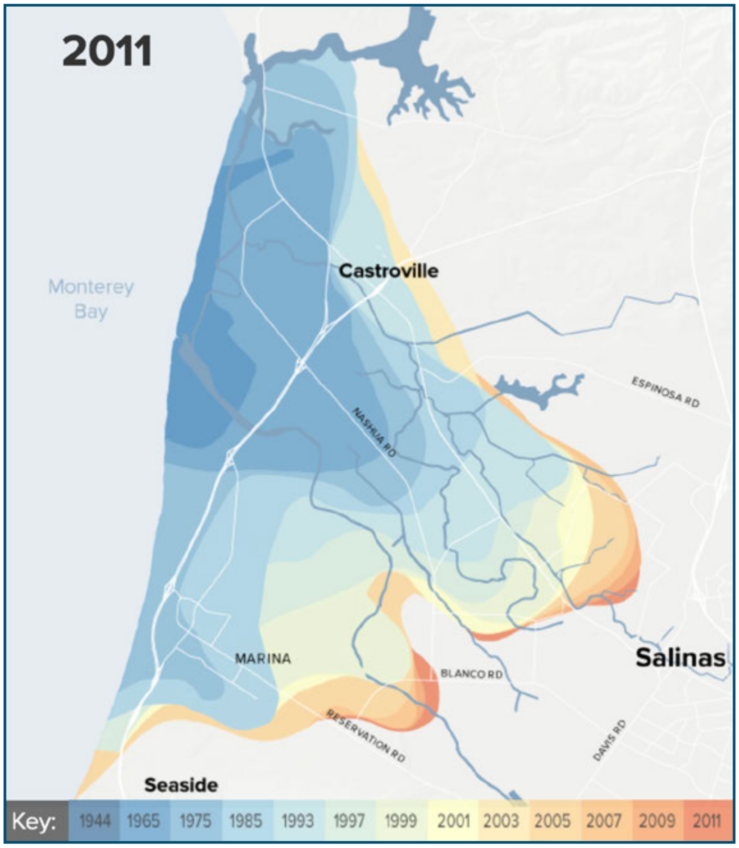
i) Quantity reduction due to overexploitation. From the economic point of view, groundwater resources are common-pool resources, so agents have incentives to maximize their private profit by extracting as much water as possible (see **section 1.2**). In many countries, these incentives have been reinforced by the relatively low costs of extraction, including low water extraction fees and heavily-subsidized electricity tariffs.

ii) Occupation or degradation of recharge zones. Urban development and changes in land use and hydrological cycles can affect the quantity and quality of water that infiltrates aquifers. Urbanization reduces the amount of runoff that infiltrates by reducing infiltration areas (i.e., the soil surface is impermeabilized) (Foster, 2020). Changes in land use also include the expansion of agricultural land, deforestation and wetland destruction. The latter leads to the loss of ecosystem services such as water retention, flood attenuation and maintenance of water quality (Scanlon et al., 2023).

iii) Deterioration of groundwater quality. Groundwater can be contaminated by natural or anthropogenic causes. On-site sanitation and, to a lesser extent, sewage outflow or accidental spillage of industrial or chemical wastes can contaminate groundwater (Foster, 2020). Aquifer recovery is not always feasible, and when it is, it often involves significant costs. Therefore, the primary emphasis should be on prevention and control measures to avoid rendering wells unusable due to groundwater contamination. The overexploitation of aquifers can contribute to this phenomenon through contamination by saline intrusion.

■ **ILLUSTRATION 7**

Progress of saline intrusion in the aquifer between 1944 and 2011 (Monterey Bay, California, United States).

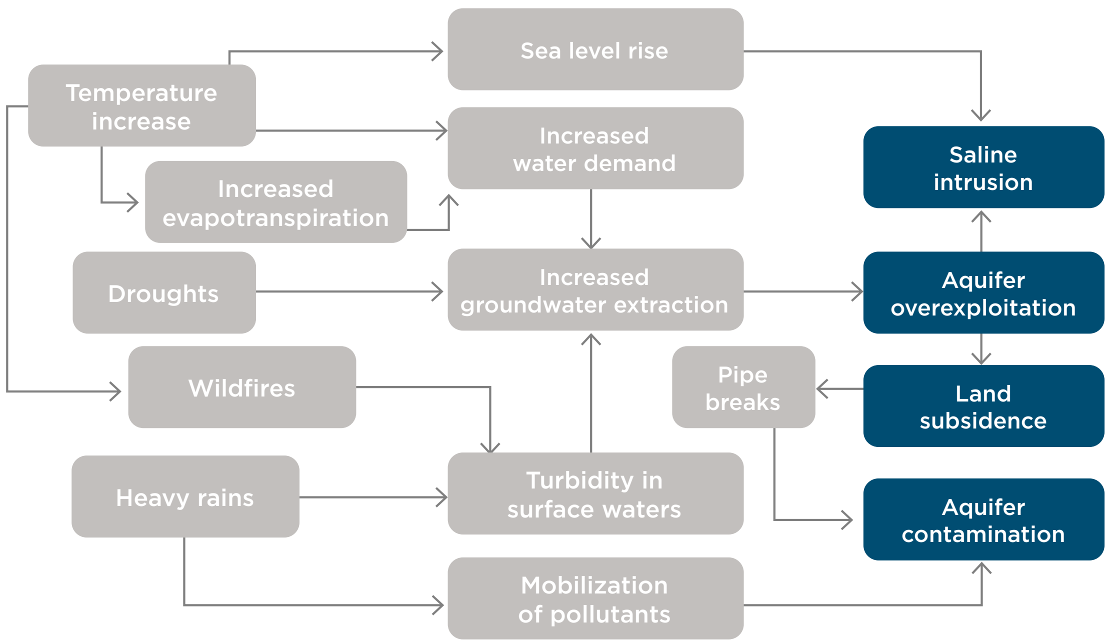


Source: Moran et al. (2014).

These threats are expected to intensify in the coming years as the effects of climate change become more intense and frequent. For instance, rising temperatures will increase the domestic and agricultural water demand (in the latter case as a result of increased evapotranspiration), leading to a greater extractive pressure on aquifers. Sea level rise may also seriously affect coastal aquifers, increasing the probability of saline intrusion. Similarly, heavy rains can increase the level of turbidity in surface sources and carry pollutants (such as pesticides, chemicals or excreta) that compromise the quality of aquifers (Caretta et al., 2022).

Illustration 8 presents the main effects of climate change and the impacts they have on groundwater.

ILLUSTRATION 8
Effects of climate change and its impact on groundwater

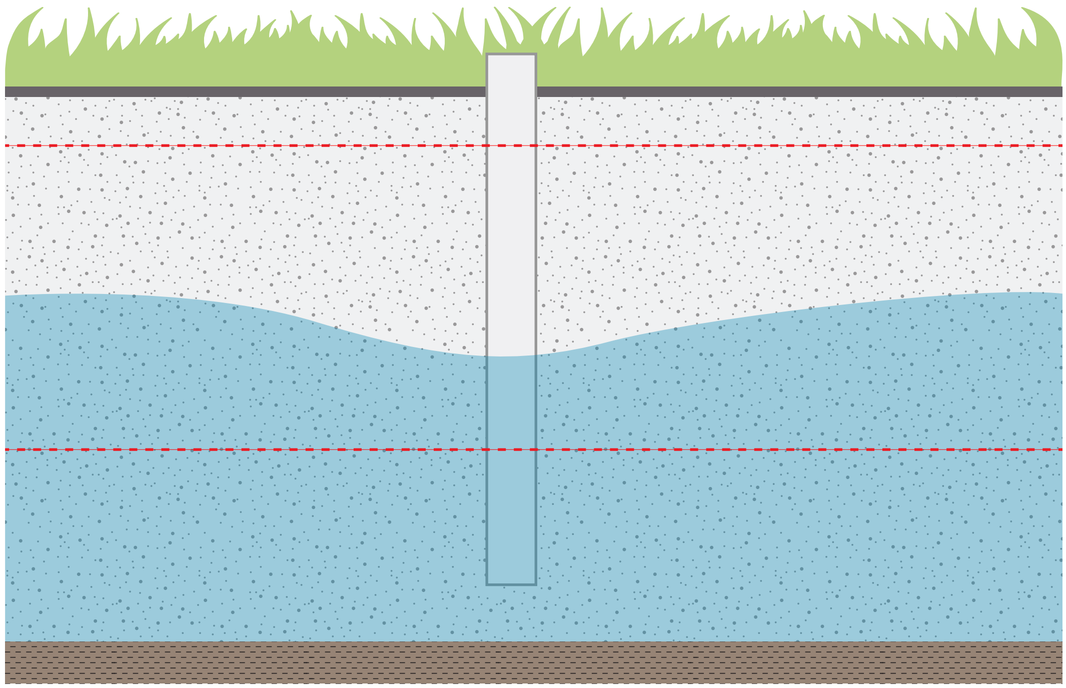


Source: Author's elaboration.

1.1.5. Overexploitation and its consequences

The term "overexploitation" is directly related to aquifer sustainability. Some consider the aquifer to be overexploited when water table levels exhibit a long-term sustained decline; indicating that withdrawal is consistently greater than recharge. In this definition, it is important to discuss what we consider "long term", because sometimes recharge occurs during large events that take place every decade, and many times water extraction is not evenly distributed over time (Foster et al., 2010). In this sense, sustainable exploitation is understood as an extraction regime that maintains groundwater levels between an upper and lower limit (delimited with red lines in **Illustration 9**), and overexploitation can be understood as a situation that leads to exceeding the lower limit. The definition of this limit will depend on different factors, such as the proximity of the aquifer to the coast or various ecological criteria (Kinzelbach et al., 2022).

ILLUSTRATION 9
Limits that determine sustainable groundwater withdrawal



Source: Kinzelbach et al. (2022).

Overexploitation of the aquifer can have reversible and irreversible consequences, which are detailed in **Table 3**.

TABLE 3
Consequences of excessive groundwater extraction

REVERSIBLE	IRREVERSIBLE
• Increased pumping costs • Borehole yield reduction • Springflow/baseflow reduction	• Phreatophytic vegetation stress (both natural and agricultural) • Aquifer compaction and reduced transmissivity • Saline water intrusion • Ingress of polluted water (from perched aquifer or river) • Land subsidence and associated impacts (aquitard compaction)

Source: Foster et al. (2010).

Additionally, a rebound of the groundwater table may occur if groundwater extraction is interrupted—for instance, because of aquifer contamination—after a long period of intense use. This rebound can cause flooding of properties, transport routes and the collapse of sewerage collection networks, as occurred in Buenos Aires in the 1980s (Foster, 2020). Authorities sometimes become aware of the importance of groundwater management when its overexploitation has caused a perceptible reduction in the yield of wells or the quality of the water extracted. However, countries must adopt a more proactive attitude to prevent the unsustainable exploitation of groundwater resources.

BOX 3

Aquifer overexploitation and land subsidence in cities

An externality caused by the excessive extraction of groundwater is the compaction of the aquifer and the resulting land subsidence. This generates serious problems in cities by creating terrain unevenness that affect urban mobility and water and sanitation infrastructure.

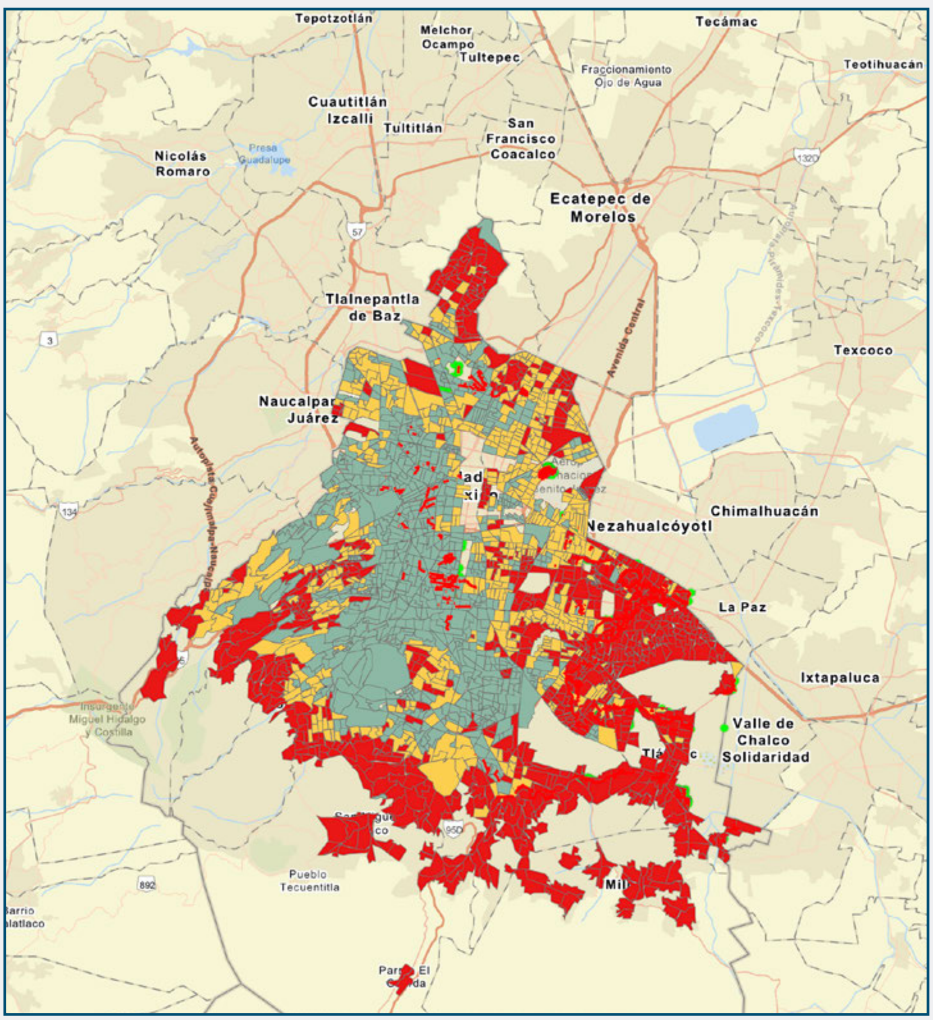
Land subsidence exerts pressure on water distribution networks, potentially leading to pipe cracks, physical water losses and, thus, an increase in non-revenue water. It can also cause cracks in sewerage collection networks, which can contaminate drinking water and the aquifers themselves (Moran et al., 2014). Finally, ruptures in water and sewerage networks have the potential to trigger flooding within the city.

In Mexico, subsidence rates are among the highest in the world, with up to 30 centimeters of subsidence per year for the period 2004-2006 in Mexico City (Galloway and Burbey, 2011). In 2017, Mexico's National Center for Disaster Prevention presented an interactive map of subsidence in Mexico City, with areas showing up to 40 centimeters of subsidence per year (see **Illustration 10**).

Mexico City is usually mentioned as a critical case worldwide that illustrates the relationship between excessive extraction and subsidence (Kinzelbach et al., 2022; Scanlon et al., 2023). In a forum organized by the UNAM Water Network and SACMEX (2013), it was pointed out that "overexploitation of the aquifer has made it possible to meet the city's water demand; however, the balance has been significantly upset by extracting more water than is infiltrated; if recharge is not increased, the problems of land subsidence in the Valley of Mexico will continue to worsen". According to Palma et al. (2022), 63% of the water demand of the Mexico City Metropolitan Zone comes from groundwater, with an associated overexploitation of 25 m^3/s.

▪ ILLUSTRATION 10

Map of land subsidence in Mexico City



Source: http://www.atlasnacionalderiesgos.gob.mx/apps/Geociencias/
Accessed December 22, 2022.

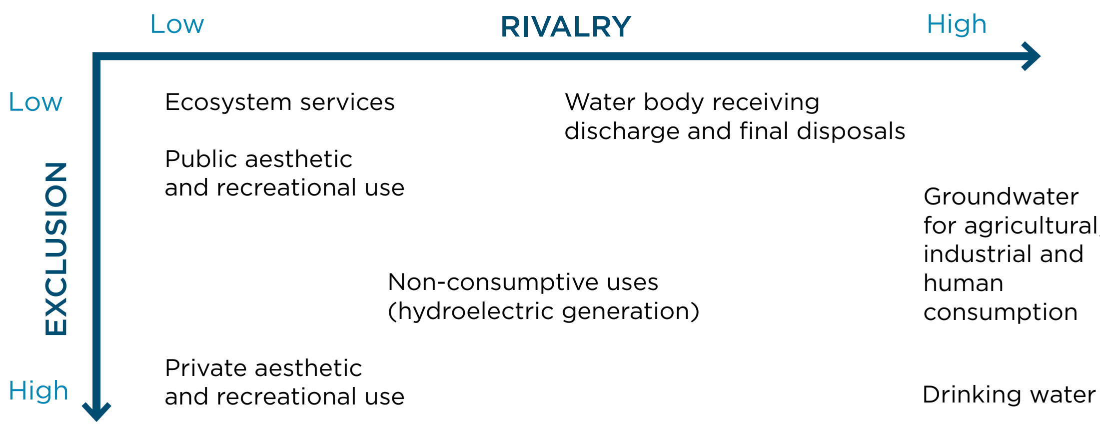
In their analysis of the case of Mexico City, Chaussard et al. (2021) find that subsidence rates have been relatively constant since at least 1950 at approximately 50 centimeters per year. The analysis concludes that, for this case, the location of water withdrawal points and the magnitude of water withdrawn do not uniquely explain subsidence rates. Instead, they find a positive linear relationship between subsidence rates and the thickness of the upper aquitard and aquifer. The authors state that, considering that about two thirds of the water consumption in the area is extracted from the aquifer, drastic water management actions (such as reuse of treated wastewater for groundwater recharge and agricultural and urban irrigation) should be implemented. According to Palma et al. (2022), hydrological analysis indicates that both recycled water and artificial recharge of aquifers with rainwater are opportunities in the case of the Mexico City Metropolitan Zone.

1.2. Types of goods and the tragedy of the commons

Goods in the economy can be classified according to their degree of exclusion and rivalry. Exclusion refers to the capacity to prevent others from consuming a good, either through physical (e.g., infrastructure deployment) or economic barriers (e.g., tariffs). Rivalry measures the extent to which one individual's consumption diminishes the availability of the good for others (Zegarra, 2014).

For example, in **Illustration 11**, drinking water is positioned in the lower right quadrant (high rivalry and exclusion). High rivalry comes from the fact that the consumption of one cubic meter by one user inevitably diminishes the supply available to others. Additionally, exclusion is possible because consuming drinking water requires a connection and paying a bill, making it fall under the category of private goods. On the other hand, ecosystem services, being a public good, are situated at the opposite end of the spectrum. No one can be excluded from their enjoyment and they benefit all citizens at the same time.

ILLUSTRATION 11
Location of water uses on the map of public and private goods



Source: Author's elaboration based on Zegarra (2014).

Groundwater resources are common-pool resources, positioned in a middle ground between these quadrants. They exhibit a notable degree of rivalry among users, with some level of exclusion from access or usage. High rivalry becomes evident when one user extracts water from the aquifer, diminishing the available stock for others. This leads to a scarcity issue, as two users cannot draw the same cubic meter of water simultaneously. This rivalry occurs both between different uses (agricultural versus domestic consumption, for example) and within the same type of use. Regarding exclusion, some administrative and economic measures can be established to exclude certain users from accessing the resource (for example, establishing the requirement to obtain a license or requesting payment for water abstracted).

However, achieving absolute exclusion can be challenging, as it can become a complex endeavor to control who accesses groundwater and how much they extract. For the former, authorities usually require a license and charge a groundwater extraction fee, simultaneously conducting inspections to detect clandestine wells. For the latter, the installation of individual meters to record the volumes extracted is not always common and authorities often rely on affidavits from users.

In the case of common-pool resources, Hardin (1968) warned that these will inevitably be overexploited in the absence of coercive measures, a phenomenon that the author named "the tragedy of the commons". Hardin pointed out that while individuals consider only the utility for themselves in exploiting an additional unit of the good, the utility in fact has two components: i) the positive component, which is a consequence of the direct benefit from exploiting the resources (in the author's example, the benefit from including a unit of cattle to be grazed in a field) and ii) the negative component derived from the overexploitation of the good (overgrazing, in the same example). The second component is shared among all individuals who exploit the common-pool resource, so the rationality of individuals leads them to consider only the first component and, therefore, to exploit as much of the good as possible. In the absence of regulation over the medium and long term, this can result in resource depletion, impacting the well-being of all users.

1.3. Optimal extraction model

The factors that affect the water level of an aquifer can be studied by formalizing them in a mathematical model. From an economic perspective and from the perspective of aquifer sustainability, we are thus able to propose public policies aimed at the optimal use of groundwater sources. This section presents a model based on models developed by Strand (2010), Hanemann (2005) and Chaitra and Chandrakanth (2005).

This is a dynamic optimization model because the problem faced by society in groundwater extraction is intertemporal: the decision to extract today carries implications for future extraction capacity, thereby influencing future benefits and costs. Thus, the objective of this problem is to maximize the present value of the net social benefits from groundwater extraction, given the existing stock.

1.3.1. Aquifer recharge equation

First, it is worth defining how the groundwater stock and withdrawals interact. We consider that the groundwater stock in a given period is a function of the water stock, recharge and extraction in the previous period:

$$G_{t+1} = (G_t + R(E_t) - E_t)$$

$$G_{t+1} = (G_t + A + \theta E_t - E_t)$$

Where:

G_t	:	Groundwater stock at the beginning of period *t*
E_t	:	Groundwater extraction in period *t*
$R(E_t)$	:	Aquifer recharge function
A	:	Natural or artificial recharge of the aquifer
θ	:	Percentage of withdrawals that are re-infiltrated

The above equation formalizes the groundwater stock as a function of recharge and discharge. We consider only the extractions made in the previous period as discharges. However, on the recharge side, we consider that a percentage of the extractions end up reinfiltrating (θ), but we also consider a fixed recharge parameter (A). This can involve the natural recharge of the aquifer (fed by other bodies of water or by infiltration of rainwater but which, ultimately, does not depend on water withdrawals) or the induced or artificial recharge as the result of human action.

1.3.2. Extraction benefits and costs

Groundwater extraction generates both benefits and costs. The social benefits include the utility generated by human consumption, as well as the value of agricultural production that uses groundwater as an input.[2] Benefits are expected to be an increasing and concave function of the volume of water abstraction; that is, $B'(E_t)>0$ and $B''(E_t)<0$. Hanemann (2005) formalizes these characteristics with a quadratic function with the following parameters:

$$B\ (E_t) = aE_t - b\ (E_t)^2$$

Concerning the cost of extraction, we define a function that depends on both the volume extracted and the groundwater stock in the period. The first component is explained both from the administrative point of view (payment of fees with rates per cubic meter extracted) and from the operational point of view (electrical energy used in pumping). Another intertemporal aspect of the model is the dependence of the extraction cost on the groundwater stock, which increases as the groundwater stock decreases (Kinzelbach et al., 2022).

[2] In addition to the value of groundwater for agriculture and domestic and industrial use, Strand (2010) notes that its value also includes its role in supporting biodiversity and preventing saline intrusion and land subsidence.

This can be formalized with a cost function that includes a direct cost of extraction (c) and a parameter (δ) that captures the sensitivity of the extraction cost to a decline in the aquifer water stock:

$$C\,(E_t, G_t) = (c - \delta G_t)\,E_t$$

The optimization problem, therefore, consists of determining the optimal extraction level that allows maximizing the present value of the social net benefit, taking into account the discount rate (r), i.e.:

$$\max \sum_{t=0}^{\infty} (1+r)^t \left[aE_t - b\,(E_t)^2 - (c - \delta G_t)\,E_t\right]$$

$$s\,.\,a \quad G_{t+1} = (G_t + A - (1 - \theta)\,E_t)$$

$$G_0 = \overline{G_0}$$

1.3.3. Solution to the problem

In solving this optimization problem and analyzing the stationary equilibrium, Hanemann (2005) finds the following conditions:

$$E^* = R\,(E^*) \;\ldots\; (1)$$

$$\frac{\delta B\,(E^*)}{\delta E} = \frac{\delta C\,(G^*,E^*)}{\delta E} + \lambda^*\left[1 - \frac{\delta R\,(E^*)}{\delta E}\right] \ldots\; (2)$$

$$\lambda^* = \frac{\dfrac{-\delta C\,(G^*,E^*)}{\delta G}}{r} \;\ldots\; (3)$$

Condition (1) indicates that, in steady-state equilibrium, the volume of water withdrawn must be equal to the volume recharged to the aquifer per period. Condition (2) indicates that the marginal benefit of water extraction must be equal to the marginal cost plus an additional premium. This premium corresponds to the marginal value of leaving an additional unit of groundwater underground, discounting the amount of water that is recharged.[3]

[3] The Lagrange multiplier (μ) measures the increase in the objective function as a result of a marginal relaxation in the constraint. In this case, it would be interpreted as the increase in the present value of the social net benefit as a consequence of having one more unit of groundwater in the stock in period t. We define the parameter λ as follows: $\lambda_t = (1 + r)^t\,\mu_t$.

This is an interesting first result as it reveals that the optimal solution—unlike the scenario in which extraction only considers private costs—requires the internalization of an additional component. In short, an optimal decision considers that part of the cost of extracting water is also the cost of not being able to benefit from water in the future. Finally, according to condition (3), the marginal value of leaving an additional unit of groundwater underground equals the present value of all future cost savings derived from not extracting it.[4]

It is worth specifically reviewing the stationary equilibrium level of the groundwater stock in the aquifer:

$$G^* = \frac{\left[\dfrac{\delta A}{r} + c - a + 2b\,\dfrac{A}{1-\theta}\right]}{\delta}$$

From a public policy perspective, certain variables influence the groundwater stock and are relevant to the current discussion: aquifer recharge (A), the volumetric cost of extracting water (c), and the percentage of water infiltrating the aquifer (θ).

There is a direct relationship between the aquifer stock and the volume of water recharged in each period that does not depend on withdrawals (A). While this largely includes natural aquifer recharge (which can be enhanced by investments in natural infrastructure), there are also activities and investments that directly or indirectly contribute to groundwater recharge. Examples include artificial recharge projects, as well as water transfers that have the indirect effect of increasing the availability of water resources in the watershed.

There is a direct relationship between the aquifer stock and the volumetric cost of extracting groundwater (c). This cost includes the payment of rates, tariffs or fees, as well as the cost of electricity. Therefore, the establishment of groundwater extraction charges and the reduction of subsidies in electricity tariffs are essential to ensure that extraction is sustainable and socially optimal.

There is a direct relationship between the aquifer stock and the percentage of reinfiltration of extracted water (θ). On the public investment side, it is important to consider that governments can play a role by developing urban green infrastructure projects that promote the infiltration of water used for irrigating parks and gardens (see **Section 3.2.2**). On the regulatory side, they can implement policies to enhance the permeability of residential, commercial, and industrial properties, thus encouraging water infiltration from both user consumption and rainfall (see **Box 5**).

[4] The present value of a perpetuity (P) is calculated as PV = P/r.

2. Importance of groundwater in LAC

Approximately 99% of the planet's freshwater is found in groundwater sources (Shiklomanov and Rodda, 2003). This has the enormous potential to be exploited for direct human consumption in urban and rural areas.[5] Regarding its availability in LAC, **Illustration 12** shows a map from the Worldwide Hydrogeologic Mapping and Assessment Program, which presents the abundance of this resource in most areas of the region, except some areas in Argentina, Brazil and Chile. Likewise, overexploitation is observed in central and northern Mexico, where there is also a low aquifer recharge rate. In addition, it should be noted that the distribution of water resources does not always correspond to the distribution of the population in the region: 35% of the LAC population lives in areas with medium-high or extremely-high water stress (Libra et al., 2022).

Additionally, the quality of aquifers should not be overlooked. While certain regions in the area may have medium or high groundwater availability, the sustainability of their utilization could be at risk if the quality of this resource is compromised. For example, according to Bretas et al. (2020), the shallow depth of aquifers in Chile, Mexico, northern and central Brazil, and northern Argentina makes them more susceptible to contamination, while important segments of the Guarani Aquifer have become salinized due to overexploitation and surface water infiltration. In Peru, overexploitation of the aquifer has led to an increase in the salinity levels of the resource in Ica (Zegarra, 2018), while in Lima some wells are out of service due to the discovery of highly mineralized water affected by marine intrusion (ANA, 2016).

[5] Although it is not within the scope of this monograph, it is worth noting that groundwater plays a significant role in irrigation, contributing to food production. The assessment needs to account for the competition across various water uses.

■ ILLUSTRATION 12
Geographic distribution of groundwater resources in LAC

GROUNDWATER RESOURCES AND RECHARGE (MM/YEAR)

VERY HIGH 300 · HIGH 100 · MEDIUM 20 · LOW 2 · VERY LOW 0

- In major groundwater basins
- In areas with complex hydrogeological structure
- In areas with local and shallow aquifers

SURFACE WATER

- Major river
- Large freshwater lake
- Large saltwater lake
- Continuous ice sheet

GEOGRAPHY AND CLIMATE

- Selected city
- Selected city, partly dependent on groundwater
- Country boundary

SPECIAL GROUNDWATER FEATURES

- Area of saline groundwater (>5 g/l total disolved solids (TDS))
- Natural groundwater discharge area in arid regions
- Area of heavy groundwater abstraction with over-explotation
- Area of groundwater mining
- Selected wetland, mostly groundwater related

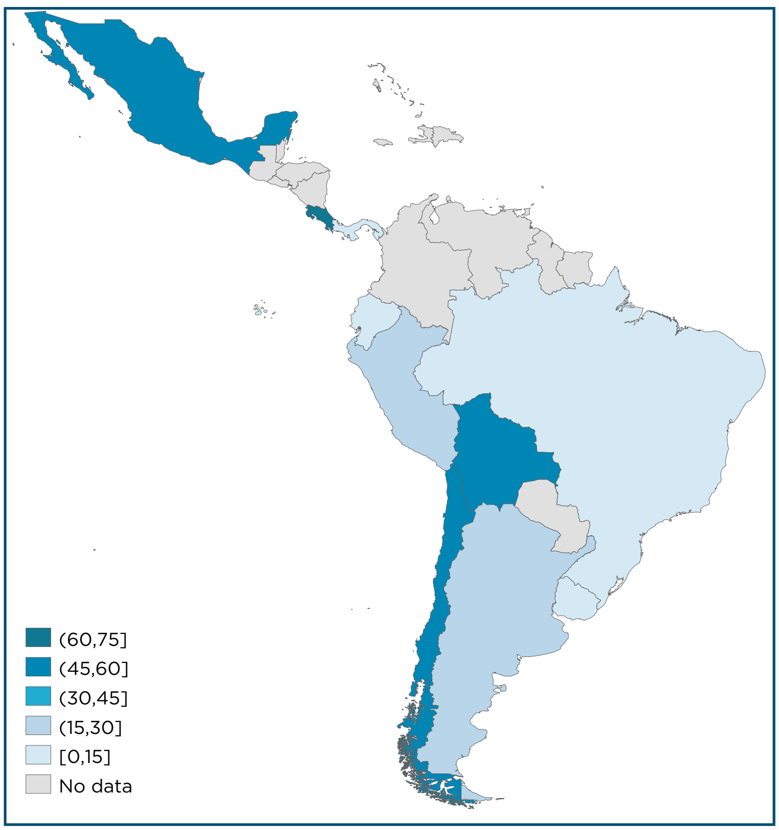
Fuente: WHYMAP (2008).

In urban areas of LAC, several water utilities use groundwater sources for partial or even total production of the water they distribute to their users. To analyze the share of groundwater in total water production, public information has been collected from different utilities in the region.

However, it is important to acknowledge that this information is limited and, in some instances, corresponds only to the largest water utilities at the national level. When data is available for multiple utilities, the determination of the national average groundwater withdrawal takes into account the size of each utility (measured by the number of connections). This weighted-average provides a more comprehensive understanding of the significance of groundwater resources in the overall production of drinking water in urban areas at the national level. The list of urban water utilities and the data used can be found in **Annex 2**.[6]

ILLUSTRATION 13

Groundwater withdrawals as a percentage of total water withdrawal in LAC urban water utilities



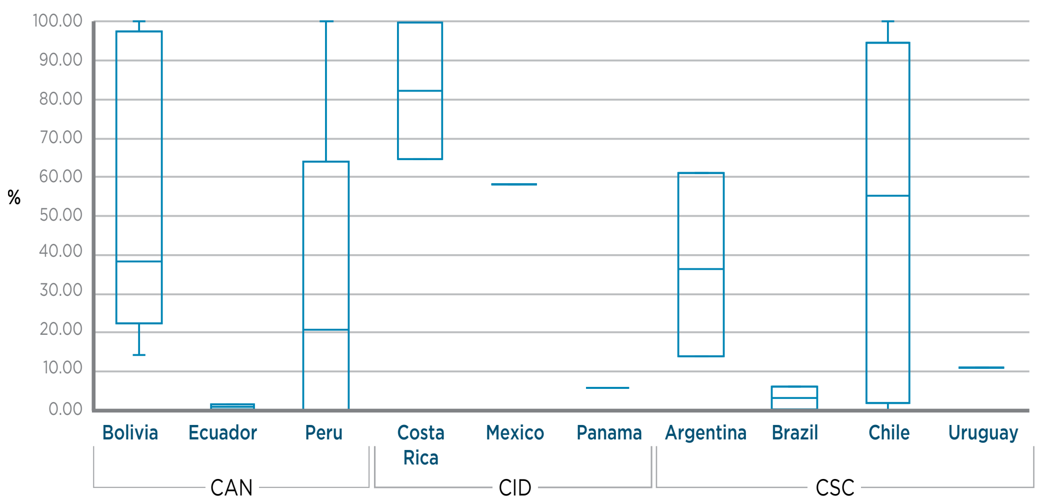
Note: Corresponds to the weighted average of the utilities for which data was found in each country, using the number of clients as the weighting factor. Sources: Aderasa - Sunass (2021), SACMEX (2022), SABESP (2021). Author's elaboration.

[6] The indicator of groundwater withdrawal reported by the utilities could include, in addition to that extracted through wells, the withdrawals from sources such as springs.

As seen in **Illustration 13**, the average percentage of groundwater use in drinking water production in a country reaches 68.1%. This corresponds to Costa Rica, where groundwater sources in AyA and Empresa de Servicios Públicos de Heredia account for 64.6% and 99.7% of total water withdrawals. Another interesting case is that of Mexico City, a megacity where 58% of the water supply comes from groundwater.[7] It is also worth noting that, although the largest water utilities in Peru (Sedapal) and Chile (Aguas Andinas) produce about one-fifth of the drinking water they distribute from groundwater sources, groundwater sources account for 100% of production in some utilities in these countries. In Bolivia, while the largest company (EPSAS, supplying La Paz) uses 15% groundwater, the next largest company (SAGUAPAC, supplying Santa Cruz) produces drinking water exclusively from groundwater sources. **Figure 1** shows the variability in the intensity of groundwater use in the companies in the region for which information has been gathered. No specific information could be obtained for countries in the Caribbean Group (CCB). However, groundwater constitutes about half of the sources used for drinking water production (UNESCO, 2022); although, due to its degradation, countries are increasingly opting to introduce water desalination technologies (Daus, 2019).

FIGURE 1

Groundwater withdrawals as a percentage of total water withdrawal in LAC urban water utilities (box and whisker plot)



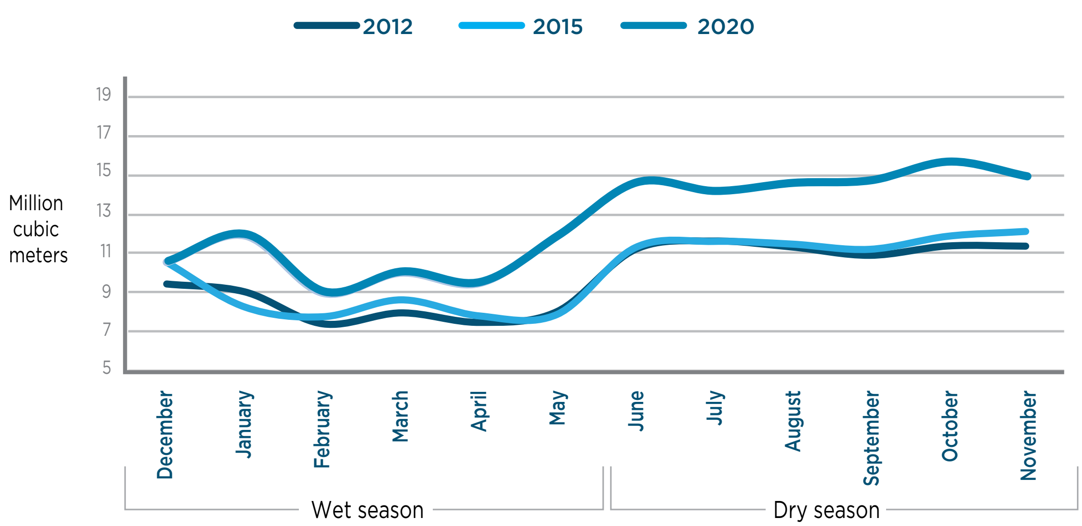
Source: Aderasa - Sunass (2021), SACMEX (2022), SABESP (2021). Author's elaboration.

CAN: Countries of the Andean Group. CID: Central American countries, Haiti, Mexico, Panama, and the Dominican Republic. CSC: Southern Cone countries.

7 According to the Mexican Institute of Water Technology (2019), 38.7% of the water used throughout the country comes from groundwater sources.

It should also be noted that the percentages shown above are annual averages. However, groundwater tends to gain more importance in certain months of the year. In the production of drinking water, utilities use an optimal combination of sources that considers the dynamics within a hydrological year. This usually consists of a wet season and a dry season. During the wet season, rainfall increases the flow of rivers (and even allows water to be stored in reservoirs), while during the dry season, rainfall reduces considerably, resulting also in a reduction of natural flows in the rivers. At this stage of the hydrological year, water utilities typically increase their use of groundwater, and they may also release stored water from reservoirs when required. **Figure 2** shows this pattern for Sedapal (Lima). Groundwater withdrawals are lower for the wet period (December - May) and increase significantly in the dry period (June - November). **Figure 2** also shows that the level of withdrawals in all months of water year 2020 was higher than in water years 2012 and 2015.

FIGURE 2
Groundwater withdrawals by periods of the hydrological year in Metropolitan Lima



Source: Information submitted by Sedapal (2021b). Author's elaboration.

Finally, it is important to mention that, in rural areas, groundwater is essential for reaching the SDGs' aim of providing safe and accessible water for all. In these areas, the low population density and distances between communities often make network-based water distribution economically inefficient, as the economies of scale found in urban areas do not apply. In such situations, the geographic distribution of groundwater allows for decentralized solutions, ensuring that households have access to a safe and affordable water supply.

Finally, it should not be ignored that groundwater extends beyond the borders of a country. This is a common phenomenon in the region and makes its management more complex. For example, according to the World Bank (2021), the Guarani Aquifer System (SAG) has an extension of more than 1.2 million km^2, a volume of 45,000 km^3, and crosses the territories of four countries: Argentina, Brazil, Paraguay, and Uruguay. Another example is the Yrendá-Toba-Tarijeño Aquifer System (SAYTT), which serves as a transboundary reservoir shared by Argentina, Bolivia, and Paraguay, with its storage and extraction capabilities still under ongoing research and analysis. Similarly, in Central America, there are 18 transboundary aquifer systems (GWP Central America, 2017).

ILLUSTRATION 14
Transboundary groundwater resources

Source: World Bank (2021).

3. Policy instruments for groundwater management

The state of aquifers is the result of discharge and recharge processes, both natural and human-induced. Consequently, effective groundwater resource management requires addressing not only the hydrogeological aspects but also user behavior. As stated by Tuinhof et al. (2010), the socioeconomic dimension is just as crucial as the hydrogeological dimension.

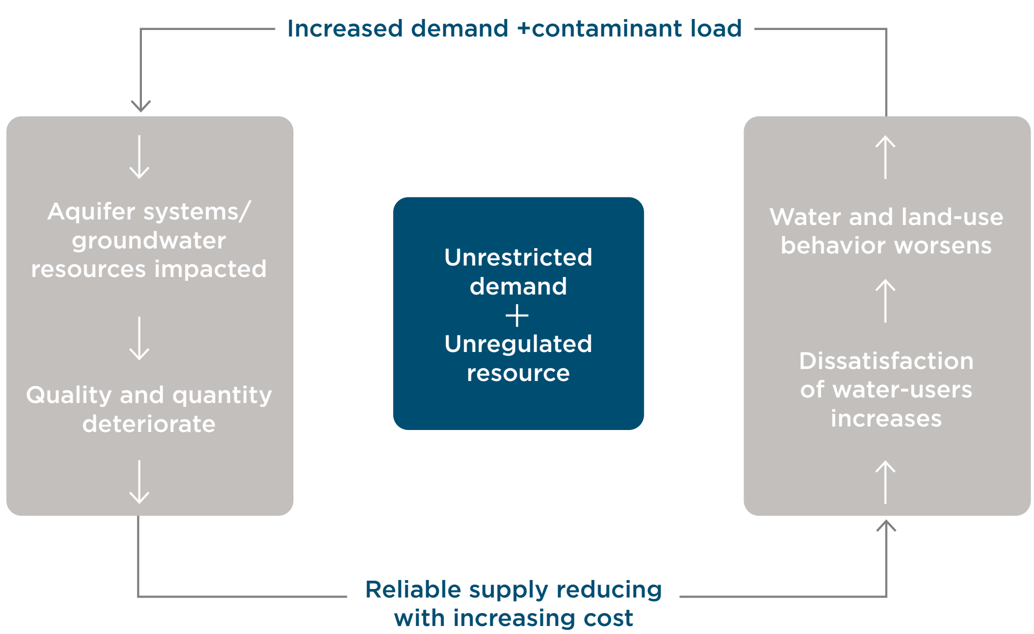
According to these authors, unrestricted groundwater demand and insufficient regulation create a vicious circle in which overexploitation leads to a reduction in water availability and contamination of aquifers. This compromises water security and increases extraction costs, generating greater dissatisfaction among users (see panel 'a' of **Illustration 15**).

This situation can be corrected to ensure the sustainability of aquifers. To this end, management measures and institutional provisions must be combined, introducing a framework for the regulation of groundwater use that allows for the allocation of rights, incentives for rational use through economic instruments, and the involvement of stakeholders, among other aspects (see panel 'b' of **Illustration 15**).

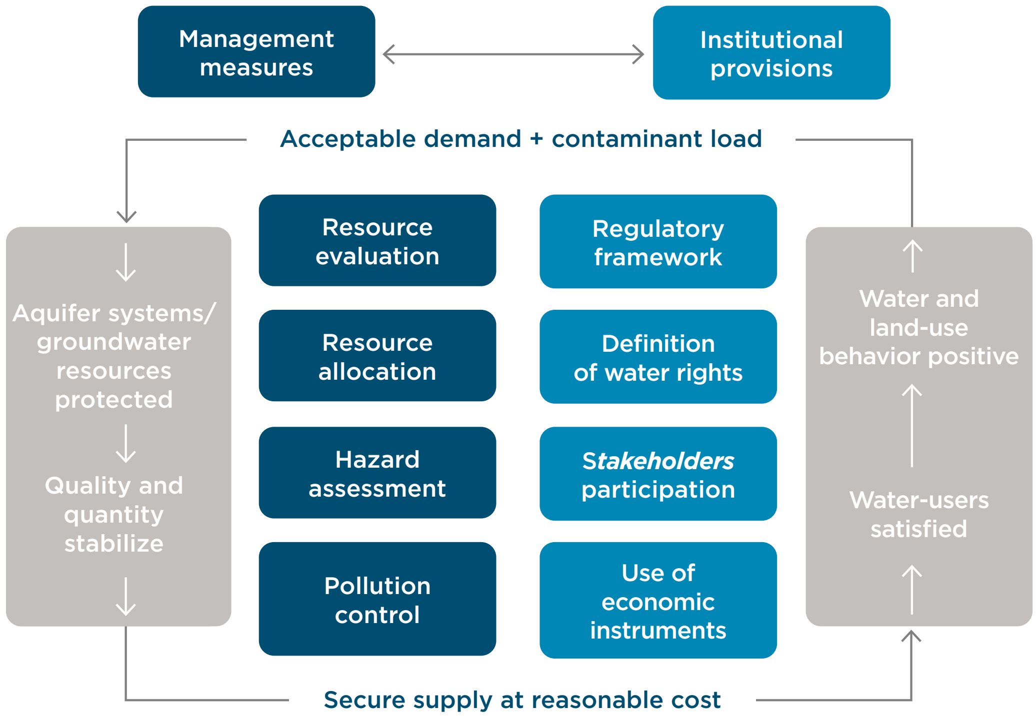
ILLUSTRATION 15

Vicious and virtuous circles in groundwater resources management

a. Vicious circle in groundwater resources management



b. Virtuous circle in groundwater resources management

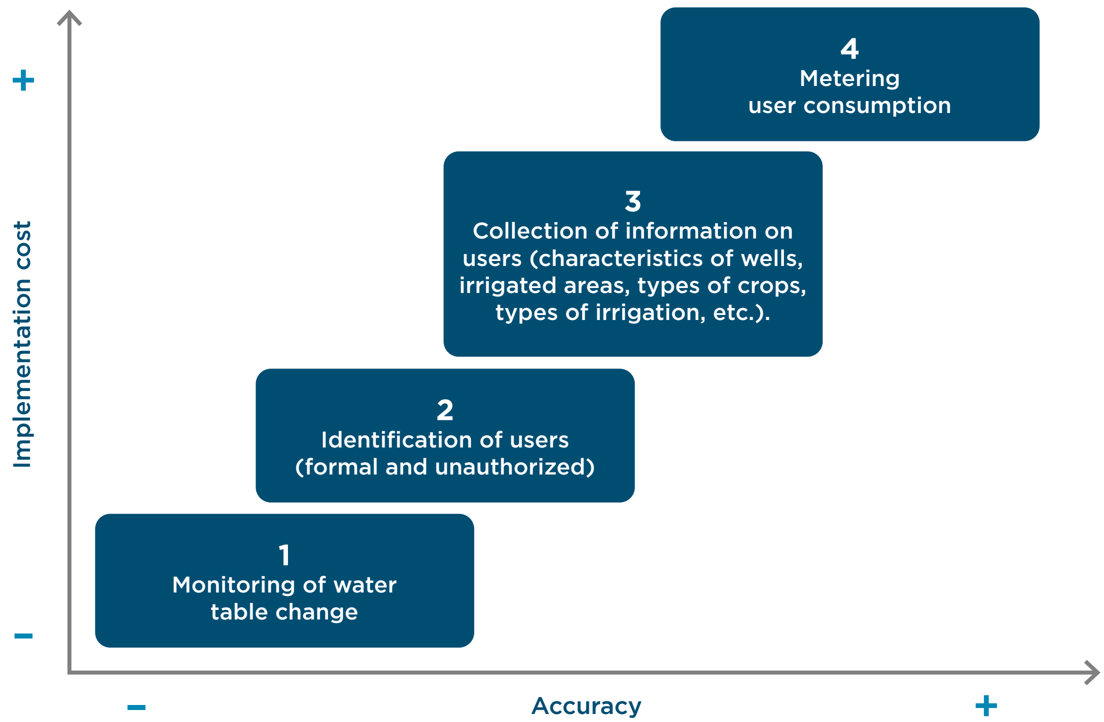


Source: Tuinhof et al. (2010).

A key element to groundwater management is the availability of information to assess whether abstractions are being made at a sustainable rate. In many countries, data on users, abstraction volumes and the groundwater table are scarce or even non-existent. According to the Intergovernmental Panel on Climate Change (IPCC), limitations in groundwater monitoring information (including information on abstractions and recharge processes) restrict the understanding of the impacts of climate change on groundwater (Caretta et al., 2022). The information available to authorities can be organized into four levels (Montginoul et al., 2016) with increasing degrees of accuracy and implementation costs (see **Illustration 16**).

The first level involves information that comes from water table monitoring. This information is fundamental for analyzing the sustainability of the aquifer, but using its variations over time as a proxy for extractions is not optimal. It can be useful for implementing restrictions on extraction upon detection of aquifer depletion. The second level of information allows to identify users. The authority needs to know the individuals or entities extracting water, whether they are authorized or operating clandestinely. This can be done through registering or self-reporting. At the third level, information on user characteristics can be collected. This includes well characteristics (e.g. horsepower), the type of industry or, in the case of agricultural users, the extent of irrigated areas, types of crops, and types of irrigation (e.g. flood, sprinkler, drip), among others. Lastly, the fourth level represents the ideal state of information, where the authority has detailed data on the consumption of each user during each period, made possible through the installation of meters.

ILLUSTRATION 16
Groundwater information ladder



Source: Author's elaboration.

Policy instruments for groundwater management can be classified into two categories: i) demand management instruments and ii) supply management instruments.

3.1.
Demand management instruments

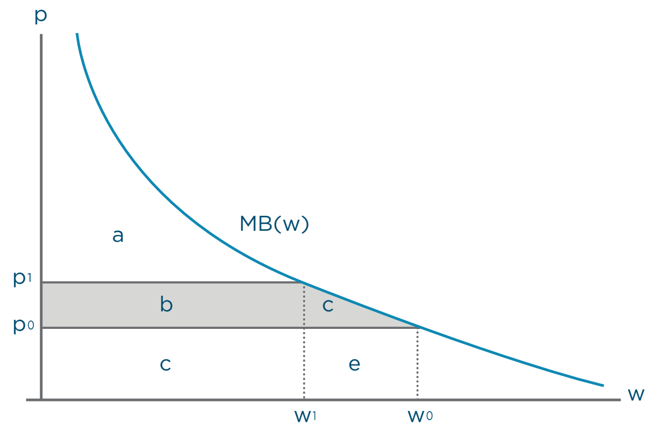
In this group we find instruments that acknowledge the importance of the socioeconomic dimension in the state of aquifers. These instruments aim to reduce the extractive pressure on aquifers. Griffin (2006) outlines policies that can be implemented from the demand side to manage water scarcity, including: i) price-based rationing, ii) quantity-based rationing, and iii) demand shifting policies.

Price-based rationing policies introduce incentives to reduce water consumption by increasing the costs incurred by users. Quantity rationing policies are usually implemented in the face of supply shortfalls and include a wide range of measures, such as the prohibition of certain water uses or a maximum ceiling on monthly consumption per user. Also included here are restrictions or prohibitions on water abstraction. Finally, demand-shifting policies seek to modify user behavior and involve a shift of the demand curve (change in the overall level of demand), rather than a movement along the demand curve. By their nature, the effects of these policies are usually seen in the medium or long term and include measures such as the promotion of water-saving habits among users and the adoption of water-efficient technologies in industry and agriculture.

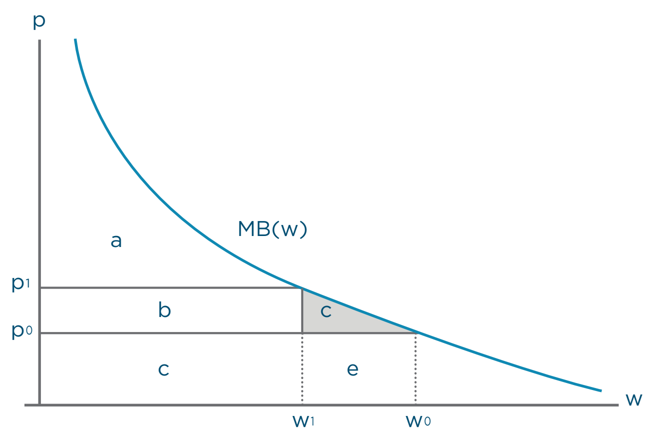
Illustration 17 depicts the welfare effect of different types of demand management policies, where the shaded areas correspond to losses in consumer surplus.

■ ILLUSTRATION 17
Effects of demand management policies on social welfare

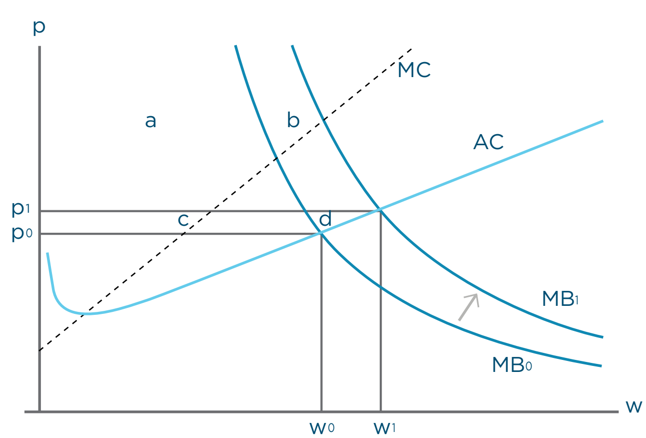
a. Effect of a price-based rationing policy on welfare



b. Effect of a quantity-based rationing policy on welfare



c. Effect of a demand-shifting policy on welfare



Source: Griffin (2006).

3.1.1. Price-based rationing instruments

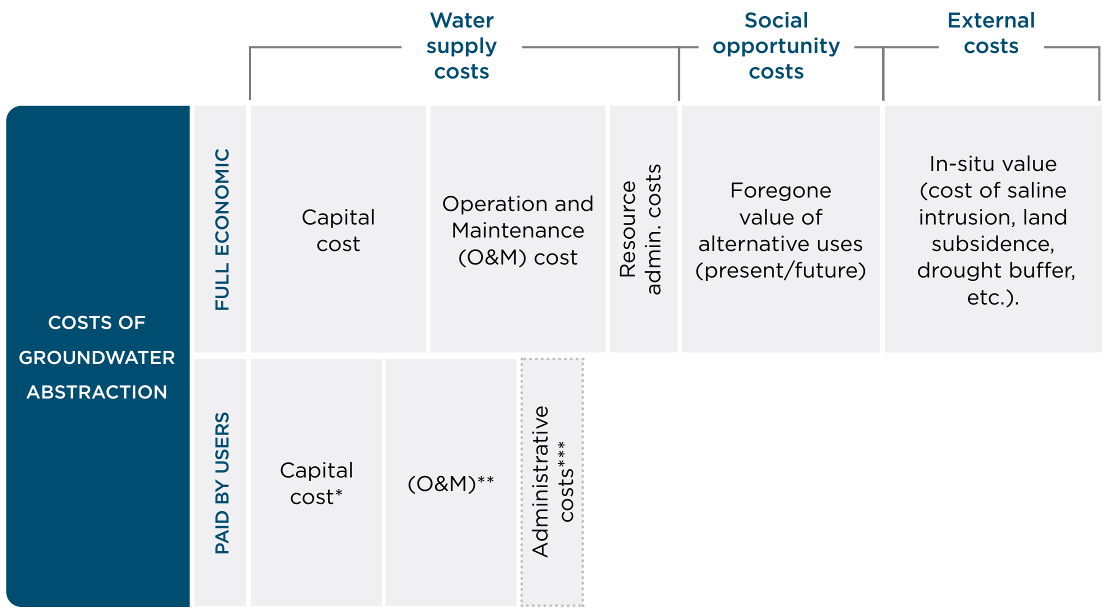
Economic instruments are "measures whose purpose is to apply incentives and market mechanisms to problems related to the environment and the management of natural resources" (Ortega, 2006). These instruments are designed and applied to adapt individual decisions to collectively-agreed objectives (Delacámara et al., 2013). The range of economic instruments is wide[8]; however, in the context of urban groundwater, prices are an important economic instrument. Ideally, they should compel private agents to consider the costs imposed on society as a whole for resource consumption, in addition to their private costs.

In the case of groundwater, users usually pay only a fraction of the capital, operation and maintenance costs and part of the administrative costs. This does not allow for the full recovery of the economic cost, which also includes the opportunity cost of foregone uses in the present and future, as well as the negative externalities caused by extraction, such as saline intrusion or land subsidence (see **Illustration 18**). According to Burnett et al. (2015), when a resource causes externalities, its marginal opportunity cost has three components: the marginal extraction cost (c in the optimal extraction model developed in **Section 1.3**), the marginal user cost (e.g., the effect on future extraction costs) and the marginal externality cost (e.g., pollution).

[8] Delacámara et al. (2013) distinguish four types of economic instruments for water management: (i) pricing mechanisms (tariffs, rates, fees, taxes, subsidies); (ii) trading of rights or authorizations, (iii) cooperative mechanisms based on voluntary adoption of new practices and, (iv) risk-based mechanisms.

ILLUSTRATION 18

The economic cost of groundwater use



* Credit is sometimes subsidized.
** Energy often subsidized.
*** Frequently not levied or do not cover real costs.
Source: Kemper et al. (2010).

An additional advantage of the introduction of economic instruments apart from their potential to discourage resource depletion, is that they can generate financial resources that can be allocated to infrastructure development, scientific and technological advancements, and enhanced resource management. Furthermore, the introduction of these instruments often leads to administrative improvements, since they require updated information on agents' groundwater extractions. (Ortega, 2006).

In urban groundwater management[9], controlling demand can involve modifying the cost of resource extraction. This can be achieved directly by adjusting abstraction fees or indirectly through changes in electricity prices (Kemper et al., 2010).

[9] According to Kemper et al. (2010), there are two categories of economic instruments applicable to groundwater. The first includes those that modify the cost of extracting groundwater, while the second corresponds to positive economic incentives. Within the latter are modifications in agricultural and food trade policies and subsidies to encourage efficient irrigation technologies. As mentioned in the introduction, this monograph focuses on urban groundwater and its potential to supply residential and industrial demands (i.e., excluding agricultural uses), so the use of (groundwater) markets for the allocation of the resource among different uses is not addressed, while the instruments of the positive economic incentives category will be mentioned in the section on demand shifting instruments. Delacámara et al. (2013) can be consulted for a comprehensive review of economic instruments for water management.

As seen in the theoretical model of optimal extraction (see **section 1.3**), there is a direct relationship between the groundwater stock and the volumetric cost of extracting groundwater. In other words, when users face higher fees, this reduces their motivation to extract, ultimately contributing to the aquifer's sustainability. Ideally, payments should be calculated based on a metered volume, rather than a volume declared by the user. However, countries often do not have information on the metered consumption of groundwater users. An alternative is to use information on electricity consumption to approximate the volume abstracted by the user (Kemper et al., 2010).

Electricity costs, which in the optimal extraction model are part of the volumetric cost of extraction, also affect the incentives to use groundwater. Consequently, it is important to highlight that subsidies on electricity prices frequently lower the extraction cost, further intensifying pressure on aquifers and diminishing the availability of groundwater resources.

3.1.2. Quantity-based rationing instruments

Quantity-based rationing can be implemented in different ways. One is the establishment of a maximum consumption limit per user, often referred as 'quotas'. The installation of meters is crucial for implementing this measure effectively, both in urban groundwater and in water used for irrigation. When meters are in place, the authority can accurately track users' consumption and impose sanctions if they exceed the authorized maximum level. However, in many countries, groundwater abstraction licensing systems still rely on affidavits or self-reported values. In such cases, the authority lacks the means to monitor users' compliance with the maximum consumption, significantly limiting the effectiveness of such systems. China's experience offers preliminary insights on the differences between quota and tiered pricing systems, although it is essential to consider the socio-political context and the design of each mechanism when interpreting the results (see **Box 4**).

Other quantity-based rationing measures, commonly employed in urban groundwater management, include temporary cessation of extraction (to allow the aquifer level to recover) and the revocation of extraction licenses or the prohibition of extraction. The latter measures are often implemented when an aquifer is declared in emergency because of unsustainable exploitation rates. To this end, the competent authorities analyze the situation of the different aquifers and establish the restricted zones (see **section 4.3** for recent experience in Chile).

BOX 4

China's experience with price rationing, quotas, and smart card innovation

According to the provisions of the Water Law in China, local authorities must regulate groundwater use in regions with overexploited aquifers. Aarnoudse and Bluemling (2017) document the experience of two cases: the counties of Minqin and Guazhou (Gansu Province) in northwest China. In both cases, smart card machines were installed in farmers' wells to monitor the extracted volume of groundwater. These machines allow farmers to use the magnetic card to turn on the pump, while the information of the extracted volume is recorded by the meter and stored on the card and the machine. The farmer can turn the pump on or off as long as the card has credit. When the credit runs out, the electrical connection is automatically interrupted, and pumping cannot resume until the credit is available again.

■ **ILLUSTRATION 19**
Smart card machine installed on a pumping station in China

Source: Aarnoudse y Bluemling (2017). Credits: E. Aarnoudse.

The installation of these machines was accompanied by a different regulation mechanism in each county. In Minqin, the authorities opted for a quota system, in which each user is assigned a maximum level of water abstraction, whereas in Guazhou, the authorities opted for a system of increasing prices that theoretically should incentivize rational abstraction of the resource. Aarnoudse and Bluemling (2017) point out that the choice of the type of mechanism and its design may be explained by the socio-political context. For example, in the case of Minqin, the central government intervened and exerted pressure to achieve targets for reducing abstractions in that county. In contrast, there was no similar pressure in the case of Guazhou.

The authors draw some important lessons. Firstly, the non-tradable quota regulation implemented in Minqin significantly restricted farmers' autonomy and, in this regard, proved to be effective in achieving the goal of reducing groundwater abstraction. Secondly, they observed that water-intensive crops are more prevalent in Guazhou compared to Minqin, primarily because farmers perceive less constraint under the tiered pricing system. However, in interpreting the latter finding, it is essential to consider the specific details of the tariff design. According to the authors, although payments increased for farmers in Guazhou, the tariff levels do not appear to be sufficiently high to induce behavioral changes. Additionally, the effectiveness of the tiered pricing system in this county is compromised as consumption is billed at the farm group level rather than at the individual user level, leading to a loss of individual incentives for reducing groundwater consumption.

3.1.3. Demand-shifting instruments

Demand-shifting policies seek to modify user behavior. Demands shifts should not be confused with movements along the demand curve. They can be understood as policies that seek to increase efficiency in the use of the resource (i.e., reducing wasteful consumption in the case of drinking water or producing the same output quantity with less water in the case of industries and agriculture). The implementation and results of these policies may require time. Consequently, their effects are anticipated to become apparent in the medium and long term.

These policies include educational campaigns and the promotion of water-saving technologies in homes, businesses and industries. An example is the set of measures implemented in Australia in the context of the Millennium Drought, where the public sector promoted rebates and appliance replacement programs for domestic users and small businesses, as well as educational programs in schools and media campaigns encouraging the rational use of water (Low et al., 2015).[10]

Implementing efficiency-oriented actions is crucial in agriculture. The IPCC underscores the fact that agriculture and irrigation represent the most substantial portion of worldwide water use, accounting for approximately 60% to 70% of total withdrawals (Caretta et al., 2022). Some measures that countries can consider—though requiring a high level of coordination—include the relocation of crops from semi-arid to humid areas or switching to less water-intensive crops, particularly in times of drought (Scanlon et al., 2023).

Other measures such as promoting irrigation efficiency (switching from flood irrigation schemes to drip irrigation or sprinklers) not only increase efficiency but can also reduce the impact on water quality caused by agricultural runoff (Scanlon et al., 2023). However, policymakers should keep in mind that these types of measures can have side effects, rendering their implementation less straightforward. For example, increasing irrigation efficiency may end up causing an expansion of irrigated areas and a net increase in water consumption at the basin or aquifer level (Scanlon et al., 2023).[11]

[10] Measures implemented included rebates and replacement programs for domestic users (showers, washing machines, toilets) and small businesses (water-saving technology). Large water-consuming companies were required to have a water management action plan with conservation targets and annual reporting. A program aimed at education in schools and the T155 water conservation campaign was launched, which sought to encourage the use per person of 155 liters, among other policies (Low et al., 2015).

[11] Scanlon et al. (2023) compare this to the Jevons paradox (i.e. increasing efficiency decreases individual consumption of a resource, but may generate an expansion in the use of technology which ends up increasing aggregate consumption of the resource).

3.2. Supply management instruments[12]

Supply management instruments include interventions that affect the hydrogeological component of aquifers, increasing groundwater availability. Some interventions directly recharge the aquifers in the upper and middle sections of the watershed. These initiatives typically entail medium and large-scale investments and activities designed to enhance natural aquifer recharge or facilitate artificial recharge (e.g., wetland conservation, water injection into the ground). On the other hand, some interventions may not prioritize aquifer recharge as their primary objective but still generate positive externalities, indirectly contributing to aquifer recharge. This latter category includes green infrastructure, as well as projects related to water transfer or water utilities replacing groundwater sources with alternative sources in drinking water production, among other approaches.

3.2.1. Aquifer recharge investments

The availability of water in urban aquifers is the product of a complex process of recharge and discharge that begins in the upper sections of the watershed. For this reason, actions aimed at the conservation and restoration of ecosystems have begun to generate growing interest. Nature-based solutions (NbS) are actions to "protect, sustainably manage and restore natural or modified ecosystems (...), simultaneously providing benefits for human well-being and biodiversity" (Cohen-Shacham et al., 2016). It is increasingly recognized that cities benefit from this type of intervention, with great potential in reducing flood and landslide risk, as well as in water provision (Oliver et al., 2021), whose costs in urban areas can be

[12] Groundwater supply management must also consider the availability of surface sources. This joint consideration in planning makes it possible to optimize the water supply and thus determine a production mix according to costs and the temporal and geographical availability of sources. This is part of Integrated Water Resources Management (IWRM), defined as the process that promotes the coordinated development and management of water, land, and related resources, to maximize economic and social welfare equitably and without compromising the sustainability of ecosystems (GWP, 2000). In this context, aquifers have a fundamental role, as they can be used as strategic reserves to cover demand in times of drought and scarcity or even store water by purifying it naturally (Arrabal and Álvarez, 2019).

reduced (Scanlon et al., 2023)[13]. In San Antonio, Texas, USA, actions are being taken to protect aquifer recharge areas, financed by a 1/8 cent sales tax that was electorally approved by its citizens (McDonald and Shemie, 2014).

NbS is a broad term that encompasses interventions that rely on nature to provide services and enhance resilience. This includes solutions different from infrastructure (such as ecosystem-based management) and natural and green infrastructure investment projects (TNC, 2019). Investment in natural infrastructure involves projects that incorporate existing or restored natural landscapes (e.g., wetlands and forests), managing them strategically to provide a range of benefits. Green infrastructure investment refers to projects designed and built in urban areas that, combined with gray infrastructure, create hybrid systems with improved resilience to climate impacts.

Available evidence in the region assesses the effectiveness of interventions in the upper sections of the watershed in enhancing water infiltration. These interventions include actions in high Andean grasslands (Mosquera et al., 2022), infiltration ditches[14] (Locatelli et al., 2020) and the construction of terraces (Willems et al., 2021), among others.

In the middle and lower sections of the watershed, interventions that contribute to aquifer recharge can also be carried out. According to WWAP - Unesco (2018), underground water storage can be enhanced through recharge or injection projects that, by constructing infrastructure or modifying the landscape, enhance the natural recharge of the aquifer and contribute to increased water security. These techniques, collectively known as Managed Aquifer Recharge (MAR), also help replenish depleted aquifers, improve water quality, and improve soil quality, among other benefits. According to Clifton et al. (2010), MAR is one of the most important adaptation opportunities for developing countries seeking to reduce their vulnerability to climate change and hydrological variability. **Table 3** presents the classifications of MAR by specific technique and method. **Annex 3** includes a graphical representation of the main specific MAR methods.

[13] In the case of New York, maintaining afforestation in the upper sections of the watershed (approximately 75% of the land) will allow the city to avoid building a treatment plant that would cost between $8 billion and $10 billion (Scanlon et al., 2023).

[14] The authors note a knowledge gap stemming from the limited number of studies assessing the impact of such interventions on water infiltration rates. Nonetheless, these interventions have been observed to notably decrease runoff and mitigate soil erosion and degradation.

TABLE 4
Classification of Managed Aquifer Recharge (MAR) techniques

TYPE OF TECHNIQUE	MAR TECHNIQUE	METHOD
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds and basins
		Controlled flooding
		Ditch, furrows, drains
		Incidental irrigation recharge
	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

Source: Prepared based on González et al. (2015) and Bonilla et al. (2018).

ILLUSTRATION 20
Artificial recharge project in the Rimac River (Lima, Peru)

Source: Sunass (2021).

In an inventory of MAR projects in Latin America and the Caribbean, Bonilla et al. (2018) identified 144 projects: in Argentina (8), Bolivia (3), Brazil (89), Chile (9), Colombia (5), Costa Rica (2), Cuba (6), Mexico (19), and Peru (3). These are shown in Illustration 21, according to the type of MAR and the level of water scarcity in the region.[15]

[15] The level of water scarcity in the region presented by the authors may be outdated, considering the dates of the sources used. For a more updated reference, we suggest reviewing Libra et al. (2022).

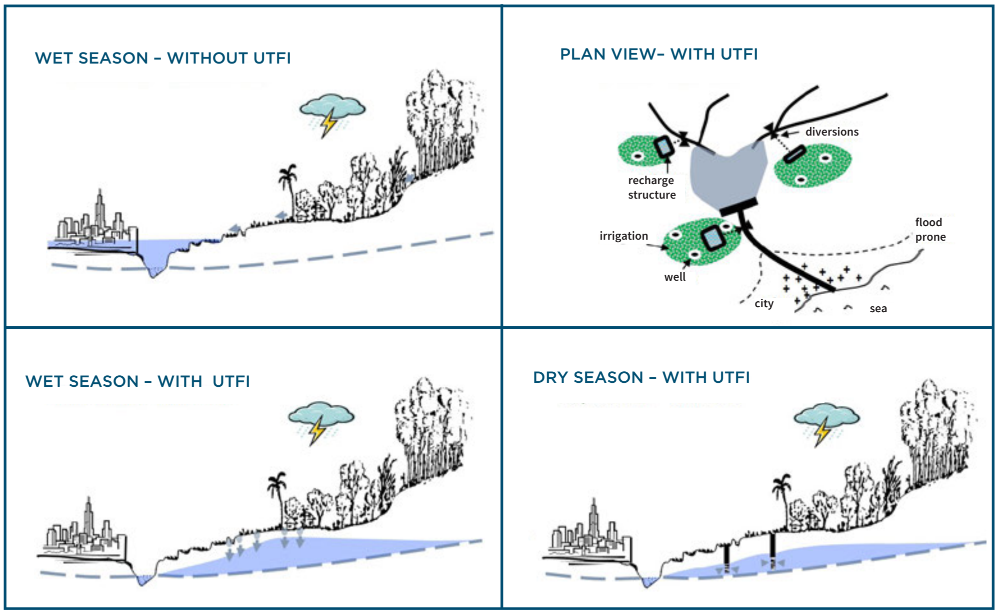
■ **ILLUSTRATION 21**
Distribution of MAR types and water scarcity in the region

Source: Bonilla et al. (2018). .

One type of MAR is underground taming of floods for irrigation, which is of particular interest to countries affected by extreme weather events and disasters in the context of climate change. This technique allows large-scale storage of flows during the wet season, reducing the vulnerability of the population to floods for subsequent use in periods of drought both for human consumption and for irrigation of agricultural areas (see **Illustration 22**).

ILLUSTRATION 22

Scheme of operation of underground taming of floods for irrigation.



Note: UTFI: Underground Taming of Floods for Irrigation.
Source: WWAP – Unesco (2018).

3.2.2. Urban green infrastructure

Aquifers receive water from the infiltration of rainwater and surface water sources. Urban planning and design are significant factors in determining groundwater availability, as they can either enhance or diminish soil permeability within urban areas.

Given this, we should consider the contribution made by Urban Green Infrastructure (UGI). This term refers to a network of nature, semi-natural areas and green spaces that provide ecosystem services, which in turn support human well-being and quality of life (European Environment Agency, 2019). Currently, there are various green infrastructure solutions that, when integrated into urban planning, have the potential to enhance aquifer recharge. These solutions also offer a range of other ecosystem services, as further elaborated in Castro Lancharro (2021a):

- **Green areas, parks, gardens and green corridors:** Urban green spaces, where trees, shrubs, and herbaceous plants are cultivated within or around cities.

- **Rain gardens, flood parks and bioretention basins:** These are ground-level depressions with planted vegetation, which serve as natural rainwater treatment areas. Bioretention basins specifically aid in the natural treatment of rainwater before it infiltrates the ground.
- **Green swales:** Shallow, wide, vegetated channels that naturally store, convey, and purify rainwater.
- **Urban riverbank parks:** Green spaces situated in natural river flood zones within urban areas, enabling excess water absorption during flooding events and reducing flood risks.

In many cases, these solutions serve to slow down the speed of runoff, thereby promoting aquifer recharge. Furthermore, many of these urban design solutions are frequently complemented by the use of permeable pavements or smart pavements, which facilitate runoff filtration (Castro Lancharro, 2021b).

ILLUSTRATION 23
Medellin River Botanical Park

Source: https://arquine.com/obra/parque-botanico-rio-medellin/. Accessed December 22, 2022.

A similar phenomenon takes place at the household level in cities with significant rainfall. Infrastructure in properties and dwellings can facilitate the infiltration of water into the ground. The example of a stormwater drainage pricing system in the United Kingdom, which includes charges and rebates, can be found in **Box 5**.

BOX 5

Stormwater charges and rebates can contribute to infiltration

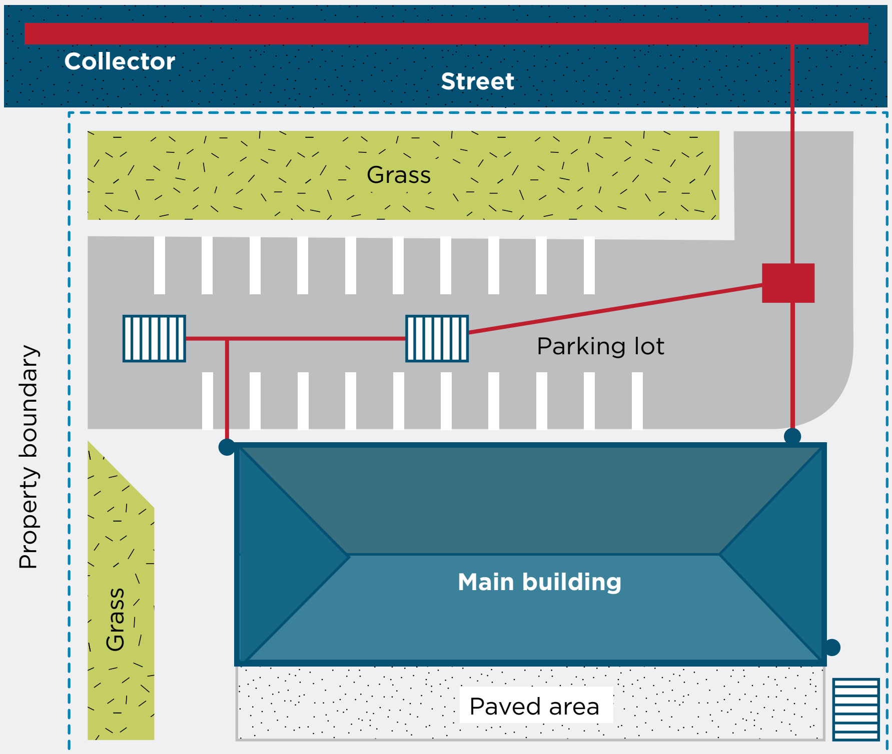
Rainfall is more frequent in certain cities, and the lack of effective management can result in problems related to road accessibility and potential flooding, adversely affecting the population. The ideal urban design for these cities should encompass a comprehensive storm drainage system that facilitates rainwater collection, conveyance, and, ultimately, either discharge or re-infiltration.

There is no one-size-fits-all model for the management of these systems. In some instances, storm drainage is overseen by water utilities; in others, it is managed directly by municipalities, while in yet other cases, it falls under the jurisdiction of municipal areas or specialized entities created for this purpose. Likewise, funding may come from various sources, including taxes and tariffs or charges. These charges can take different forms, such as fixed fees, consumption-based charges, or user-specific rates based on factors like the type of user, and more.

In the interest of efficiency, it is logical that the cost of the service should be shared by all users, with those who derive the greatest benefit from it contributing more. Thus, in 2003, the Water Services Regulation Authority in England and Wales (OFWAT) recommended that storm drainage should no longer be charged based on property value, because this was not a good indicator of the amount of rainwater that a given property imposed on the drainage system (OFWAT, 2022a). Instead, the regulator proposed charges based on the area of the property, since this variable better captures the runoff that subsequently ends up in the collection networks and, therefore, the cost that a user imposes on the system.

However, this system has been further refined by introducing rebates. Users have the option to apply for reduced payments by demonstrating that a portion or the entirety of the rainwater falling on their property does not contribute to the stormwater collection system (OFWAT, 2022b). This can be achieved, for instance, by having green areas on their property that naturally facilitate the re-infiltration of runoff (see **Illustration 24**).

■ **ILLUSTRATION 24**
Drainable and permeable areas on a property



Source: OFWAT (2022b).

This scheme introduces incentives for users to take actions that can lead to a reduction in their stormwater drainage payments. For example, users can implement soakaways to collect water and facilitate natural dispersal and drainage, or transform impermeable areas into permeable ones, which may include creating green spaces and permeable gravel parking lots. Another approach is to demonstrate that they have installed gutters to channel rainwater from their roofs to nearby green spaces or rivers (OFWAT, 2022c).

By introducing these economic instruments effectively, households are encouraged to incorporate green or permeable areas into their properties. This not only alleviates the strain on storm drainage infrastructure, minimizing the risk of flooding but also indirectly contributes to aquifer recharge through rainwater infiltration.

3.2.3. Other investments by water operators

Some of the investments that water operators make to increase coverage or improve the quality of drinking water service can also increase the recharge or recovery of aquifer levels.

The implementation of water transfers, for example, increases the availability of water in the basin and, therefore, the amount of water that will end up infiltrating naturally. Also, in many countries, to reduce the extractive stress on aquifers and allow their gradual recovery, operators invest in surface catchment sources. This includes investments in river intakes and water treatment plants, as well as the construction of seawater desalination plants (see **Illustration 25**). Having alternate water sources also contributes to the recovery of aquifer levels.

ILLUSTRATION 25
Seawater desalination plant in Atacama, Chile

Source: Government of Chile - Sistema de Empresas (SEP).

4. Case studies in LAC

4.1. Peru: Groundwater monitoring and management tariff

4.2. Costa Rica: Water use fee

4.3. Chile: declaration of restriction and prohibition zones

4.4. Chile: the water resilience plan in Santiago

Groundwater resources play a crucial role in providing water across many countries in the region. Some cities, as outlined in Chapter 2, rely entirely on groundwater for their drinking water supply. This chapter examines various groundwater policies implemented in the region, highlighting specific experiences. One of these experiences is the establishment of a special groundwater regime in Peru, where the regulatory agency sets tariffs for non-agricultural groundwater extraction. Another case is Costa Rica, which revised the water use fee to include a payment for water environmental services, aimed at funding the protection, conservation, and restoration of water recharge areas and fragile ecosystems. This chapter also includes two experiences in Chile. Firstly, it discusses the declaration of restriction and prohibition zones in aquifers, following an analysis conducted by the Chilean Water Directorate. Secondly, it covers the implementation of a Resilience Plan by Aguas Andinas, the water utility in Santiago. This plan has significantly increased the system's operational autonomy, thus improving the utility's capacity to withstand climatic shocks.

4.1. Peru: Groundwater monitoring and management tariff

The Peruvian legal system contemplates the payments to be made by individuals or entities authorized to use water. In the case of groundwater[16], these users are required to pay for two concepts with different natures: i) an economic retribution for the use of water and ii) a tariff for groundwater monitoring and management. The retribution serves as compensation for the utilization of water as a public good, while the tariff covers the cost of the service provided to users who benefit from groundwater monitoring and management (Sunass, 2017).

In 2015, the Government of Peru created the Special Regime for Groundwater Monitoring and Management in charge of the Water and Sanitation Utilities (EPS).[17] Under this new regulatory framework, the National Superintendency of Water and Sanitation Services (Sunass) was assigned the role of developing a methodology and subsequently of calculating the tariff that water utilities will charge users who

[16] See Water Resources Law (Articles 90 and 91) and its Regulations (Articles 170-179 and 189).
[17] By Legislative Decree No. 1185, published on August 16, 2015.

extract water from the aquifer. The service they provide is named groundwater monitoring and management service (GMMS). It is essential to note that this regulation initially covers non-agricultural users falling under the responsibility of an EPS and is primarily applicable to Sedapal and Sedalib, the water utilities in the Metropolitan Lima and La Libertad regions. In these areas, aquifers were reserved in favor of these utilities by previously approved legal norms. However, the regulatory framework allows for potential extension to other EPS that obtain the necessary authorization from the National Water Authority (ANA) to provide the GMMS.

Under this special regime, the EPS makes investments aimed at conserving or increasing the availability of groundwater. These investments include natural and artificial aquifer recharge actions. Additionally, they are mandated to conduct comprehensive studies and establish a robust monitoring system. This system encompasses essential components such as measuring groundwater levels, operation and maintenance of systems, metering and monitoring groundwater extraction, among others (Legislative Decree No. 1185).

In this context, it is important to define the service provided by EPS to users who extract groundwater. The GMMS has two components (Sunass, 2017):

i) Groundwater monitoring component: This includes activities and investments aimed at measuring and assessing the quality and quantity of groundwater resources.

ii) Groundwater management component: This includes those activities and investments that improve or increase groundwater availability. In some cases, these are carried out as part of the provision of drinking water and sanitation services but have a positive externality on the aquifers (which must be remunerated). In other cases, these activities and investments are carried out explicitly to recover or preserve the aquifers.

Sunass approved the methodology, principles and criteria for determining the GMMS tariff (see **Illustration 26**). The first criterion considered is that of reliability in the provision of water services. This means that, considering that population supply is the priority, the tariff must contribute to the EPS ensuring sufficient quantity and quality of groundwater. The second criterion is the economic and financial sustainability of the provision of groundwater resources, which means that the tariffs charged should allow the EPS to recover all the costs incurred in providing the GMMS. This means that tariff calculation will allow recovering costs of activities and investments that support or increase water infiltration and that reduce the extractive pressure on the aquifer (such as the exploitation of alternative water sources). The third criterion is the opportunity cost to users of the lack of water availability. As previously mentioned, the economic cost of abstraction also includes the value of foregone present and future alternative uses. In the case of Peruvian regulations, this means that tariff calculation will use, as a maximum limit, the cost that users would incur if the EPS did not carry out actions and investments to make groundwater available. Finally, the criterion of willingness to pay enables tariff setting to consider the user's valuation of groundwater extraction, which depends on the benefit obtained and the capacity to substitute this resource for other alternatives (Sunass, 2016).

ILLUSTRATION 26
Principles and technical-economic criteria applicable to the calculation of the tariff

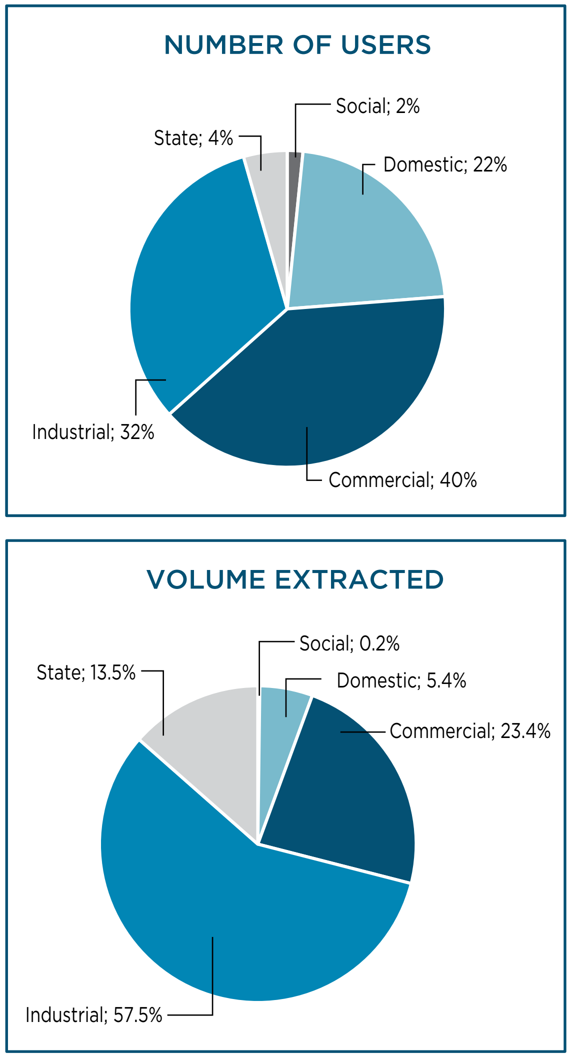
PRINCIPLES	TECHNICAL-ECONOMIC CRITERIA
1. Economic efficiency 2. Financial viability 3. Simplicity 4. Transparency 5. Non-discrimination	1. Reliability in the provision of water services 2. Economic and financial sustainability of the provision of groundwater resources 3. Opportunity cost for users of not having groundwater availability 4. Willingness to pay of users

Source: Resolution N° 007-2016-SUNASS-CD. Author's elaboration.

In both 2017 and 2021, Sunass set the tariffs for the GMMS provided by Sedapal. As of December 2020, a total of 1,751 users in Metropolitan Lima must pay the associated tariffs. Out of this user base, 40% fall within the commercial category, while 32% are classified under the industrial category. A closer examination of the extracted volume reveals that industrial users are responsible for a significant 57% share of the over 58 million cubic meters extracted by non-agricultural users in total, as reported by Sunass in 2021.

■ **FIGURE 3**

Percentage of users and volume of groundwater withdrawn by category (Lima)



Source: Sunass (2021). Author's elaboration.

In calculating the tariff for the GMMS in compliance with the approved technical-economic criteria, Sunass considered both the operating, maintenance and capital costs of activities directly related to this service. Sunass also partially considered costs associated with conjunctive use, which indirectly contributes to recharging aquifers and reducing the extractive pressure on them. These include drinking water treatment plants, as well as water transfers and the implementation of a desalination plant, implemented through public-private partnership contracts. **Table 5** shows the GMMS tariffs currently in force in Sedapal's service area.

TABLE 5
Tariffs for groundwater monitoring and management service (Sedapal)

CATEGORY	RANGE (m^3/month)	TARIFF (USD/m^3)
Social	0 to more	0.13
Domestic	0 to 30	0.15
	30 to more	0.54
Commercial and others	0 to 100	0.54
	100 to more	0.63
Industrial	0 to 400	0.81
	400 to more	0.95
State	0 to 2000	0.54
	2000 to more	0.63

Note: Rates do not include value-added tax. The exchange rate used is 1USD=3.85PEN.
Source: Sedapal (2022).

The first aspect to analyze is the impact of the new tariffs on the amount paid by non-agricultural groundwater users. Prior to the introduction of the new regime, Sedapal imposed a tariff on these users, representing 20% of the drinking water and sewerage tariff applicable to users connected to the network (Sunass, 2017). **Table 6** displays a calculation of the monthly billing impact for commercial and industrial users who extract groundwater. The increase resulting from the implementation of the new tariffs in 2017 ranges from 2.8% on average for low-consumption commercial users (40m^3 on average) to 67.9% for high-consumption industrial users (more than 6 thousand m^3 per month, on average). In 2022, the approved tariffs recorded a cumulative increase of 32% in relation to the level previously established in 2017.

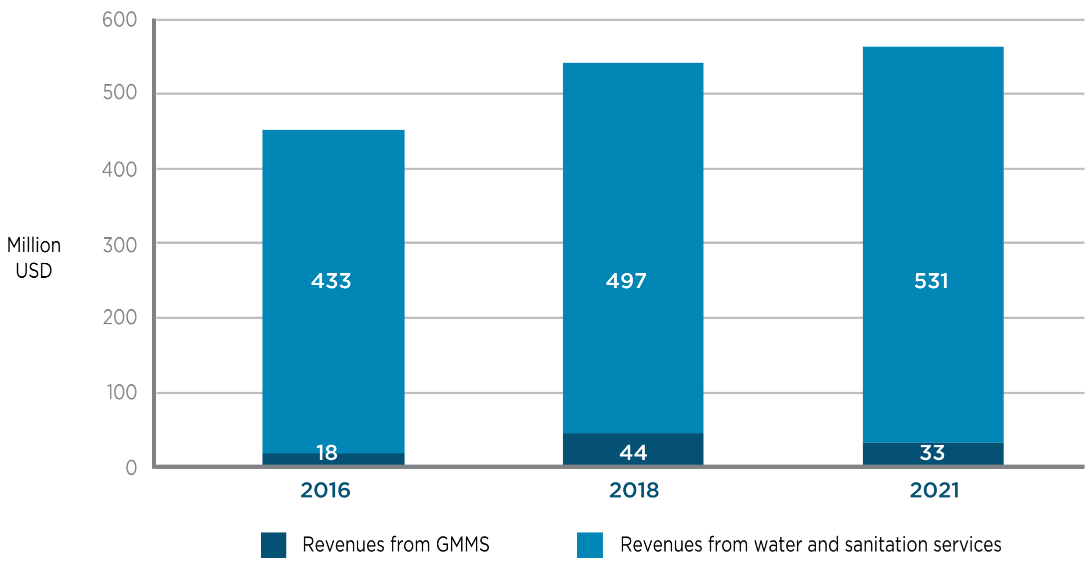
TABLE 6
Impact of the approval of the new GMMS tariffs on commercial and industrial users

CATEGORY	NUMBERS OF USERS	CONSUMPTION RANGE	AVERAGE CONSUMPTION (m^3, pre tariff 2017)	BILLING				
				PRE TARIFF 2017	POST TARIFF 2017		2022	
				USD	USD	Δ%	USD	Δ%
Commercial	465	0 to 100	40	15.80	16.25	2,8%	21.48	32,2%
	337	100 to more	2,546	1,050.12	1,200.09	14,3%	1,585.46	32,1%
Industrial	340	0 to 400	83	35.17	51.05	45,2%	67.48	32,2%
	466	400 to more	6,306	2,672.11	4,487.61	67,9%	5,930.53	32,2%

Note: Rates do not include value-added tax. The exchange rate used is 1USD=3.85PEN.
Source: Author's elaboration based on information from Sunass (2017) and Sedapal (2022).

A second aspect to review is the impact of the approval of the new regime on Sedapal's operating revenues. As can be seen in **Figure 4**, revenues from groundwater user charges in 2018 are 2.5 times the revenues recorded one year before implementation of the new tariffs (i.e., in 2016). Despite this significant increase, the vast majority of Sedapal's revenue, as expected, comes from billing for water and sanitation services to users connected to the network. In 2021, GMMS billed revenues accounted for 6% of the utility's total revenues.

FIGURE 4
Evolution of Sedapal's annual operating revenues



Source: Author's elaboration based on Sedapal's Audited Financial Statements. The exchange rate used is 1USD=3.85PEN.

Finally, publicly available information does not permit the analysis of two aspects that could be explored in greater depth. The first is the effectiveness of tariffs as an economic instrument. Although it may be too early to measure the effect on aquifer recovery, a start can be made by analyzing the impact on the average consumption of users (i.e., the impact on water extraction). This will make it possible to evaluate whether the approval of tariffs under the new regime has introduced incentives for the efficient use of water resources. A second aspect pending study is to analyze the progress in the implementation of activities and investment projects related to the GMMS. Although tariff approval is accompanied by an investment program, it is necessary to evaluate progress in the formulation and execution of investment projects, which in some cases correspond to natural infrastructure.

The establishment of tariffs is an important step in contributing to the sustainable exploitation of aquifers in Peru. The pending agenda entails bolstering the institutional capacity of operators in different regions across Peru, enabling them to obtain the necessary authorization and capabilities to be in charge of groundwater monitoring and management services. Also, the existing legal framework excludes agrarian users from the regime. However, it is necessary to include these users and their incentives in the analysis. The problem must be addressed with an approach that integrates the different uses and combines economic instruments, demand-shifting policies (encouraging irrigation efficiency, for example) and supply-side policies (aquifer recharge). An important case in Peru is the Department of Ica, where the overexploitation of aquifers puts the regional economy (which relies on agro-industrial activity) at risk. Thirty five percent of the groundwater extracted at the national level comes from that region (Sunass, 2017), and there is a decline in the level of aquifers that may compromise their sustainability.

4.2. Costa Rica: Water use fee

In Costa Rica, the water use fee (*canon por aprovechamiento de agua*) was first introduced in the Water Law passed in 1942. Decades after its implementation, the Ministry of Environment and Energy (MINAE) proposed a reform based on a diagnosis of the problems they identified. One such problem demonstrated that the fee value set was too low to provide a disincentive to inefficient consumption. Likewise, the fee was designed as decreasing block tariffs, which were a function of a range of flow (liters per second) rather than the actual consumption made by the user (Ortega, 2006). **Table 7** presents the structure of the fee for domestic use before the reform.

TABLE 7
Groundwater use fee for domestic purposes (before the reform)

RANGE (liters per second)	ANNUAL AMOUNT (USD)
From 0 to 0.10	16.16
Excess of 0.10 to 0.25	14.14
Excess of 0.25 to 0.50	12.12
Excess of 0.50 to 1	10.10
Excess of 1 to 5	8.08
Excess of 5 to 10	6.06
Excess of 10 to 15	4.04
Excess of 15 to 20	2.02
From 20 onwards	1.01

Note: Plus USD 0.10 per liter per second for control and monitoring.
The exchange rate used is 1USD=495CRC (as of December 2005 according to the Central Bank of Costa Rica).

Source: Ortega (2006).

According to MINAE (2016), there were four main issues with the water use fee before the reform:

i) It granted a minimum value to the resource.

ii) It promoted resource hoarding and sub-optimal utilization.

iii) It considered only administrative costs.

iv) Many large users did not pay for it.

These shortcomings are indicative of an approach that remains prevalent in many countries. This approach involves the establishment of administrative fees with the aim of collecting a minimum amount to fund customer service activities. However, it does not incorporate incentives to ensure the efficient use of the resource or its availability in terms of quantity, quality, and timeliness.

In 2006, the environmentally-adjusted water use fee (*canon ambientalmente ajustado de aprovechamiento del agua*) fee was approved by decree 32868-MINAE. The reform established this new fee as an economic instrument for the regulation of water use and management, thus allowing the availability of water for different uses. The new fee comprises two components: i) payment for the right to water use, and ii) payment for environmental water services. The collection of the first component is used for administrative expenses, control, monitoring, planning, etc., while the second component finances the costs of protection, conservation and restoration of recharge areas and water fragility (Ortega, 2006; MINAE, 2016).

The environmentally-adjusted water use fee was approved with differentiation between surface and groundwater, for eight different uses (human consumption, industrial, commercial, agro-industrial, tourism, agriculture, aquaculture, and hydro power). The fee also uses the volume extracted as the unit of measurement, as can be seen in **Table 8**, which displays the domestic fee approved after the reform.

TABLE 8
Groundwater use fee (after the reform)

USE	USD/M^3	
	SURFACE WATER	GROUNDWATER
Domestic consumption	0.0025	0.0028

Note: The exchange rate used is 1USD=588CRC (in effect as of December 2022 according to the Central Bank of Costa Rica).

Source: MINAE (2016).

Currently, the Water Directorate collects the fee and transfers it to the various institutions for the purposes listed in **Table 9**.

TABLE 9
Allocation of the fee to institutions in Costa Rica

INSTITUTION	PERCENTAGE	OBJECTIVE
National System of Protected Natural Areas	25%	Carry out projects for the protection of water resources.
National Forest Financing Fund	25%	Carry out projects oriented to the Payment of Environmental Services.
Committee for the Management and Planning of the Reventazon River Basin	5%	Regulate the planning, execution, and control of water conservation activities in the upper Reventazón River Basin.
National Water Directorate	45%	Carry out projects aimed at optimizing water resource management.

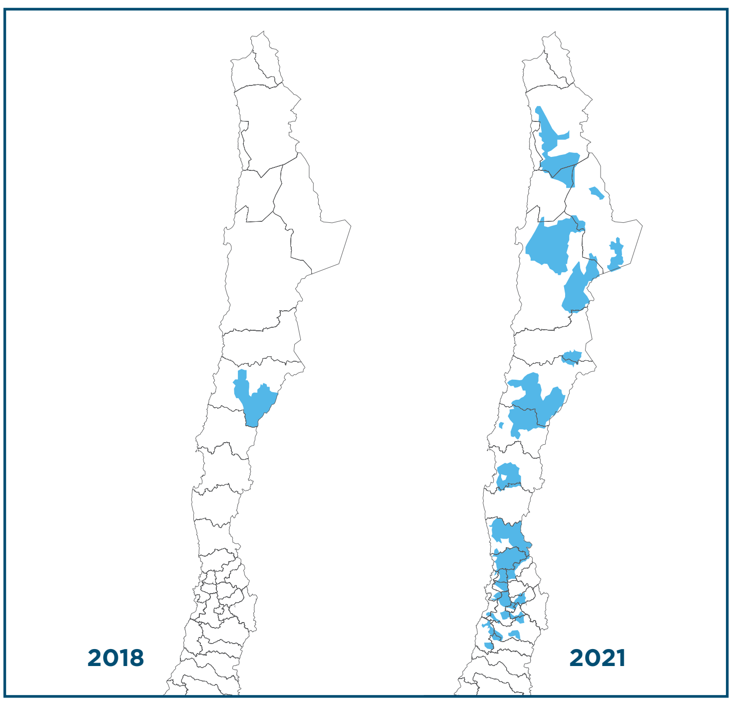
Source: Water Directorate (2022). Author's elaboration.

4.3.
Chile: Declaration of restricted and prohibited areas

In the case of Chile, the General Directorate of Water has two instruments to protect the state of aquifers. In cases of serious risk, the authority declares a restriction area, allowing only for provisional use rights to be granted. In cases where the sustainability of the resource is compromised, the authority declares a prohibition zone, making it impossible to grant exploitation rights.

Currently, there are 197 aquifers declared as a restriction area, which represents 53% of the aquifers in the country, while the prohibition zones in Chile have increased notably between 2018 and 2021 (**Illustration 27**). This was a consequence of a detailed study of the state of groundwater, after which the aquifers with prohibition status increased from 6 to 100 (Government of Chile, 2021).

ILLUSTRATION 27
Zones with declaration of prohibition in Chile (2018 and 2021)



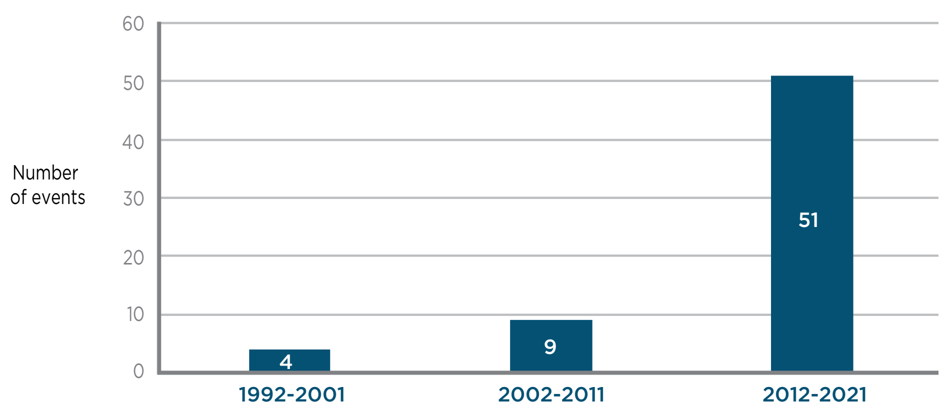
Source: Government of Chile (2021).

4.4. Chile: The water resilience plan in Santiago

The provision of drinking water services is particularly affected by the effects of climate change, which are becoming more frequent and intense. One such effect is the increase in rainfall that causes the displacement of materials and, in the case of the water utility in the city of Santiago de Chile, increases the turbidity level of the Maipo and Mapocho rivers (Aguas Andinas, 2021). Extreme turbidity events have increased considerably in recent years (see **Figure 5**), which severely limits the possibility of treating surface sources. As a result, the utility has proposed to increase the autonomy of drinking water supply to 48 hours through the implementation of a resilience plan.

FIGURE 5

Frequency of extreme turbidity events in Santiago de Chile

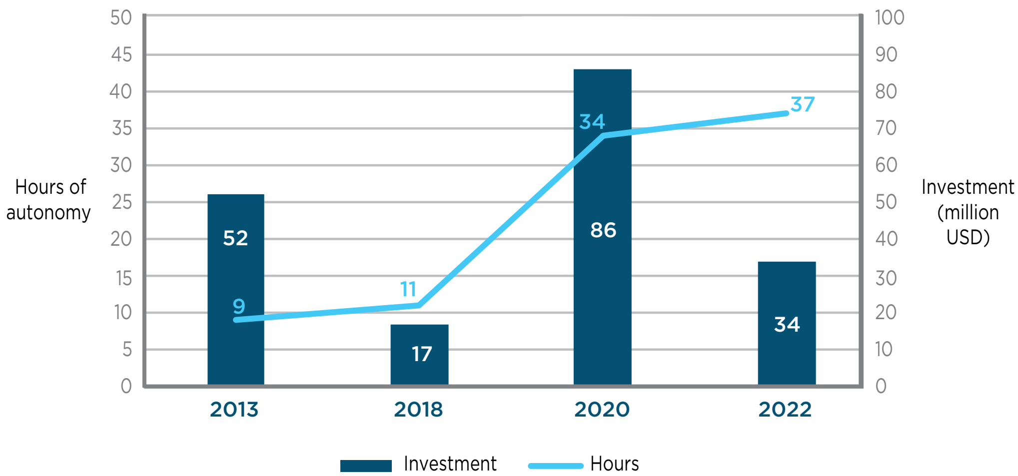


Source: Aguas Andinas (2021). Author's elaboration. Nephelometric Turbidity Unit (UNFT) is the indicator used to measure turbidity. Extreme turbidity events are considered to be those with a duration of more than 12 hours over 3,000 UNT and peaks over 5,000 UNT.

As part of this comprehensive plan, the initial phase (involving an investment of USD 52 million) extended the autonomy from 4 hours in 2011 to 9 hours in 2013. This phase encompassed the construction of 7 new wells and 14 water storage ponds. Subsequently, the second stage (with a budget of USD 17 million) introduced 16 new wells and established 9 water storage ponds, resulting in an increased autonomy of 11 hours. The third and most extensive phase, which marked a pivotal achievement in the plan, saw the implementation of the Pirque Mega Ponds (with an investment of USD 86 million), culminating in an autonomy of 34 hours by 2020. Finally, investments in the Cerro Negro - Lo Mena wells, situated to the south of Santiago (USD 34 million), elevated the autonomy to 37 hours by 2022.

FIGURE 6

Resilience Plan investments and increased hours of autonomy in Santiago de Chile



Source: Aguas Andinas (2021), Aguas Andinas (2020). The exchange rate used is 900CLP/USD. Author's elaboration.

BOX 6

The role of groundwater in access to water in rural schools in Uruguay

The Cooperation Fund for Water and Sanitation (FCAS) is an instrument of the Spanish Cooperation, managed in collaboration with the Inter-American Development Bank. It develops programs for institutional strengthening, community development and promotion of water and sanitation services in 18 LAC countries, focusing on rural and peri-urban areas.

In Uruguay, the FCAS has financed the Rural Drinking Water and Sanitation in Schools Program, which has provided access to water and sanitation in 325 rural communities in the country's 18 departments (Olmedo and González, 2022). With the installation of the respective wells, it has been possible to guarantee education in hygienic conditions for students, increasing attendance and punctuality to classes. In addition, some wells use solar-powered pumping systems, making them a clean and sustainable solution.

5. Conclusiones

1. Groundwater is essential for economic activity and human development in Latin America and the Caribbean.

Groundwater is a natural resource that is essential for human activities: it supplies drinking water to rural and urban populations, is an important input for industrial activities, and allows irrigation of agricultural land, thus contributing to food security. It can represent a significant percentage of the drinking water distributed in megacities such as Mexico City (58%), and even 100% in other cities in the region.

2. Groundwater offers several advantages for population water supply.

The use of groundwater sources for supplying drinking water offers several notable advantages when compared to surface sources. First, groundwater extraction and treatment typically incur lower costs in contrast to the extensive infrastructure and processes needed for purifying water from rivers or the sea. The second advantage lies in the decentralized nature of groundwater sources. This decentralization enables the production of drinking water closer to areas of demand, resulting in reduced losses during conveyance and distribution. These characteristics make groundwater an appealing option for addressing gaps in access to safely managed water, particularly in rural settings. The third advantage is that they tend to be a more stable source, as they do not depend as heavily on climatological factors such as rainfall.

3. Aquifers face a significant threat from unsustainable exploitation due to population growth and deforestation.

Aquifers have faced increasing pressure from extractive activities, primarily as a result of demographic and economic growth, and this situation has been further exacerbated by the impacts of climate change. Furthermore, urban development and deforestation significantly impact the patterns of aquifer recharge. The unsustainable exploitation of groundwater has consequences such as the reduction of available water (for current and future service provision) and contamination of the water resource (saline intrusion), which can render certain aquifers unusable and compromise water security.

4. Overexploitation of aquifers also results in land subsidence, which can cause serious problems in cities.

Excessive groundwater pumping also leads to aquifer compaction and subsequent land subsidence. In Mexico City, this subsidence can be as high as 40 centimeters per year. This phenomenon not only results in uneven terrain within urban areas but also exerts stress on water distribution and sewerage systems. Consequently, it contributes to elevated levels of physical water losses, an increased risk of flooding, and the potential for contamination of both drinking water sources and aquifers.

5. In the context of climate change, groundwater is a strategic natural asset that acts as a reserve and ensures the resilience of the water service during extreme weather events.

Cities are vulnerable to extreme weather events and disasters that occur with greater frequency and intensity in the context of climate change (Cavallo et al., 2020). When surface water sources are adversely affected by events like droughts (resulting in reduced availability) or heavy rainfall and landslides (leading to increased turbidity or damage to intakes), groundwater assumes the role of a natural reservoir. It ensures the continuous supply of drinking water services, effectively providing cities with an essential resilience factor. In other words, groundwater gives cities the ability to provide water services autonomously for several hours, without the need for surface sources.

6. Groundwater resources are common-pool resources requiring regulation to ensure their sustainability.

Without any groundwater regulation, individuals tend to base their extraction decisions solely on their private benefits and costs. This results in excessive extraction, surpassing the sustainable level and causing resource depletion—a phenomenon referred to as the "tragedy of the commons" (Hardin, 1968). In In such a scenario, we can anticipate the emergence of a vicious circle where both the availability and quality of the water resource diminish, while the dissatisfaction among water users continues to grow. It is necessary to regulate groundwater, considering different types of instruments. Addressing this issue requires a systematic approach, underpinned by robust institutional capacities, effective coordination among governmental entities, and the establishment of a comprehensive information system (Ortega, 2006).

7. Prices should reflect the full economic costs of groundwater extraction to encourage sustainable use.

It is not uncommon to find groundwater users who do not pay for the full economic costs of their extractions. In many cases, what they pay is not even enough to cover capital, operation and maintenance costs. Let alone other parts of economic costs such as opportunity costs (due to reduced present and future availability) and the externalities that extraction imposes on third parties (aquifer contamination, land subsidence, and impact on public services). Additionally, since electric power for pumping is an important part of extraction costs, tariffs that are too low may encourage a level of extraction that is not optimal. Groundwater extraction fees or tariffs should also encourage rational and sustainable use of water resources.

8. Cities can employ tools like extraction restrictions or bans as necessary.

Groundwater users sometimes lack meters, which should be addressed for more effective pricing policies. When authorities identify a sustained decrease in aquifer water levels, they can resort to instruments such as partially or completely limiting groundwater extraction. For instance, in Chile, the number of aquifers with extraction prohibitions increased from 6 in 2018 to 100 in 2021.

9. Integrated groundwater management should include demand-shifting policies to promote efficiency in all water uses.

Population growth, urbanization, and growth in food demand will increase the current pressure on aquifers in the coming decades. One way to reduce this pressure is to implement policies that seek to "shift demand", by increasing efficiency in water use. In urban water demand, this implies promoting more efficient technologies in households and industry and carrying out behavioral change campaigns. However, the importance of agriculture in water consumption cannot be ignored. It accounts for between 60% and 70% of global withdrawals. Consequently, strategies should be implemented in this sector, including crop relocation, seasonal changes to less water-intensive crops, and the promotion of efficient irrigation, among others.

10. On the supply side, cities should consider projects for aquifer recharge in upper and middle watershed areas, including investment in natural infrastructure.

Underground water storage is an ecosystem service provided by aquifers that can be enhanced through activities and investment projects. Globally, efforts to conserve and restore ecosystems are gaining momentum because of their ability to secure water resources and lower service costs. Countries should advocate a blend of policies supporting or enhancing recharge in upper watershed areas, Managed Aquifer Recharge (MAR) projects, and initiatives conducted by water operators to boost water availability in watersheds and reduce extractive pressure on aquifers.

11. Urban green infrastructure can also boost groundwater availability.

Urban design can enhance soil permeability within cities. This not only mitigates flood risks during heavy rainfall but also fosters water infiltration and augments groundwater availability. At the household level, implementing stormwater charges and rebates based on permeable surfaces can incentivize residents to reduce pressure on drainage systems, further promoting infiltration.

12. Integrated groundwater management requires adequate governance, inter-institutional coordination, and information for decision-making.

The cases examined in this document underscore the vital role of governance and information in shaping policies for the sustainable management of aquifers. It is imperative for countries to reevaluate their regulatory frameworks and institutional structures, integrating groundwater regulations into comprehensive water resource management. This process should prioritize coordination among various sectors (such as agriculture, energy, mining, and industry) and different levels of government. Additionally, in many countries, data related to users, extraction volumes, and water table levels are either limited or non-existent. Leveraging innovation and technological advancements is crucial to acquire detailed and comprehensive information. This rich data can then inform the design of effective policies aimed at ensuring the sustainable utilization of groundwater resources.

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6. Annexes

Annex 1.
The evolution of the static water level of wells operated by Sedapal (Lima, Peru).

For the analysis of changes in the water levels of wells operated by Sedapal, we used a database provided by this utility (Sedapal 2021b). This has information on the static level and monthly dynamic level for each of the wells, as well as information on pumping hours and the district of location.

We chose to analyze the average static level of the wells at the district level because, unlike the dynamic level, this indicator is less sensitive to temporal changes such as the monthly extraction level. By definition, changes in the static level of a well are expected to reflect medium or long term changes resulting from the dynamics of discharge and recharge of the aquifer.

The following table displays the average static level of wells per district for each year within the 2011-2020 period. The final columns provide data on the changes in static levels, including absolute values (in meters) and relative values (in percentage), along with the calculated average annual change in meters.

It is important to emphasize that the static levels of wells in a district are influenced by factors such as topographic elevation and the historical extraction patterns of wells. Therefore, while absolute static levels may provide insights into resource exploitation, the primary aim of this exercise is not to draw comparisons between districts but rather to examine the decade-long evolution of static well levels within each district.

ANNEX 1.

Evolution of the average static water level of wells operated by Sedapal (2011 - 2020)

DISTRICT	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
ATE	38.3	35.5	33.2	32.6	29.9	31.4	30.6	31.0	33.3	32.4
BARRANCO	46.5	46.0	46.2	45.9	46.8	47.1	47.5	46.2	45.2	49.4
BELLAVISTA	19.2	19.7	20.5	20.4	23.1	24.6	24.7	21.9	24.5	23.8
CARMEN DE LA LEGUA	24.0	22.8	25.1	26.0	27.3	29.9	30.8	31.1	31.0	32.1
CALLAO	13.1	14.2	14.3	15.4	15.3	17.2	17.8	17.6	16.3	18.4
CARABAYLLO	15.0	15.3	15.9	16.3	15.4	19.6	15.8	15.6	16.2	17.4
CHACLACAYO	8.2	7.0	7.0	8.0	8.4	8.4	8.7	7.7	7.9	7.9
CHORRILLOS	24.4	23.3	22.0	21.8	22.1	23.2	23.7	24.2	24.7	25.6
CIENEGUILLA	7.6	8.9	8.7	9.2	8.8	9.8	9.9	10.3	11.5	10.9
COMAS	12.0	13.0	13.3	14.1	12.9	13.3	15.7	13.7	13.8	14.4
EL AGUSTINO	31.3	30.4	24.8	25.9	26.8	27.3	24.4	25.1	28.5	29.4
LA MOLINA	59.0	57.7	57.7	57.0	56.6	56.4	58.1	58.7	62.6	58.2
LA PUNTA	3.6	3.0	4.2	2.3	2.6	4.2	3.1	3.5	3.7	5.2
LIMA	57.0	56.3	56.7	57.2	56.7	58.7	57.4	55.9	59.2	61.0
LINCE	84.6	84.1	84.5	82.2	N/A	83.8	86.0	86.0	87.1	86.8
LOS OLIVOS	14.2	13.8	14.6	17.3	17.4	17.9	18.9	16.2	16.8	11.7
LURIGANCHO - CHOSICA	11.9	12.4	12.5	13.3	13.2	14.7	14.9	14.9	16.1	14.7
LURIN	5.6	5.0	5.6	6.2	8.3	8.1	9.7	9.0	9.4	9.9
MIRAFLORES	64.2	62.5	62.1	62.0	61.9	63.1	65.4	65.0	66.6	68.3
PACHACAMAC	5.5	6.1	6.7	7.2	7.1	8.8	10.1	9.9	11.4	10.9
PUCUSANA	74.0	74.8	75.5	75.6	77.6	76.2	77.4	76.6	76.5	78.9
PUEBLO LIBRE	53.6	53.4	54.0	53.2	53.6	55.4	54.9	55.0	55.8	56.1
PUENTE PIEDRA	7.2	8.5	8.8	10.1	10.0	10.0	11.7	11.1	11.6	11.6
SAN MARTIN DE PORRES	22.3	25.9	23.5	24.6	24.6	27.7	22.6	25.9	25.4	29.0
SAN BORJA	84.9	83.3	83.5	82.5	85.5	82.2	83.7	82.6	83.6	82.2
SAN ISIDRO	74.4	73.5	73.7	74.6	75.2	72.8	76.1	75.0	75.4	77.1
SAN MIGUEL	36.3	36.3	36.8	36.7	36.7	38.3	38.8	38.5	38.3	39.9
SANTA ANITA	42.1	42.4	42.4	43.9	46.3	46.0	46.9	46.4	47.7	48.2
SAN JUAN DE LURIGANCHO	31.8	27.1	31.6	32.0	30.3	31.0	29.8	29.4	33.6	34.4
SURCO	61.1	61.8	59.6	61.9	62.8	61.8	63.4	63.4	64.6	64.1
SURQUILLO	68.3	69.2	68.9	71.7	71.3	73.1	73.4	73.1	74.8	75.1

(continued)

DISTRICT	CHANGE 2011-20 (METERS)	CHANGE 2011-20 (%)	ANNUAL CHANGE (METERS/YEAR)
ATE	6.0	-16%	▲ 0.7
BARRANCO	-2.9	6%	▼ -0.3
BELLAVISTA	-4.7	24%	▼ -0.5
CARMEN DE LA LEGUA	-8.1	34%	▼ -0.9
CALLAO	-5.4	41%	▼ -0.6
CARABAYLLO	-2.4	16%	▼ -0.3
CHACLACAYO	0.3	-4%	▬ 0.0
CHORRILLOS	-1.1	5%	▼ -0.1
CIENEGUILLA	-3.3	44%	▼ -0.4
COMAS	-2.4	20%	▼ -0.3
EL AGUSTINO	2.0	-6%	▲ 0.2
LA MOLINA	0.8	-1%	▲ 0.1
LA PUNTA	-1.6	44%	▼ -0.2
LIMA	-4.1	7%	▼ -0.5
LINCE	-2.3	3%	▼ -0.3
LOS OLIVOS	2.5	-17%	▲ 0.3
LURIGANCHO - CHOSICA	-2.8	24%	▼ -0.3
LURIN	-4.3	76%	▼ -0.5
MIRAFLORES	-4.1	6%	▼ -0.5
PACHACAMAC	-5.4	98%	▼ -0.6
PUCUSANA	-4.8	7%	▼ -0.5
PUEBLO LIBRE	-2.5	5%	▼ -0.3
PUENTE PIEDRA	-4.4	61%	▼ -0.5
SAN MARTIN DE PORRES	-6.7	30%	▼ -0.7
SAN BORJA	2.6	-3%	▲ 0.3
SAN ISIDRO	-2.7	4%	▼ -0.3
SAN MIGUEL	-3.6	10%	▼ -0.4
SANTA ANITA	-6.1	15%	▼ -0.7
SAN JUAN DE LURIGANCHO	-2.6	8%	▼ -0.3
SURCO	-3.0	5%	▼ -0.3
SURQUILLO	-6.8	10%	▼ -0.8

Source: Author's elaboration based on information submitted by Sedapal (2021b).

Annex 2.
Groundwater withdrawals as a percentage of total water withdrawal in LAC water utilities

COUNTRY	WATER UTILITY	PERCENTAGE OF TOTAL WITHDRAWALS (%)	CONNECTIONS
Argentina	Agua y Saneamientos Argentinos	13.96	2,253,952
Argentina	Agua y Saneamiento Mendoza	36.28	347,306
Argentina	Compañía Salteña de Agua y Saneamiento	61.09	318,866
Bolivia	EPSAS	14.36	429,794
Bolivia	SAGUAPAC	100.00	248,476
Bolivia	SELA	95.35	82,404
Bolivia	SEMAPA (Cochabamba)	30.07	76,466
Bolivia	COSAALT	38.40	41,212
Brasil	SABESP	6.00	9,840,000
Brasil	Aguas de Juturnaiba	0.14	83,368
Chile	Aguas Andinas	19.46	1,238,598
Chile	ESSBIO	52.00	737,943
Chile	ESVAL	55.34	440,142
Chile	Nuevo Sur	94.54	258,574
Chile	Empresa de Servicios Sanitarios de los Lagos	68.14	233,561
Chile	Aguas Araucanía	72.17	215,902
Chile	Aguas del Valle	67.17	194,067
Chile	SMAPA	100.00	179,409
Chile	Aguas de Antofagasta	1.95	123,830
Chile	Aguas del Altiplano	100.00	113,115
Chile	Aguas Chañar	100.00	92,718
Chile	Aguas Cordillera	13.47	57,522
Chile	Aguas Magallanes	0.00	51,917
Chile	Aguas Décima	0.00	43,127
Chile	Aguas Patagonia de Aysén	0.00	28,344
Costa Rica	AyA	64.58	667,752
Costa Rica	Empresa de Servicios Públicos de Heredia	99.74	73,162
Ecuador	EPMAPS	1.50	650,007
Ecuador	Interagua (Guayaquil)	0.27	558,472
Mexico	SACMEX	58.00	2,000,000
Panama	IDAAN	5.90	672,159
Peru	Sedapal	18.98	1,586,330
Peru	SEDAPAR	12.80	323,264
Peru	SEDALIB	47.96	186,596
Peru	EPS Tacna	33.38	97,063

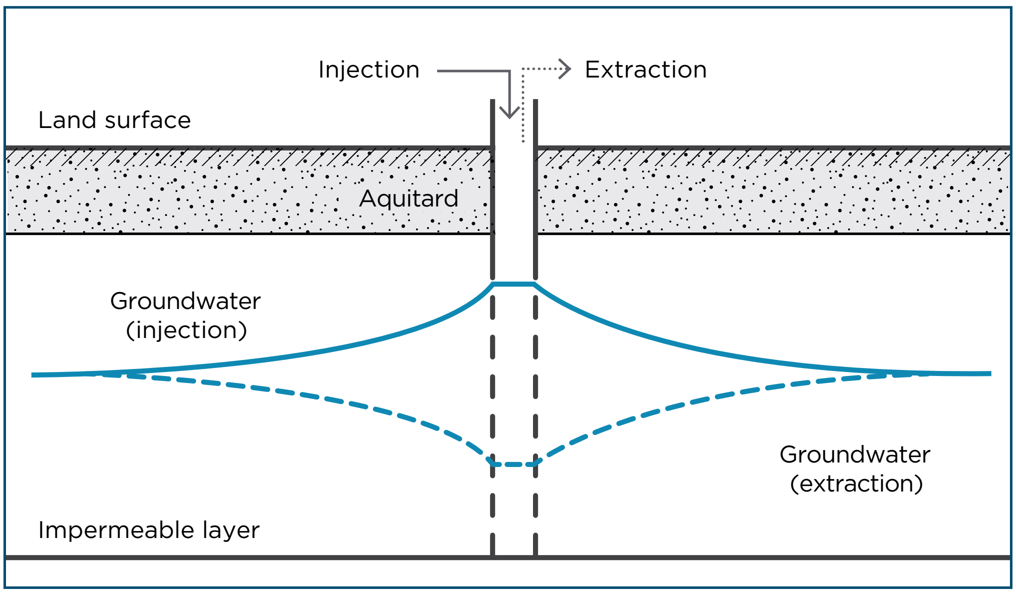
(continued)

COUNTRY	WATER UTILITY	PERCENTAGE OF TOTAL WITHDRAWALS (%)	CONNECTIONS
Peru	Sedaloreto	0.00	95,358
Peru	Sedacusco	60.14	94,036
Peru	Sedachimbote	64.84	92,278
Peru	Sedaayacucho	0.00	62,858
Peru	Sedajuliaca	0.00	58,986
Peru	Emapica	100.00	58,148
Peru	Semapach	86.46	52,101
Peru	Emapa San Martín	0.00	50,416
Peru	Agua Tumbes	34.18	47,522
Peru	Sedacaj	0.00	46,314
Peru	Seda Huánuco	24.53	44,920
Peru	Emsapuno	2.43	43,798
Peru	Emapa Cañete	73.91	39,364
Peru	EPS Chavín	0.00	32,183
Peru	Emapacop	29.83	31,722
Peru	Aguas de Lima Norte	100.00	31,505
Peru	EPS Ilo	0.00	27,214
Peru	EPS Selva Central	9.18	26,902
Peru	Emapisco	100.00	25,707
Peru	EPS Moquegua	25.55	23,310
Peru	EPS Barranca	44.99	19,344
Peru	EMAPAT	0.00	19,289
Peru	Emapa Huaral	61.84	18,716
Peru	Empssapal	0.00	17,377
Peru	Emusap Abancay	100.00	17,087
Peru	Moyobamba	0.00	15,055
Peru	Emapa Pasco	0.00	12,967
Peru	Emapa Huancavelica	0.00	10,917
Peru	Emapavig	97.42	9,300
Peru	Epssmu	22.55	8,753
Peru	Emaq	0.00	8,369
Peru	Emusap Amazonas	0.00	8,333
Peru	Aguas del Altiplano	0.00	7,407
Peru	EPS Rioja	0.00	7,288
Peru	Emsap Chanka	100.00	5,637
Peru	Emapab	0.00	5,580
Peru	Emapa Y	0.00	5,480
Peru	Emsapa Calca	100.00	4,560
Peru	Emsapa Yauli	100.00	3,537
Uruguay	OSE	10.82	1,171,730

Fuente: Aderasa - Sunass (2021), SACMEX (2022), SABESP (2021). Author's elaboration.

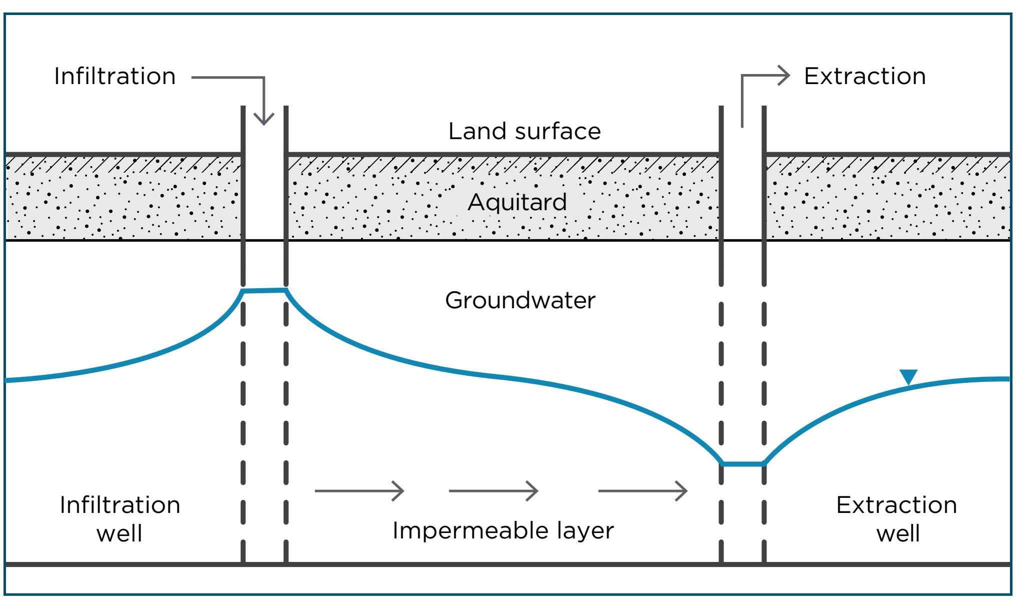
Annex 3.
Graphical representation of the main MAR methods

Aquifer Storage and Recovery (ASR)



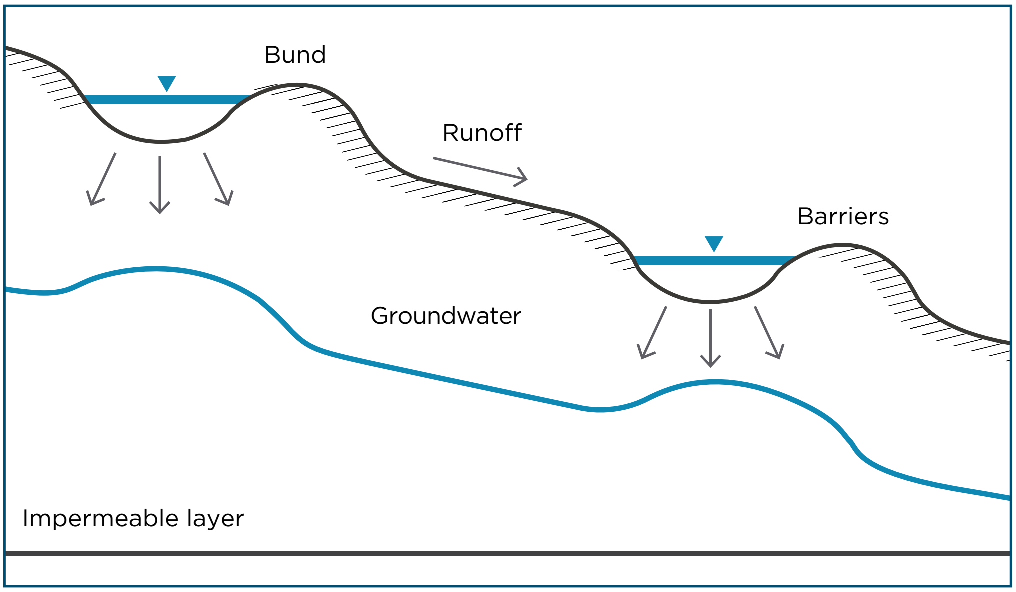
Source: INOWAS (2022)

Aquifer Storage, Transfer and Recovery (ASTR)



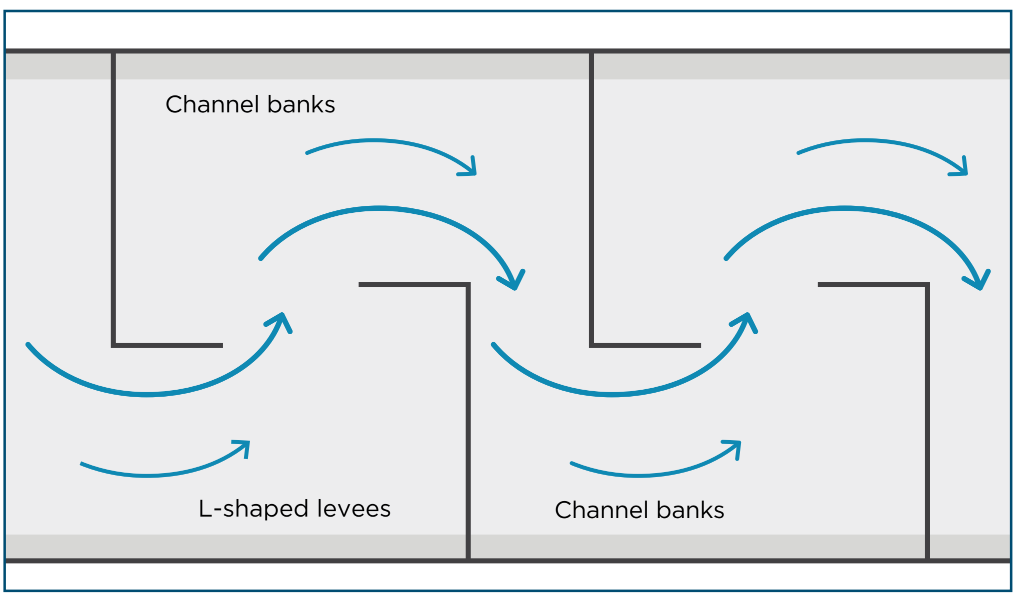
Fuente: INOWAS (2022)

Barriers and bunds



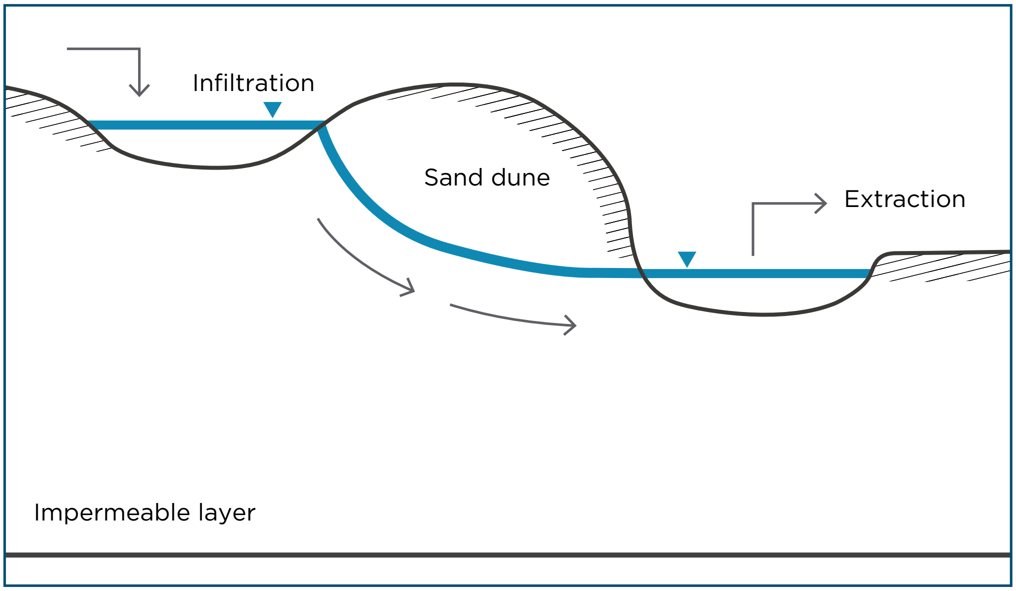
Source: INOWAS (2022)

Channel spreading



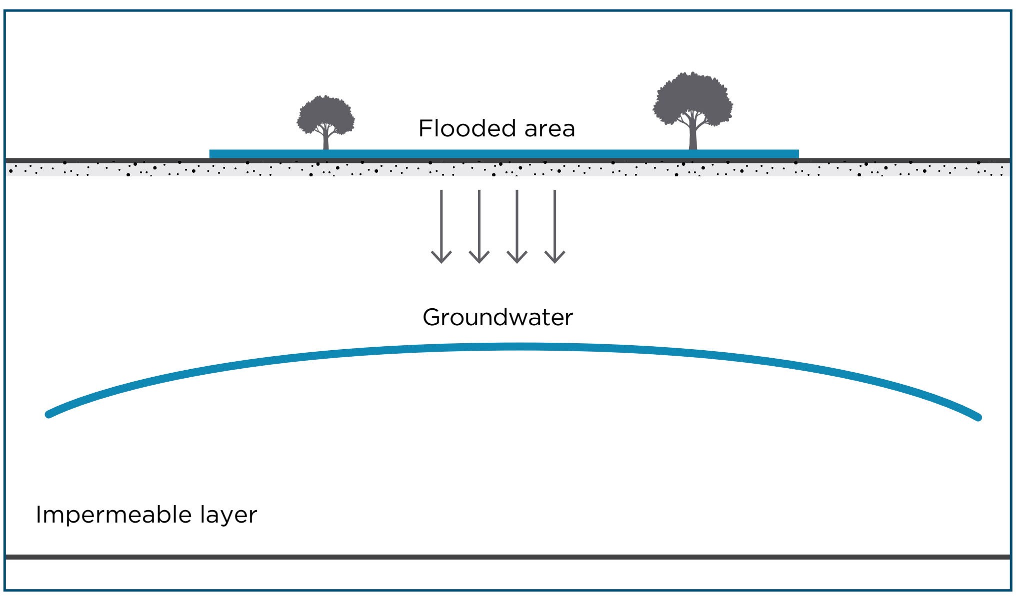
Source: INOWAS (2022)

Dune filtration



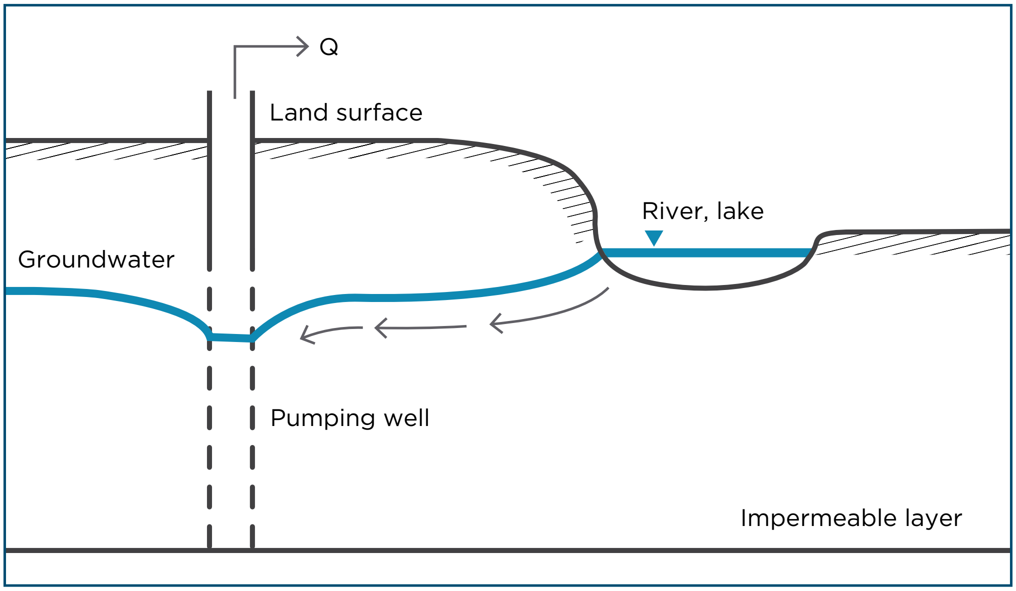
Source: INOWAS (2022)

Controlled flooding



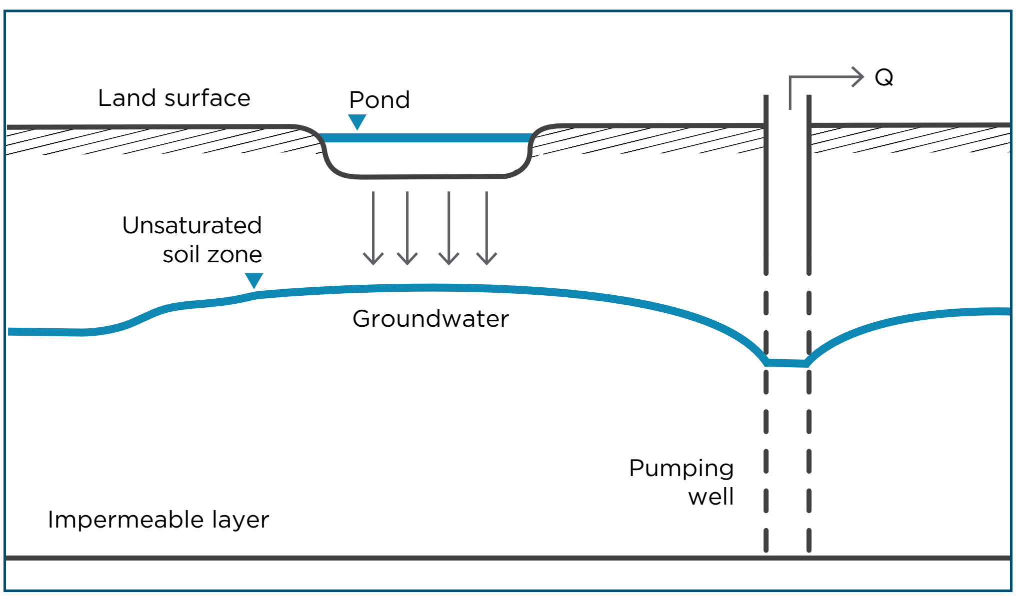
Source: INOWAS (2022)

Induced bank filtration



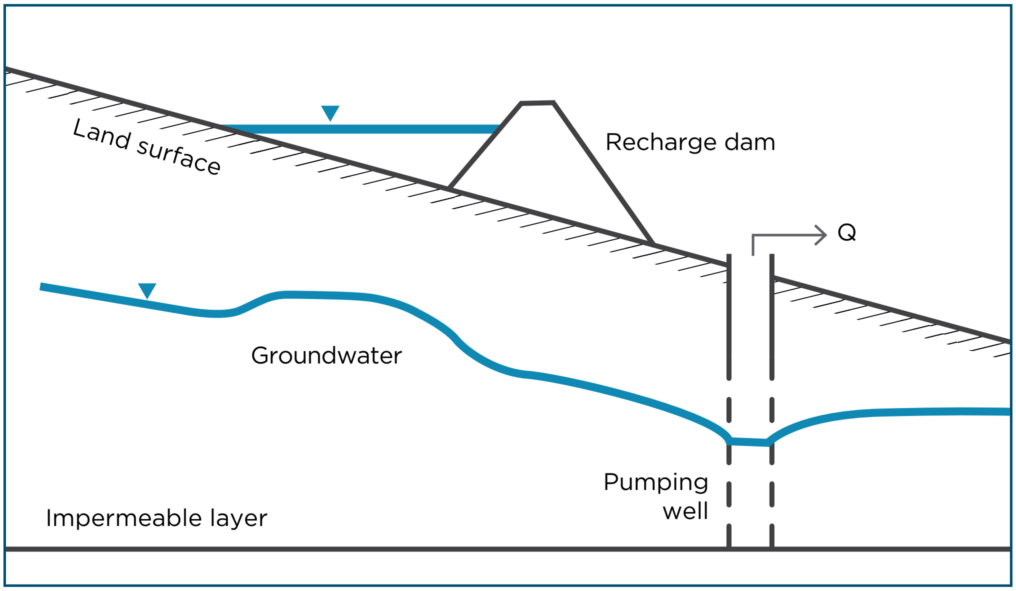
Source: INOWAS (2022)

Infiltration ponds and basins



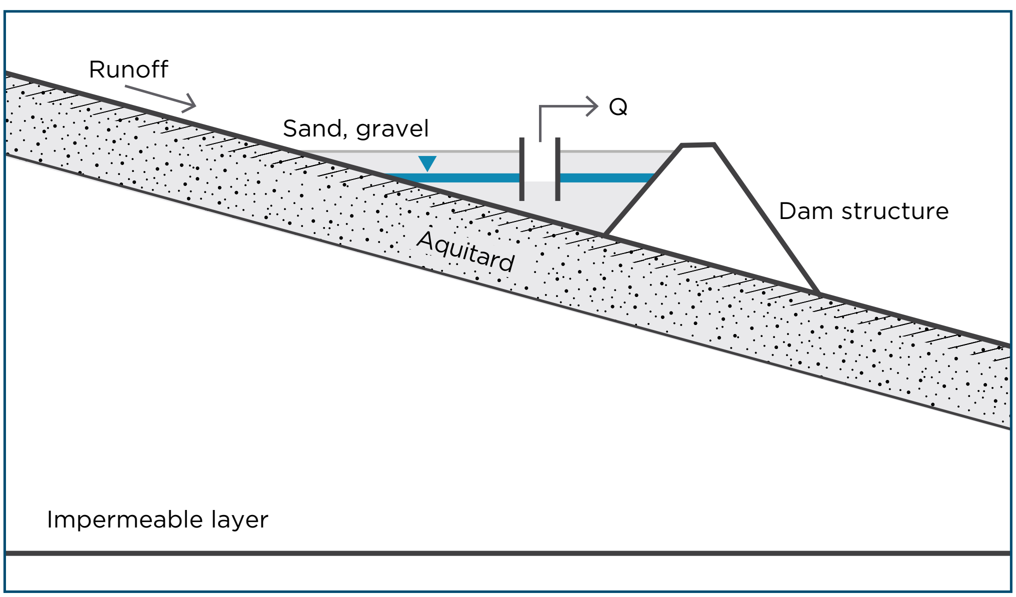
Source: INOWAS (2022)

Percolation ponds



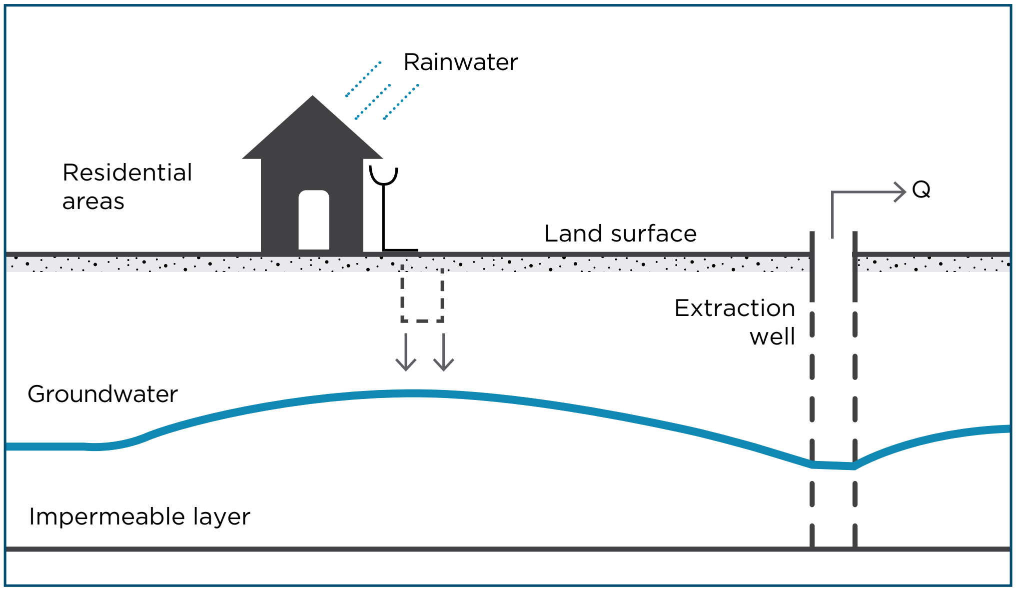
Source: INOWAS (2022)

Sand dam



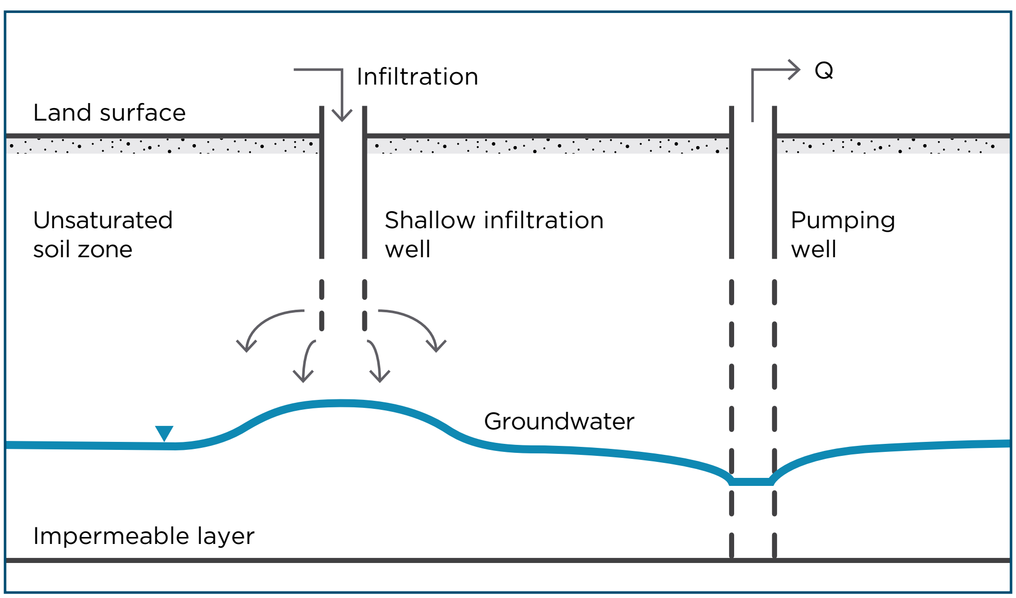
Source: INOWAS (2022)

Rooftop rainwater harvesting



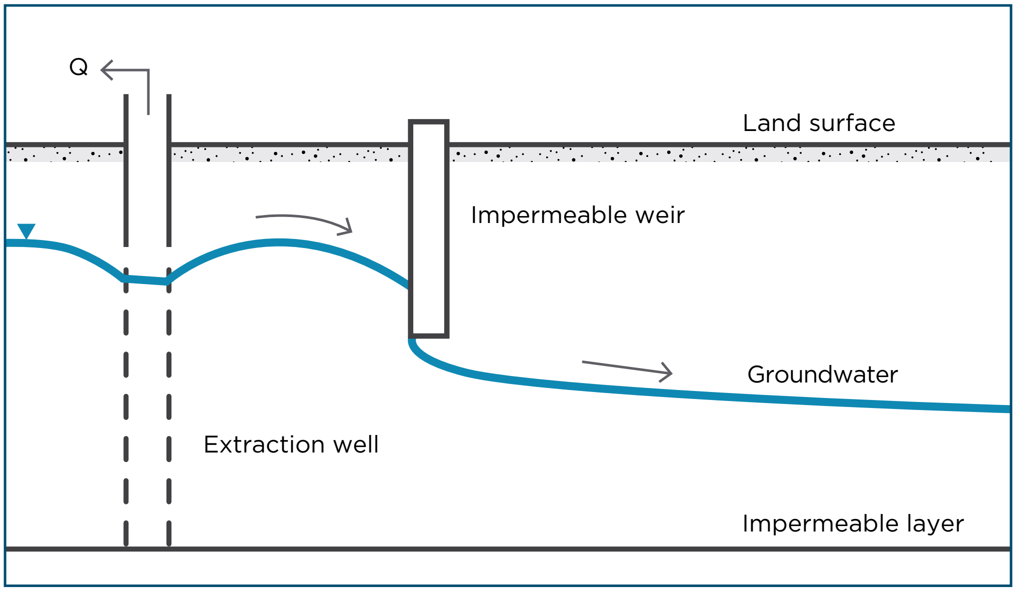
Source: INOWAS (2022)

Shallow well / shaft / pit infiltration



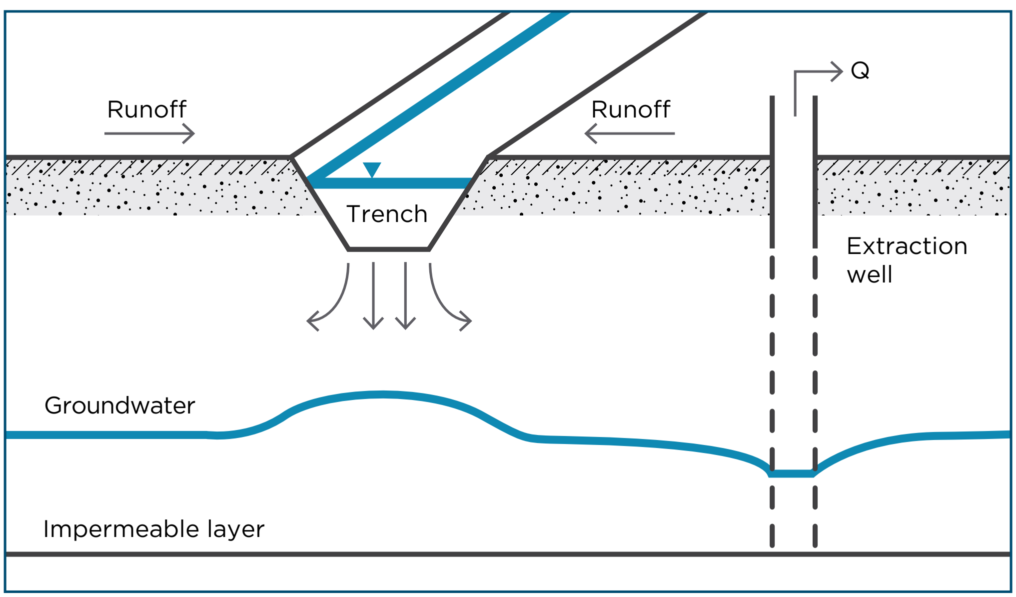
Source: INOWAS (2022)

Sub-surface dams



Source: INOWAS (2022)

Trenches



Source: INOWAS (2022)

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