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Rainwater harvesting technologies in arid plains of Argentina: small local strategies vs. large centralized projects

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Access to water has been and remains one of humanity's greatest challenges. Especially in arid plains exposed to significant climatic fluctuations and future global change trends. In the past and present, local communities of the arid plains of central-western Argentina (i.e., Guanacache Lagoons, Cuyo region) have developed multiple strategies to manage water supply problems. The aims of this study are: i) to characterize the different water harvesting technologies (pre-Hispanic and modern) used, and ii) to compare the small local strategies of water harvesting (bottom-up solutions) with the large centralized projects (top-down solutions). On the one hand, we show the transformations of these technologies over time, and the challenges faced by inhabitants in the context of climate change trends. On the other hand, we analyze the role of the state through hydraulic policies and projects implemented by the provincial states over the last two centuries and how this impacted the study area. This review is based on a historical and archaeological bibliography, and recent publications about the region, including articles based on our ethnographic fieldwork. Our results demonstrate the valuable experience accumulated by local populations in water harvesting methods, particularly in areas where groundwater is deep and saline, and shows the adaptability of these technologies in contexts of increasing scarcity. We considered that local indigenous knowledge can largely contribute to the sustainable management of water resources. This study might be useful for decision-makers and water managers in drylands around the world to find and equitable approach that combines technical advances with local knowledge.

KEYWORDS

water scarcity, indigenous people, local knowledge, rainwater harvesting, rurality, water policies, climate adaptions, drylands

1 Introduction

Since ancient times, arid plains have had virtually non-existent natural freshwater sources (Noy-Meir, 1973). Humans have developed water harvesting technologies to inhabit these areas and sustain an economy based on livestock and agriculture (Mbilinyi et al., 2005; Oweis, 2017). A traditional method is *in-situ* rainwater harvesting, which solves the problem locally without the need for inter-basin water transfers (Búrquez et al., 2024). However, access to water remains a pressing issue, especially in plains regions far from "liquid water-generating sites" (Farley et al., 2005; Poca et al., 2020) and in drylands, characterized by water scarcity and low precipitation (FAO, 2021). This article focuses on Guanacache as a gateway to a wider area of South America: the great dry plains (from Chiquitania to the Monte desert) that contain ecosystems with limited or no water resources. The drought periods will increase in the future, according to the IPCC report (2023). To address this, it is necessary a change planetary policy (Latour, 2018) with adaption actions that consider the natural variability and future hazard projections (Huang et al., 2017). This paper aims to narrow the gap between technological development, local knowledge and ancestral practices, from a transdisciplinary perspective of sociohydrological approach (Wesselink et al., 2017).

The provinces of Cuyo (Mendoza, San Luis and San Juan; central-west of Argentina) host vast dry sedimentary plains. Between eastern Mendoza, western San Luis and southern San Juan are situated the "Guanacache Lagoons". This is a marsh complex formed in the past by the Mendoza and San Juan rivers, fed by surface and groundwater originated in the Andes mountains and, to a lesser extent, by the Vinchinca-Bermejo River (Contreras et al., 2011; Prieto and Rojas, 2012). In periods of greater water abundance, this system extends for 2,500 km^2 (Calderón Archina and Alvarez, 2022). Since prehispanic times, indigenous people have lived Guanacache lagoons (Sarmiento, 1845). This local indigenous group is recognized as "Huarpes Laguneros" (native name registered in colonial archives). They developed an extensive irrigation canal systems with water of Andes rivers (Damiani, 2002; Prieto et al., 2008). During the Colonial period, according to the documentation we will show, Guanacache did not experience major changes. However, since the late 19th century, a process of environmental degradation has been affecting the area and reduced to 20% of its original size (Alvarez, et al., 2024). The changes are associated with the development of an agro-industrial model centered on wine production (Richard-Jorba, 2009). This produced a territorial fragmentation between irrigated areas (oasis) and non-irrigated areas (desert), inhabited by rural and indigenous populations (Alvarez, et al., 2024).

The historical case of water appropriation was conducted and legitimized by the State of Mendoza through legal mechanisms and hydraulic infrastructures that made possible the distribution of water for wine production and to supply local elites and migrants. Superintendence of Irrigation in Mendoza (conformed by the Water Law of 1884) encouraged the intensification of irrigated lands (oasis) and promoted the design and construction of irrigation canals and dams to capture water resources in detriment of dry areas (Escolar and Saldi, 2013). The changes were linked with the arrival of European people (Devoto, 2003) because they facilitated the access of immigrants to irrigated areas in Mendoza, as agricultural workers or landowners in crops and vineyards (Richard-Jorba, 2010; Escolar and Saldi, 2016). In brief, with the advent of republican state, was adopted an agroindustrial model along with water policies that support it. Water governance was configured to promote the distribution and concentration of river water in the upper and middle reaches of the Mendoza and San Juan rivers, privileging one part of the population over the other.

Water concentration in the oasis area and snowfall decrease pattern in Central Andes (IPCC, 2023), caused a gradual drying of Guanacache lagoons (Escolar and Saldi, 2016; Calderón Archina and Alvarez, 2022). Nevertheless, a large part of the regional literature characterizes Guanacache as a natural desert. As in other drylands around the world, there is a dominant discourse that considers water scarcity as a natural condition against which communities have to deal (Otero et al., 2011). Although some studies suggest natural, geological and social factors that influenced the wetland degradation (Vitali, 1940; Abraham and Prieto, 1981), they conclude that water scarcity is a local problem, without explaining how the population copes with it. Previously, we have shown that this is a historic conflict of water distribution involving dispossession and how Huarpe Laguneros have resisted and struggled over decades (Escolar, 2021; Calderón Archina, 2022). In this article, we asked how Lagoon inhabitants (rural population with indigenous ancestry) and regional governments dealt with water shortage in Guanacache. We are also interested in the extent to which water scarcity can be induced or aggravated by the consequences of poor or inequitable water management (Mukheibir, 2010).

The aim is to understand how water harvesting technologies have adapted to the environmental changes, from a socio-hydrological perspective. This implies considering humans and their actions as an integrated part of water cycle dynamics and their co-evolution (Sivapalan et al., 2012). Therefore, we conducted an exhaustive review in order to (i) characterize the different ways of water access by local population over the last millennium (temporal line), and (ii) compare the multiple ways of local and centralized rainwater harvesting developed over the last two centuries. We analyzed the state intervention in water management and its effect on Guanacache. To do this, we focus on three periods: pre-Hispanic, Colonial and Republican periods.

2 The study area

Guanacache Lagoons are a system of lagoons, marshes and wetlands that cover parts of the territories of Mendoza, San Juan, and San Luis estates, located in the central area of the phytogeographic province of Monte and southern Arid Chaco (Oyarzabal et al., 2018; Niborski et al., 2022). This system originates from the confluence of the Mendoza and San Juan rivers, whose sources are located in the glacial and periglacial environments of the Andes Mountains. The flow that supplies this lacustrine system primarily originates from snow-glacier melt, with 66%–76% of the total discharge occurring between October and March (Lauro et al., 2019), and flows into the Desaguadero River, which continues southward, crossing the natural boundary between Mendoza and San Luis. Annual

A) PRE-HISPANIC PERIOD

- Irrigation channels of 50 km, Iglesia Valley, San Juan (Damiani, 2002).
- Canals of 35 km from Mendoza River, Huentata Valley, Mendoza (Prieto, 2008).
- Inca domination in Mendoza and San Juan (Damiani, 2002). There were improvements and modernization of channels and canals (Bárcena, 1998).

B) **COLONIAL PERIOD (16th - 18th centuries)**

- 1561: the Spanish founded the Huentata Valley (current city of Mendoza).
- Based on the existing infrastructure, the conquerors developed an irrigation network to supply individual crop plots from the Mendoza River.
- 1845-1890: first written descriptions of the Guanacache Lagoons as a communal space where the Huarpes hunted and fished (Sarmiento, 1845; Rosales, 1878).
- 1890: The lagoons are a site of inter-ethnic contact among indigenous groups that still retained some autonomy (Vignati, 1931; Zamorano, 1950).

C) **REPUBLICAN PERIOD (19th - 21st centuries)**

- 1860-1914: Arrival of European immigrants to Mendoza, San Juan, and San Luis.
- 1984: The promulgation of the Water Law initiated a process of water concentration in the upper reaches of the main rivers (such as the Mendoza and Tunuyán rivers).
- 1910: First evidence of the drying of the Guanacache lake system (Zamorano, 1950).
- 1936-1940: Great drought in Guanacache (Escolar, 2021).
- 1937: The Huarpes of the lagoons began claiming water rights from the Mendoza government.
- 1990: Environmental Treaty of Nuevo Cuyo signed between Mendoza, San Juan, and San Luis.
- 1994: Indigenous pre-existence recognized in the reform of the National Constitution.
- 1999: Guanacache Lagoons declared a Ramsar Site.
- 2000: Inauguration of the Nogolí dam, transporting water from the Central Sierra of San Luis to the arid plain adjacent to Guanacache.
- 2014: Inauguration of the first section of the weir works on the Desaguadero River to increase the water supply to the Guanacache lagoons.

FIGURE 1
Rainwater harvesting technologies developed over the last millennium in the arid plains of central Argentina. Left. Illustrative photos of the systems and representative situations. From top to bottom. 1) Pre-Hispanic irrigation canals. 2) Pre-Hispanic berm dams. 3) Huarpe indigenous person in a canoe on one of the Guanacache lagoons (1878). 4) Canal developed in the 19th century by European settlers. 5) Map of the parceling of the Mendoza River by European settlers. 6) Huarpe protests over the drying up of the lagoons (1937). 7) Jagüel well. 8) Rooftop harvesting. 9) Large centralized project of check dams on the Desaguadero River. Right. A chronosequenc of significant events that occurred during this period.

precipitation varies between 200 and 400 mm, with rainfall events concentrated in the summer warm season (Magliano et al., 2015a). Dry native forests of *Neltuma flexuosa* and *Larrea divaricata* are the dominant vegetation (García et al., 2017; Oyarzabal et al., 2018). Soils are entisols with gentle and long slopes toward the Desaguadero River (Peña Zubiate et al., 1998).

Local population is spread over large tracts of land, grouped in small settlements or isolated homesteads dispersed across the territory (Triviño, 1977; Triviño, 2020; Calderón Archina, 2021). Population density is low (4 inhabitants per 1,000 ha, National Census 2021), characterized by low-income rural communities. Extensive cattle ranching is the main activity and the native forest provides fodder resources (Rueda et al., 2013; Fernández et al., 2020). Most lack running water and sanitation facilities. Groundwater is the main source for domestic and livestock use, however, a recent study shows that all groundwater have arsenic concentrations above the permitted limit for human consumption (Gómez, et al., 2019). In the last decades, a significant part of the population has come to recognize themselves as Huarpe indigenous people (Escolar, 2007; Calderón Archina, 2022). The last national census recovered 25,615 huarpe individuals in Cuyo, Guanacache has the highest concentration (Instituto Nacional de estadísticas y censos, 2024).

In this paper, we relied on the bibliographic material available for the region and in previous studies based on fieldwork from ethnographic (Calderón Archina, 2016; Calderón Archina, 2022; Escolar, 2007), ethnohistorical (Escolar, 2021), archaeological (Heider, 2020) and hydrological research (Magliano et al., 2024; Niborski et al., 2022). The fieldwork was conducted in rural communities in northwestern San Luis and northeastern Mendoza between 2000 and 2019 years. The figures we present were elaborated based on published bibliographic material, historical archives, photographic documents and field interviews.

3 Native rainwater harvesting development

Since pre-Hispanic times, Guanacache has been a refuge for the Huarpes, other indigenous groups, African slaves and mestizos (Escolar and Saldi, 2016). In part, because of its wetland environment that allowed sustain some autonomy of Colonial and Republican States (Calderón Archina, 2022). The local population is the result of the interaction between these groups, with a predominantly indigenous ancestry. Today a large part of the population recognize themselves as Huarpe or indigenous descent (Escolar, 2007). However, we have chosen refer to the local people as native "Laguneros" for the past and "peasant" at present (is the livelihood of Guanacache population). Peasant is not synonymous with indigenous, but in this case the first category allows the inclusion of whole Guanacache population, they identify as themselves with their livelihood (Calderón Archina, 2022). While they do not always identify themselves as Huarpes.

Over hundreds of years, local inhabitants developed different rainwater harvesting systems to compensate lack of water (bottom-up solutions). Through these technologies (not fully documented), they partially solved the problem of access to water. Based on the bibliographic review, we divided the lagoon system into three stages and identified six water access technologies (Figure 1), that were developed over the years, some abandoned, others retained or adapted. The first stage, which covered the prehispanic and colonial periods, was characterized by a regional management of water and a communal use of the lagoons. Native people had rainwater catchment and water transport (Damiani and García, 2011), which allowed them to preserve a certain autonomy during the colonial period (Vignati, 1953; Zamorano, 1950), even in the last quarter of the 19th century (Escolar, 2021). This period is characterized by pre-Hispanic irrigation canals (technology 1). The earliest structures date back 2,000 years (Gambier, 1977; Damiani and García, 2011). Indigenous works became more complex and developed an extensive system before the conquest. Damiani (2002) shows different levels of complexity associated with the hydraulic structures: The main canals were supplied from Mendoza and San Juan rivers, and transported water through a network extended up to 20 km forming a multilevel canal system. This infrastructure required geomorphological knowledge and collective work for its construction and maintenance (García and Damiani, 2020). As was demonstrated in northern Argentina (Raffino, 1975; Giovannetti and Raffino, 2014), systems of this magnitude indicate a complexity of social organization. Their abandonment is related to the rivers deviation towards irrigated oasis (Escolar, 2021).

Another pre-Hispanic technology is the berm dam (technology 2) (García and Damiani, 2020). This low dam (40–60 cm) is built on slopes and natural elevations to redirect water and to moist drought lands or to prevent flooding in residential areas. It is an ancestral technique that is still in use, mainly to prevent exceptional flooding and to provide moisture on uncultivated land to grow wild vegetation (Besio, 2021; Escolar, 2021; Calderón Archina, 2022). Other major technologies were developed in the transition from the Pre-Hispanic to the Colonial period: Bucket wells (technology 3), impoundments (technology 4) and jagüel wells (technology 5). It is difficult to determine the antiquity of these water harvesting techniques. Heider (2023) suggests that they existed before Conquest and were optimized with the arrival of Spanish. There is evidence of use of bucket wells from 3000 BP in the region (Heider et al., 2024). These are hand-dug wells with a diameter of 1.5 m and up to 10 m deep, which reach seasonal water tables, especially after the rainy season, and provide access to quality water (Heider, 2023). Actually, they continued in force and are very common near houses or settlements, primarily for irrigation.

Impoundments are an ancestral technology, but there are no dates in the area before Conquest. Their construction is currently based on local knowledge and involves a collective and manual practices with shovels and rakes (Magliano et al., 2024; 2015b). The surface area of 0.1–1 ha and a depth of 1–2 m, are enclosed by a U-shaped or horseshoe-shaped embankment (Niborski et al., 2023). They are located in mid-slope areas with clay soils to reduce water loss through soil infiltration, or in landscape sites where inhabitants observe signs of surface runoff (Magliano et al., 2019; 2023). The jagüel wells are structures similar to impoundments, but smaller and with access to seasonal groundwater layers (like bucket wells). Sbarra (1961) and Carrión, 1981 suggested a West Indian origin for these technologies and they would have spread throughout South America after the Spanish conquest. They are lined with a wooden shuttering to contain sandy soil. The exposed water surface is large enough for livestock (cows and goats) to drink directly. These technologies are found in areas closest to groundwater, such as interdune valleys (Meglioli et al., 2021). The oldest records date from late colonial times, 18th century (Heider, 2023) to the early 20th century (Roig, 1970), some of them have shown sustained use for more than 120 years (Pastor, 2014) and some are still in use.

The second stage started with the development of the agro-industrial model at the beginning of the Republican Period. The modern hydraulic infrastructure included diversions, dams, canals and irrigation networks supplied by the major rivers of the region (Alvarez et al., 2024) in the upper and middle zones of the basins. The lagoon population was relegated to non-irrigated lands (Martín et al., 2010; Escolar, 2021). However, at the beginning of 20th century, native people continued to consume and trade fish (Martinez, 1961; Prieto, 1974) and Guanacache was an important production area for wheat, maize, alfalfa and horticultural crops with centralized irrigation (Escolar and Saldi, 2013). According to oral testimonies, irrigation canals in Guanacache plains continued working until the mid-20th century (Abraham and Prieto, 1981). Water harvesting technologies (2, 3, 4, and 5) continued to be applied until the beginning of this period. The literature does not mention significant changes.

The third stage is characterized by the adaptation of the water supply as a consequence of the gradual drying up of Guanacache system. Regional studies have recorded different drought periods during the early 20th century (Castellanos, 1926; Rusconi, 1949). A dramatic event identified by the ancient settlers was the great drought of 1936–1937 (Escolar and Saldi, 2016). Increasing water scarcity brought a diversification of local rainwater harvesting techniques. Although the water harvesting technologies (2, 3, 4 and 5) remain in use, they present some difficulties. For instance, the use of bucket wells is hindered by the hard access to groundwater, so, peasant have replaced them. They draw water directly from the Desaguadero River using an electric pump (Besio, 2021). In this context emerged cisterns and the roof

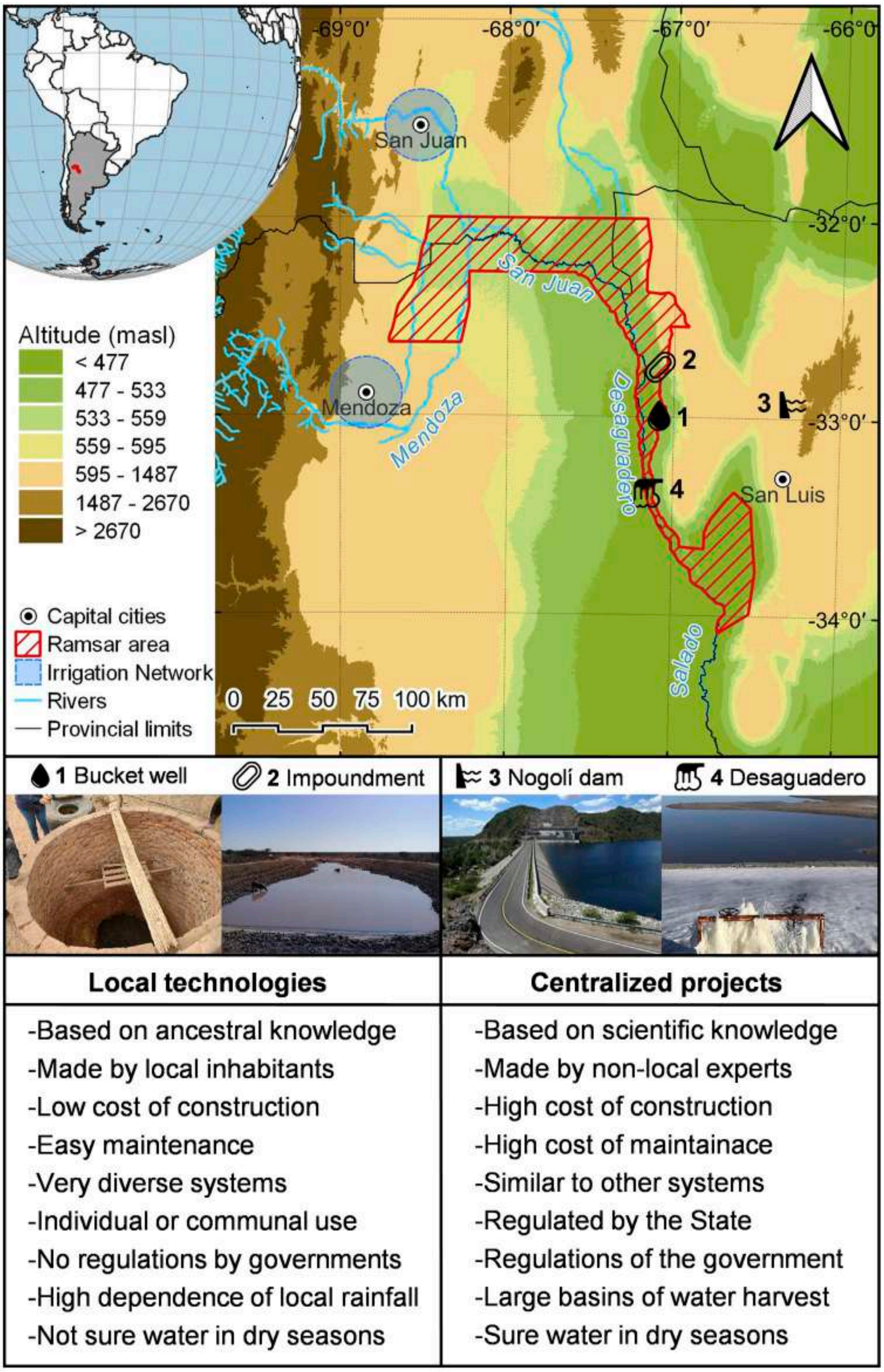

FIGURE 2
Study area and comparison of small local strategies (bottom-up solutions) vs. large centralized projects (top-down solutions) to harvest and conduct water in the arid plains of the Guanacache Lagoons.

collection for harvest rainwater on ceilings. Peasants put containers to accumulate water that is used for drinking (by both humans and livestock) and for domestic activities (Ramilo et al., 2014). Whereas the cisterns and impoundment constructions are usually supported by politics and NGOs. For example, the Wetland Foundation carries out small-scale soil and wetland restoration works, using a system similar to dams but with lower-cost techniques and materials that serve as drinking stations for livestock (Calderón Archina, 2022). There is an eventual support that does not solve the problem of water supply.

3.1 Rainwater harvesting strategies and centralized projects

From the past to the present, local population has been able to access water by making effective use of ponds and water redistribution systems (canals and berm dams) and address water scarcity in dry periods. Most of these technologies are based on ancestral knowledge from indigenous pre-Hispanic cultures. The Guanacache system began to dry up because the water extraction of river basins that supplied the lagoons. In this context, from the 20th century onward, natives had to abandon some of these technologies (irrigation canals), adopt others (jagüels, dams) and develop new rainwater harvesting technologies *in situ* (cisterns, roof catchment). These adaptation strategies have been the key to continuing to live and produce in the area, given that the main livelihood is livestock rearing.

The water expropriation forced the Huarpe Laguneros to leave community water management and replace it with the various techniques described, which are constrained to family organization. According to local narratives and memories, the deterioration of the Guanacache system was perceived as gradual (Calderón Archina, 2022). Drought periods became more frequent and prolonged. For this reason, there was no immediate social reaction. Lagoon people began to claim their irrigation rights from the Provincial State of Mendoza (Figure 1) in the 1930s (Escolar and Saldi, 2016), years of a major drought period. The historical depth of the water demand is an intersection between indigenous identifications and water disputes that have shaped recent experiences of Huarpe collective organization (Calderón Archina, 2016; Calderón Archina, 2022). There is recent visibility of the Huarpe groups and their water and land demands, in the context of a three-decade-long drought period (Magliano et al., 2024). In response, throughout the 21st century, the provincial government of San Luis implemented two centralized projects to address water scarcity surrounding the dry lagoons (Figure 2). One of them consist of a restoration project related to the declaration of Guanacache as a Ramsar site and its extension in 2007 (Calderón Archina, 2016). Whereas the second project is the extension of the supply network of Nogolí dam, which transports water from San Luis mountain range. In the last 2 decades, the impoundments technique (4) has been complemented with water from Nogolí dam aqueduct, to support livestock and goat production (Magliano et al., 2024).

Nevertheless, these project did not resolve or mitigate the problem of water lack (Calderón Archina, 2022). In general, residents appreciate the construction projects especially because this has been a historically marginalized area in terms of policies and public works (Calderón Archina, 2022). Although, users point to constant failures in the water supply from the Nogolí dam aqueduct, as well as the poor quality of the transported water. They also warn that the proximity of the check dams to flood-prone lands was not considered. As a result, major floods can obstruct certain roads and isolate small communities (Calderón Archina and Alvarez, 2022). In neither case was the population consulted. The government did not take into account the local knowledge and practices associated with water harvesting. Considering the experience accumulated by the inhabitants could have avoided the problems that these works presented and optimized their use (Calderón Archina and Alvarez, 2022; Magliano et al., 2015b). In conclusion, major developments do not bring significant improvements to the water supply problem, even though, local people value the works as a palliative to the worsening water deficit.

4 Discussion

Water scarcity is a pressing problem in arid areas and the current context of climate change indicates that drought will increase. Guanacache case shows how the natives have been able to inhabit the arid plain for thousands of years. However, water shortages have been increasing over the last hundred years and this is mainly the result of unequal management of water resources (Escolar and Saldi, 2016; Calderón Archina, 2022). In response to the process of drying up, native people have adapted and diversified water harvesting techniques, but they continue without sufficient water for their consumption and their livestock. In the last decades, local governments have attempted to relief the problem of supplying water, but these have design deficiencies and failures in distribution and quality water. We believe that a satisfactory solution requires a change in water policies, which should ensure a constant flow of water to Guanacache Lagoons and promote the restoration of the system (Alvarez et al., 2024; Calderón Archina and Alvarez, 2022). Consider the millenary experience associated to water technologies described and the resilience capacity of the native population, it is essential to incorporate local knowledge to solve environmental troubles (Liwenga, 2008; Chikwanha et al., 2021). Local knowledge we refer involves practices, knowledge and memories that remit to the indigenous ancestry.

Recent studies have demonstrated that local knowledge is effective in managing water scarcity (Aklan et al., 2022; Sioui, 2022). For example, based on indigenous knowledge, people in central Tanzania use seasonality and landscape diversity to cope with such environments, ensuring continuous crop production throughout the year (Liwenga, 2008). Whereas farmers in the semi-arid and arid Mediterranean region had to combine an ancient water harvesting system with new irrigation techniques (e.g., drip irrigation, micro-sprinklers, sub-surface drip irrigation) due to annual rainfall variability; this has resulted in a considerable improvement in biomass and cereal production (Stroosnijder et al., 2012). These cases prove that adaptations of traditional techniques are necessary, but that changes should not ignore indigenous knowledge and local practices. Instead, they should be included as knowledge co-producers (Zarej et al., 2020; Taddei, 2023). Their incorporation into climate change policies will support to develop effective adaptation strategies that are cost-effective, participatory and sustainable (Ajani et al., 2013; Pili and Ncube, 2022).

5 Conclusion

Water scarcity is a limiting factor in drylands. However, as we have shown, it is not just a natural condition. Lack of water can be exacerbated by poor and unequal water policies. This implies that water scarcity can be the result of power relations in unequal societies (Nicolas Artero, 2020). Reversing this required a water governance change to find more equitable and sustainable ways of accessing water. Based on local experiences in the arid plains of central-western Argentina, we found that (i) over time, native people have developed diverse and complex rainwater harvesting systems to address drought issues, and (ii) it is essential that policies and institutions incorporate and combine local knowledge with centralized technical developments to access to fresh water. A comprehensive solution could improve the situation. Local solutions were adequate half a century ago, but today are not enough. Instead, centralized hydraulic works face numerous costly problems of maintenance and stability in the future, and they are not fully accepted by communities.

In the next decades, with projected climate change, millions of people will be living under severe water stress conditions (Stringer et al., 2021). Will require an equitable approach that considers multiple and interrelated risks and develops solutions that include the values that matter to communities (Kettle et al., 2014). To achive this, is necessary to combines technical advances with local knowledge. Our results demonstrate the valuable experience accumulated by indigenous and peasant in water harvesting techniques and the adaptability of these in contexts of increasing scarcity.

Author contributions

AC: Investigation, Writing–original draft, Writing–review and editing. DE: Conceptualization, Investigation, Writing–review and editing. GH: Conceptualization, Investigation, Writing–review and editing. MN: Methodology, Software, Writing–review and editing. EJ: Conceptualization, Investigation, Supervision, Writing–review and editing. PM: Conceptualization, Supervision, Writing–review and editing, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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