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Research paper

Proposed recharge of island aquifer by deep wells with regenerated water in Gran Canaria (Spain)

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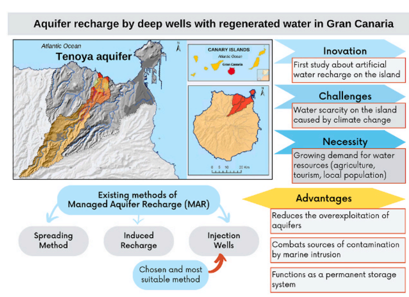
HIGHLIGHTS

- MAR as an option to complete the water cycle in the Canary Islands.
- Reclaimed water to be used in the Canary Islands as a means of reducing pressure on the aquifer.
- Artificial aquifer recharge gains momentum in an island climate change scenario.

GRAPHICAL ABSTRACT



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ABSTRACT

Managed aquifer recharge (MAR) and, in particular, recharge by direct injection into the aquifer through wells or boreholes allows for a series of very interesting solutions to solve various technical and environmental problems related to management of the urban water cycle. These problems include the overexploitation of water resources, marine intrusion or contamination of groundwater by irrigation returns. The island of Gran Canaria presents several of these problems; thus, the feasibility of implementing a recharge system has been studied to provide a solution to some of them, using a resource of great potential such as reclaimed water. A detailed characterization of groundwater quality in the study area was carried out, complemented by a field campaign with water sampling from the surrounding catchments, in situ analysis and subsequent laboratory analysis. Specifically, an MBR treatment with disinfection is proposed, where the final conclusions indicate that this is a technically and economically viable project, innovative in its application on islands, a priori with an acceptable productive recharge capacity, possibly scalable after the experimental phase and extrapolable to other locations with similar conditions. In addition, it presents a set of important environmental benefits with respect to conservation of and

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improvement of the state of the groundwater bodies in the studied area, as well contributing to knowledge of and research into water management in volcanic lands and islands.

1. Introduction

The management of water resources is one of the main political, socioeconomic and environmental problems facing mankind today (Cruz-Pérez et al., 2022). The scarcity of these resources means that they must be managed as efficiently and sustainably as possible to guarantee the needs of the population and future generations (Vargas-Amelin and Pindado, 2014). In terms of management, there is a technique that is still in the research and development phase, even though it has been known since ancient times (Pulido-Bosch and Sbih, 1995). This technique is the managed aquifer recharge (MAR) (Dillon, 2005) based on altering the hydrological cycle by increasing the natural recharge of groundwater through human intervention, guaranteeing the storage of water of a certain quality in the aquifers (Dewandel et al., 2021).

Managed artificial recharge (MAR) of aquifers allows water to be deliberately introduced into the ground, thereby extending the life of a valuable resource such as water, as well as helping to combat drought and high demand for groundwater (Jódar et al., 2022). MAR systems using treated or reclaimed water have been developed extensively in the United States, for example, in Orange County in California (Plumlee et al., 2022). In Spain, interesting projects have been developed in recent years, such as the hydraulic barrier of the Llobregat aquifer in Catalonia (Ortuño et al., 2012). In the specific case of the Canary Islands, theoretical studies have been carried out, but at present, there are no real MAR projects underway (Naranjo Ayala, 2008; Ortiz Villalobos, 2012).

Internationally, MAR systems have been developed, especially in arid areas with low rainfall, salinized soils and water (Besser et al., 2021). It is clear that climate change will aggravate the water situation in arid and semiarid areas of the world, so reducing water demand and closing the water cycle becomes vital in countries such as Tunisia (Hamed et al., 2022). Furthermore, the proliferation of irrigated crops and the importance of tourism in the Mediterranean area (Besser and Hamed, 2021) may affect groundwater hydrochemistry (Ncibi et al., 2022), positioning MAR as a groundwater quality recovery technique.

Among the advantages of an MAR model, the following should be highlighted as fundamental in the context of application: i) it reduces the overexploitation of aquifers by guaranteeing a higher recharge rate than the natural one, so that groundwater extraction becomes a more sustainable process (Abd-elaty et al., 2022); ii) it allows combating sources of contamination through marine intrusion by creating water barriers that progressively improve their quality and help to protect the resources of the aquifer itself (Ortuño et al., 2012); iii) it serves to improve the quality of reclaimed water, contributing to better resource management (Yuan et al., 2017); and iv) it functions as a permanent storage system without losses due to evapotranspiration and without the use of surface infrastructures to store water (Kagabu et al., 2020). These four advantages have great hydrological repercussions on Gran Canaria; the island's aquifer, in general, suffers from major overexploitation caused mainly by agriculture and, to a lesser extent, by the increase in population and tourism demands. Overexploitation has also caused the aquifer to be affected to varying degrees by pollution of marine (Cruz-Fuentes et al., 2014) or anthropic origin (Ruiz-García et al., 2019), which affects a large part of the island's coastal areas.

MAR is an innovative solution for Gran Canaria for a number of reasons. Since the 1960s, the demand for water resources for agriculture, the increase in population, the development of tourism and industrial activity has led to continuous overexploitation of the island's aquifer, resulting in a significant drop in piezometric levels, especially in the bodies of water close to the coast (Custodio et al., 2016). The loss of groundwater quality and the scarcity of resources due to the climatic conditions of semiarid regions means that the water cycle, which does not include the use of reclaimed water, is unsustainable over time (Cruz-Pérez et al., 2022). In the Canary Islands, the response to this problem has been to promote nonconventional sources of water resources, such as seawater desalination (Gómez-Gotor et al., 2018). This pattern of managed artificial recharge is postulated as a solution for other arid parts of the world (Gale, 2005) that are heavily dependent on desalination and have diminished groundwater resources, such as in Qatar (Mohieldeen et al., 2021). The recovery of quantitative and qualitative water status in Gran Canaria is far from meeting the objectives of the Water Framework Directive, which, for groundwater bodies, are the following (EU, 2000): a) to prevent or limit the entry of pollutants and to avoid deterioration of water bodies; b) to protect, improve and regenerate water bodies and ensure a balance between abstraction and recharge; and c) to reverse significant and sustained trends in the increased concentration of any pollutant derived from human activity.

One of the main disadvantages of implementing an MAR system is having the necessary quantity and quality of resources, with sufficient availability in time and guaranteed supply, without reducing the resources allocated for other consumptive uses (Hasan et al., 2019). In particular, in Spain, reclaimed water is relegated to last place in regard to using it to recharge aquifers, since its environmental use is not defined, with priority being given to other uses such as agriculture or recreation (Ricart et al., 2019).

This article examines the managed recharge of aquifers through the use of deep recharge devices or deep wells, reusing reclaimed water. Based on various previous studies, the suitability of both the situation and location and the recharge device to be designed is assessed to implement a managed aquifer recharge system with the greatest possible guarantee of success. The main objective of this initiative is to improve the quality of groundwater, with secondary objectives being the prevention of contamination by salinization and underground storage for its recovery for agricultural irrigation.

1.1. Study area

The feasibility study presented in this article is located on the island of Gran Canaria, which belongs to the archipelago of the Canary Islands (Fig. 1), an outermost European region belonging to Spain. The existing purification and regeneration treatments, geographical situation, existing hydraulic infrastructure, availability of water resources, environmental impacts and hydrogeological characteristics were evaluated by choosing a specific area for the study. This information was cross-referenced with maps of groundwater bodies on the island of Gran Canaria using geographic information systems (GIS). From this information, four potential areas for the study were obtained; the Tenoya Wastewater Treatment Plant (WWTP) was chosen as an interesting location and case study for the development of an experimental pilot plant (Fig. 2). The Tenoya WWTP is located in the municipality of Las Palmas de Gran Canaria and has fewer than 5000 equivalent inhabitants and an average flow of 900–1000 m^3/day. During the study and field work, the plant was in the execution phase for technical upgrading.

Previous studies indicate that there is great potential in the use of reclaimed water on the island, where only 12.8 hm^3 is consumed, with a forecast increase to 20 hm^3 in the coming years (CIAGC, 2013). In the wetter northern region, only 2.6 hm^3 is consumed, which represents only 30% of the installed production capacity in this region. In Tenoya, demand is small, mainly agricultural, with a monthly average of 24,000 m^3/month compared to the WWTP Tenoya's capacity of approximately 45,000 m^3/month. Furthermore, the availability of the resource is greater in the wet season than in the summer. The water quality of the Tenoya WWTP would require tertiary treatments to comply with direct recharge in accordance with the national regulations of RD 1620/2007 (BOE, 2007).

The main characteristics that position the Tenoya WWTP as a place of great interest for implementation of an experimental pilot system are the following: i) It is a small WWTP, with a newly commissioned treatment system, which guarantees sufficient quality conditions for recharge with reclaimed water; ii) It is located in an area where agricultural irrigation with reclaimed water is not very widespread; iii) It is located in a hydrological basin in the north of the island, with favorable climatic characteristics, with a high natural recharge in the summit area; iv) There are a number of groundwater catchments in the surrounding area that have brackish water quality and, therefore, require desalination equipment in their operation; v) The neighboring catchments of the aquifer are abandoned or are being exploited for uses other than for human consumption, so there are no health problems from a sanitary point of view; vi) There is no major competition or stress for reclaimed water, ensuring its availability for recharge; vii) There is an underwater outfall that allows the treatment plant to work safely against uncontrolled spills, which improves its operation and production; and vii) The quality of the groundwater shows signs of salinization and, in general, is of poorer quality than the recharge water. No physical or chemical interactions between the recharge water and the native waters of the aquifer have been specified.

This project represents a solution that makes better use of resources through the joint use of available resources, and it entails significant environmental benefits in the recharged aquifer. Specifically, an MBR treatment with disinfection is proposed that would guarantee the quality requirements 5.2 for aquifer recharge by direct injection of the national regulation RD 1620/2007 (BOE, 2007). The system would be paid for by the water administration due to the environmental purpose and the need to demonstrate its operation. This is a free aquifer exploited by wells with desalination plants, where the rest of the wells are abandoned.

The saturated zone is located in the fractured phonolitic formation with variable transmissivities. According to SPA-15 (1975), the transmissivity is 5–10 m^2/d, exceptionally reaching 25 m^2/d, with a storage coefficient of 0.01–0.1%, occasionally reaching 0.5%. Exploitation flow rates are also variable, ranging from 2 to 10 L/s. On the other hand, pumping tests carried out by the Spanish Geological and Mining Institute in the phonolites obtained transmissivities of 60–100 m^2/d and 30 m^2/d, the most frequent, showing that transmissivities of 25–30 m^2/d are not so exceptional in the phonolites (Naranjo Ayala, 2008).

The groundwater is brackish, with high mineralization due to the high residence time, endogenous CO_2 emanations and saline upwellings caused by pumping. Furthermore, the waters in the area to be recharged are mainly sodium chloride, with conductivities above 3500 μS/cm and chlorides >700 mg/L.

2. Methodology

Previous studies conducted in the area made it possible to know the state of the target aquifer and provided the basic information necessary for subsequent design of the deep recharge device. Among the studies carried out, the following can be highlighted.

2.1. Hydrogeological study

Very relevant conclusions were drawn in this section. In general, the main subway flow follows the preferential drainage lines, particularly that of the Tenoya ravine, where the largest number of groundwater abstractions are located, in this groundwater body. On the island of Gran Canaria, there are 10 groundwater bodies (Martín Rodríguez and Cabrera Santana, 2013), and here, we are specifically studying water body number ES70GC003, which has 64 groundwater extraction wells, and the volume of water extracted is 3 hm^3/year (CIAGC, 2013).

A hydrogeological study entailed an important series of works, both cabinet and field, during a campaign conducted in 2014. An important bibliographic compilation (MITECO, 1975; Naranjo Ayala, 2008; Santamarta, 2013) and documentation on the study area (CIAGC, 2013) were carried out, including an inventory of water points in the study area, analysis of piezometric evolution, and a conceptual interpretation of the functioning of the subway flow.

The state of the groundwater in the coastal aquifer of the Tenoya ravine shows a brackish water quality, highly mineralized due to different processes and the presence of endogenous CO_2 emissions, making it unsuitable for human consumption. They were characterized as sodium chloride, with high magnesium and bicarbonate contents. A field campaign was carried out to take samples from the inventory of water points in the recharge area of the Tenoya ravine (mainly wells) between 2013 and 2014, supplemented with data available from 2010 onwards to increase the amount of data in the coastal aquifer environment (Fig. 3).

The campaigns consisted of sampling with in situ analysis with a multiparametric probe (conductivity, temperature, pH and dissolved oxygen) and laboratory water analysis of basic parameters (Cl, SO_4, HCO_3, CO_3, NO_3, Na, Mg, Ca, K, pH, EC, NO_2, SiO_2, TDS, SAR, NH_4, P, B, Cu, Fe, Mn, Zn, Hardness).

The main hydrogeochemical characteristics of the study area (2010–2014 campaign) were as follows: conductivity (EC) variable in the range of 3500–6000 uS/cm; chloride (Cl) variable in the range of 700–1300 mg/L; sulphate (SO4) variable in the range of 250–350 mg/L; nitrate (NO4) variable in the range of 20–100 mg/L; and bicarbonate (HCO3) 800–1300 mg/L.

For 4 wells in the area (0061-CP, 0158-TP, 0778-TP and 5033-TP),

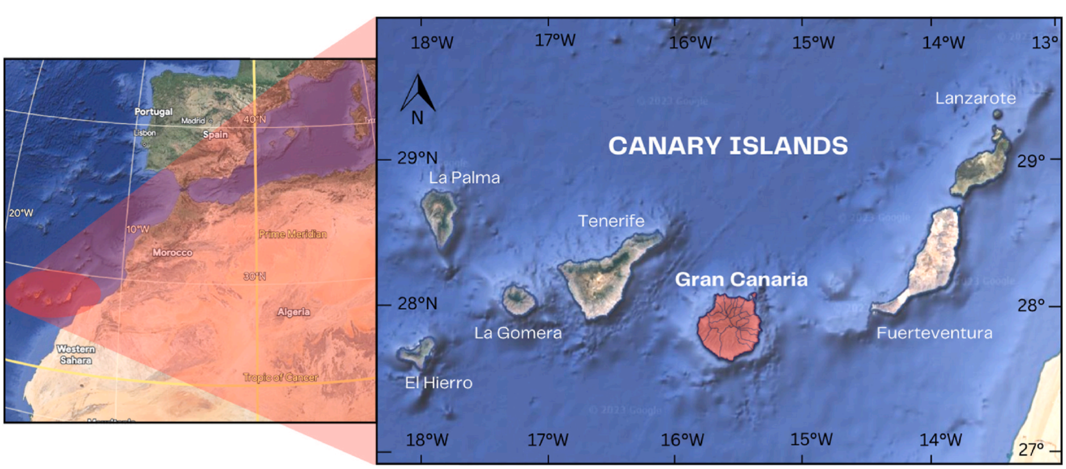

Fig. 1. Canary islands (Spain).

punctual analyses of the evolution of the basic parameters (2003–2013/2014) were also carried out, indicating a worsening trend in quality, especially in the years of most intensive exploitation, and ionic ratios (rNa/rK, rMg/rCa, rSO_4/rCl, rCl/$rHCO_3$) in comparison with the chloride content (rCl), with no possible processes of contamination by marine intrusion being detected.

The aquifer has suffered a significant drop in levels in recent decades and is currently found in the intended area at approximately 40–50 m deep and between 0 and 3 m above sea level, depending on the state of exploitation. In the study area, the hydraulic gradient is practically null, forming a wide region from the coastal area to several kilometers inland. The saturated thickness in the area was estimated to be greater than 100 m. The operating regime of the exploitations has decreased in recent years, although they continue to produce distortions in this coastal zone. Regarding the hydraulic parameters of the aquifer, the transmissivities and specific flow rates were determined to be higher than those estimated for the phonolitic formation according to the SPA-15 results, which could indicate a significant degree of fracturing.

In general, there has been a significant decrease in active catchments in the last 10–15 years, and it is common to find many abandoned wells in this ravine (Emilio Custodio et al., 2015). Active farms have associated brackish water desalination plants with reverse osmosis treatments, in most cases with low production yields. All the nearest surrounding catchments use water for agricultural use, which is an advantage from the point of view of sanitary control (Sharip et al., 2012).

2.2. Climatological and water balance study

The average annual rainfall in the basin studied in the series of years 1964–2006 is 354 mm/year, which means an average annual volume of 48.5 hm^3/year. According to other studies (Cabrera et al., 2013), natural recharge is estimated at 9–16% of the total volume of precipitation, somewhat lower than the 20% foreseen in the hydrological planning, which occurs mainly in the upper and middle zones, with very little infiltration in the coastal zone with recharge volumes estimated at 1.4 hm^3/year.

2.3. Geological study

From the available lithological columns, the structure and geometry of the aquifer were conceptually deduced, the main geological formations of the basin were differentiated, and the main geotechnical characteristics were estimated for the design of the boreholes. This work corroborated that the aquifer under injection is mainly formed by phonolites with different degrees of fracturing, and the upper materials in the ravine surface zone are mainly recent sedimentary deposits with variable thicknesses along the stream (Fig. 4).

The phonolitic formation is the one that presents the saturated zone in the coastal aquifer over older, more impermeable alkaline basalts. The Tenoya ravine has superficial outcrops and is estimated to be approximately 200 m thick, with multiple strata of scoriaceous levels and diaclastic rock with a thickness varying between 2 and 20 m, with a slight dip towards the sea and different degrees of fracturing and permeability. The majority of the materials are competent and well-supported in the wells drilled. At the top of the formation are more recent, permeable and not very compact materials, mainly sedimentary and alluvial deposits in the gully bed area. Geological information is limited, with only a few stratigraphic columns from boreholes in the area.

From the data collected in the geological and hydrogeological studies, the starting parameters for the borehole of the recharge device were selected. The basic formulation of well hydraulics (Villanueva and Iglesias, 1984) was used to design the borehole. A lack of knowledge of the exact characteristics of the point where drilling would be carried out in the initial phase of the project created uncertainty; therefore, different hypotheses were considered (Table 1), mainly varying the hydraulic parameters of transmissivity (100-10 m^2/day) and aquifer thickness (200-100 m).

With these data, different theoretical calculations have been used to define the basic design parameters for the design of the ASR device, which are summarized as follows.

- The recharge capacity was estimated using Thiem's formula modified for the consideration of the rises in the injection well in the free aquifer, both considering Jacob's upwards correction (>15% saturated thickness) and without it. Several simulations were carried out varying the transmissivity (10–100 m^2/day) and the radius of influence (10 and 500 m). It has been observed that for transmissivities greater than 50 m^2/day, the theoretical admitted flow rates for the case study exceed the daily production of reclaimed water from the Tenoya WWTP and that for transmissivities greater than 25 m^2/day, specific flow rates would be obtained that are greater than 0.25 L/s/

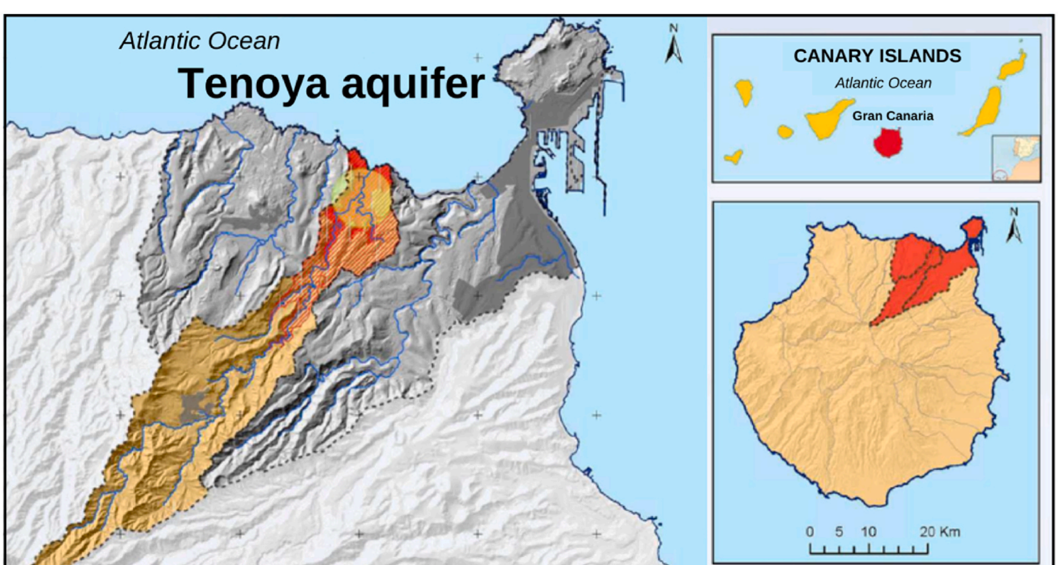

Fig. 2. Location of the study area: shown in red is the area selected for the injection of reclaimed water from the Tenoya Wastewater Treatment Plant in Las Palmas de Gran Canaria (Canary Islands, Spain). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

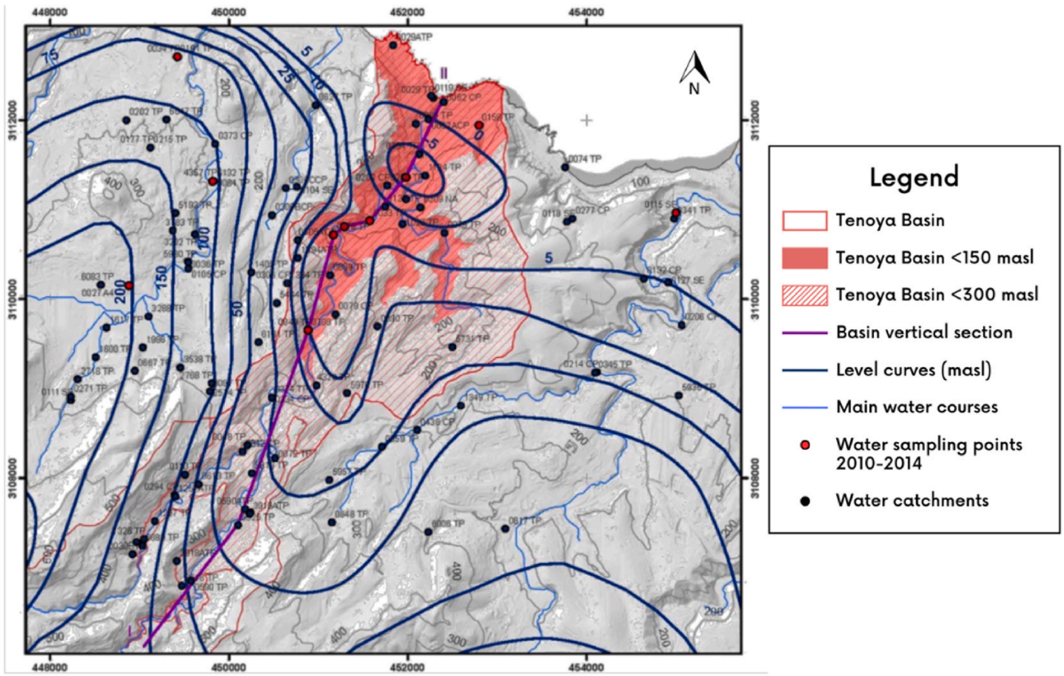

Fig. 3. Piezometric map of the Tenoya aquifer. Period 2010–2014. Source: Own elaboration.

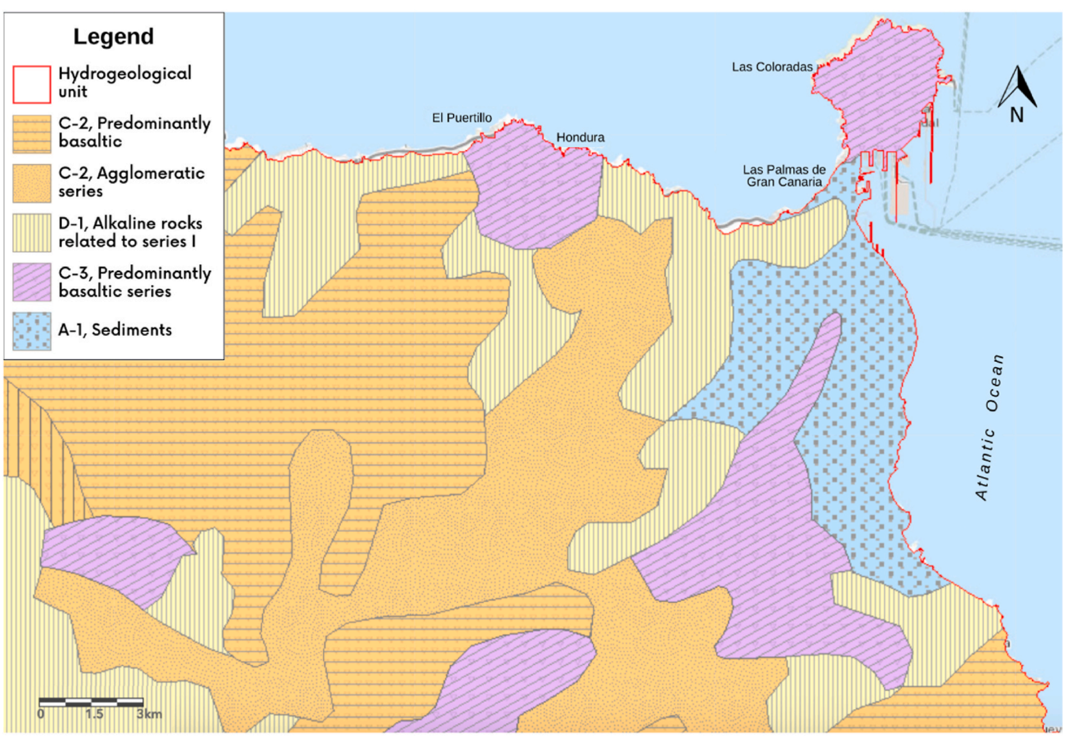

Fig. 4. Lithographic map of the site selected for the study. Source: Adapted from the Official Maps of the Geological and Mining Institute of Spain.

m, which is a recommended reference value (Fernández Escalante, 2010), so a single recharge borehole would be sufficient in this case.

- The recharge pressure is limited to a maximum ascent of 35.5 m with respect to the static piezometric level inside the borehole and without the ascents being high or reaching the borehole head. In this case study, there is also a wide safety margin with respect to the theoretical allowable pressure to avoid hydraulic fracture pressure in the water formation. Safety gradients of 0.12–0.2 atm/m have been considered (E. Custodio, 2000).
- Clogging is the most limiting factor in the design of the device. For the theoretical calculation, an approximation has been made of the total ascent due to the head losses produced by the recharge in the well (estimated using Jacob's formulation in the variable regime), plus those produced by clogging over time. This estimate only considers the physical clogging due to deposition of suspended material on the filtering zone considering an unfavorable suspended solids content of 5 mg/L. The permeability of the sediment deposit is considered to be invariant over time, with a conservative value of

Table 1
Starting data for calculation of the design parameters.

Parameters	Data	Unit
Device	ASR	–
Depth	116,5	m
Depth Filters	75	m
Diameter Tubing	0,35	m
Bore Diameter	0,4	m
Thickness Tubed	0,005	m
Aquifer Type	Open	–
Dynamic Piezometric Level of Recharge	90	m
Dynamic Piezometric Level of Pumping	45,5	m
Static Piezometric Level	54,5	m
Filter Zone Thickness	36,5	m
Transmissivity	100–10	m^2/day
Aquifer Thickness	100–200	m
Storage Coefficient	0,01	–
Effective Porosity	0,01	–
Recharge Water	Reclaimed	–
Sediment Density Clogging	1100	kg/m3
Suspended Solids Content	0,005	kg/m3
Permeability Sediment Clogging	0,01	m/day

0.01 m/day. With the fixed design data of maximum rise within the borehole and a fixed transmissivity of 50 m^2/day, different simulations were carried out for different time periods of continuous recharge (7, 15, 30, 45 and 60 days) and with different recharge flow rates to determine the total rises and compare the clogging ratios with reference values. The results obtained showed less clogging for a design without gravel packs and total lift levels within the set limit for flows below approximately 800 m^3/day. However, only for flows below 200 m^3/day are acceptable clogging ratios of 0.01 m/day obtained (Jeong et al., 2018), conditioned by the suspended solids content considered.

- The refuelling time determines the maximum duration of each refuelling cycle before refurbishment of the device is required to restore injectivity. It has been determined with the same theoretical approach as the clogging ratio. For different flow rates, the time in which the total ascent, including clogging, reaches the maximum limit of limited ascent inside the well of 35.5 m above the static level is obtained. The results indicate that for flow rates of less than 500 m^3/day, the cycles would be more than 295 days, allowing for approximately a single action each year.
- The extraction or recovery capacity was calculated using Jacob's formulation for a variable regime to obtain the pumping duration that does not produce drops of more than 15 m, as this would affect the proposed pumping chamber. The results obtained for a transmissivity of 50 m^2/day and a storage coefficient of 0.01 show that for flows of less than 600 m^3/d, the drops are admissible with a continuous pumping of 72 h. However, recovery is not a priority objective of the device but rather a guarantee of maintenance and cleaning to prevent clogging, so that for short cleaning pumping (0–30 min), an extraction flow rate of approximately 1000 m^3/d would be acceptable. For this purpose, it is recommended that the extraction flow rate is higher than the injection flow rate.

3. Results and discussion

3.1. Hydrochemical study

Based on the hydrochemical analysis, it was possible to compare the groundwater from the catchments bordering the project area and the reclaimed water to be used as recharge water (Table 2). This comparison verified the better quality of the recharge water with respect to the original aquifer water and assessed their possible interaction.

From the results obtained in this study, the brackish composition of the waters was corroborated, and the main facies was the sodium chloride type. It was observed that salinity increases depending on the dynamic or static state of the catchments, since Canary wells are partially penetrating in the saturated zone, causing an increase in salinity when dynamic pumping levels are maintained continuously with respect to static levels during periods of inactivity in extraction. This phenomenon occurs due to saline upwelling cones from deeper water (Herrera and Custodio, 2003). This could indicate that there are saline upwellings from interphase mixing waters. However, no evidence of marine intrusion was observed from the spatial representations and ion ratios performed.

Table 2
Comparison between the values obtained in two of the sampled wells and the values that the water from the Water Regeneration Station should have to comply with RD 1620/2007, which establishes the legal regime for the reuse of treated water.

Parameters	Unit	Tenoya Water Regeneration Plant	Well 1	Well 2
Electrical conductivity	µS/cm	700 ± 50	4023 ± 20	5560 ± 20
Temperature	°C	21 ± 4	24 ± 1	25,6 ± 1
pH	–	7,3 ± 0,5	6,5 ± 0,1	6,1 ± 0,2
Turbidity	NTU	2 ± 0,5	–	–
TSD	mg/l	1000 ± 100	2834 ± 20	3786 ± 20
SAR index	(meq/l) 1/2	–	6,4 ± 0,1	6,2 ± 0,2
Hardness	mg $CaCO_3$/l	–	1094 ± 20	1588 ± 20
LSI Index	–	–	–	–
Alkalinity	mg CaCO3/l	–	706 ± 5	782 ± 5
Bicarbonates (HCO_3)	mg/l	100 ± 50	861 ± 10	955 ± 10
Chlorides (Cl)	mg/l	200 ± 50	802 ± 25	1370 ± 25
Nitrates (NO_3)	mg/l	9,9 ± 5	63,7 ± 2	19 ± 3
Sulphates (SO_4)	mg/l	10 ± 10	275 ± 10	375 ± 10
Orthophosphates (PO_4)	mg/l	9,1 ± 5	–	–
Sodium (Na)	mg/l	100 ± 25	483 ± 10	569 ± 10
Calcium (Ca)	mg/l	15 ± 5	141 ± 5	231 ± 5
Magnesium (Mg)	mg/l	10 ± 5	178 ± 5	243 ± 5
Potassium (K)	mg/l	5 ± 5	30,3 ± 1	25,6 ± 2
Boron (B)	mg/l	0,5 ± 0,2	0,96 ± 0,1	1,02 ± 0,2
Ammonium (NH4)	mg/l	0,3 ± 0,1	0,06 ± 0,05	0,11 ± 0,06
BOD5	mg/l	1,39 ± 0,2	–	–
COD	mg/l	62,16 ± 0,25	–	–
Suspended solids (SS)	mg/l	4,61 ± 1	–	–
Escherichia coli	UFC/100 ml	0 ± 1	–	–
Intestinal Nematodes	Eggs/l	0 ± 1	–	–

3.2. MAR

Given that deep recharge experiences are different, depending on their location, an evaluation of alternatives among the different existing devices was proposed, according to the literature consulted (Jeong et al., 2018; Ousrhire and Ghafiri, 2022). Managed artificial recharge systems by deep wells or boreholes are typically used in areas where the use of surface systems is inadequate, either because there is little space for the implementation of surface systems or because the aquifers are not highly transmissive or have alternating permeable and impermeable layers (Fernández Escalante, 2010). Therefore, the selected technique was aquifer storage and recovery (ASR); due to the orography of the Canary Islands, surface recharge, such as the floodwater spreading method (FSM) (Jahangirzadeh and Ghanbarzadeh Lak, 2021), is more complicated to install in these islands due to insufficient land available for its implementation and the depth of the water table. Because the high cost of ASR hampers its use, a recent study in Kansas ensured that low-cost wells installed with direct-push (DP) technology can present a cost-effective and efficient alternative for ASR projects in unconsolidated near-surface aquifers (Liu et al., 2016).

The investment costs for the development of the project are estimated to be between 385.00 and 770.000 Million Euros, depending on possible variations in geological conditions. The annual operating and maintenance costs are estimated at 40,000 Euros. For the recharge storage volume of 147,500 m^3/year, considering a useful life of 30 years, a unit cost of 0.36–0.42 €/m^3 is estimated. By way of comparison, hydrological planning includes the construction of regulating reservoirs with a capacity of 40,000–120,000 m^3, with estimated investments of between 2.0 and 6.2 million Euros. In Gran Canaria, the price of reclaimed water is 0.42–0.49 €/m^3, while desalinated water is 0.59–0.70 €/m^3.

The ASR devices are based on a borehole with a diameter of less than 1 m that can function as an injection borehole or as a water extraction borehole (Majumdar et al., 2021). This versatility allows storage and recovery of the recharged water when necessary. In addition, it performs

Fig. 5. Location of the artificial recharge well next to the Tenoya WWTP.

well against clogging, allows periodic cleaning and improves the management of specific quality problems in the well (Missimer et al., 2011).

Finally, after the simulations were developed, reasonable results were obtained, slightly conservative and allowing good operation of the system, as well as correct sizing of the equipment and elements to be installed. The results obtained can be summarized as follows: i) Recharge capacity = 500 m^3/day ii) Extraction capacity = 1000 m^3/day iii) Clogging rate = 0.071 m/day iv) Recharge times = 295 days per cycle, and v) Cleaning frequency = daily. Subsequently, the dimensions of the device to be executed were determined: borehole depth, drilling and casing diameter, depth and length of the filtering zone and location of the pump.

The borehole is located in the northern part of the internal plot of the Tenoya treatment plant for technical reasons of operability, available power supply and remote-control facilities, less installation of transport pipes for recharge and extraction and protection against flooding (Fig. 5). The discharge of the cleanings is facilitated by the return to the treatment plant. There is a reservoir that allows additional regulation for the experimental phases of the pilot. The location allows for a less extensive pizometric control network around the device by also taking advantage of existing wells that only use water for agricultural irrigation.

The final solution adopted was adapted to the planned installations of the Tenoya wastewater treatment plant, occupying the smallest possible surface area and with the necessary safety precautions, guaranteeing easy execution and operation (Fig. 6). Three sets of elements of the system can be distinguished: the borehole elements, the recharge-extraction installations and the aquifer control piezometers.

First, the elements that make up the recharge borehole were designed: PVC-U casing and grids, cementations with special chloride-resistant grout, surface grouting, borehole closure head and the piezometric tube for control. Second, the elements that would form part of the recharge installations were developed: submersible pump, flow control valve, injection-extraction column, wellhead, valves, hydraulic conduits and control equipment (Fig. 7). Finally, three control piezometers were designed around the aquifer to monitor the operation of the system.

The quality of the recharge water is very important in the application of depth techniques; any deviation in the control parameters could cause complex contamination that would then need to be resolved and could possibly affect other users (Waterhouse et al., 2020). In addition, it is necessary to know its composition in depth to avoid possible unfavorable physicochemical interactions, clogging processes or bacterial proliferation in the injection well (Escalante et al., 2020).

The waters were characterized to check their qualitative status in accordance with the maximum allowable values (MAV) established in the Spanish Royal Decree 1620/2007 (BOE, 2007) for their intended use of aquifer recharge by direct injection. These maximum allowable values are as follows: i) intestinal nematodes (1 egg/10 L); ii) *Escherichia coli* (0 CFU/100 ml); iii) suspended solids (10 mg/L); iv) turbidity (2 NTU); and v) nitrates (25 mg NO_3/l).

The requirements established for reuse in this specific instance are among the most restrictive regulated uses (Jodar-Abellan et al., 2019). This guarantees water with very remarkable physicochemical, microbiological and chemical conditions. The required MAVs were as follows: i) intestinal nematodes: 1 egg/10 L; ii) *E. coli*: 0 CFU/100 ml; iii) suspended solids: 10 mg/L; iv) turbidity: 2 UNT; v) total nitrogen: 10 mg N/L; and vi) nitrates: 25 mg NO_3/L. Although the regulations are very specific regarding groundwater quality, ecology and microbiology are also of great importance in managed artificial recharge projects, as they are altered by the soil moisture produced by recharge (Barba et al., 2019).

Therefore, based on the laboratory analyses studied and the existing forecasts (Table 2), it was determined that the quality of the reclaimed water expected from Tenoya Station could be used as recharge water. Currently, monitoring water and ensuring that it is free of emerging pollutants (EPs) is becoming vital in a world where an increasing number of chemicals are invading everyday life (Valhondo et al., 2016). On the island of El Hierro (Gasco Cavero et al., 2023), also located in the Canary archipelago, water samples were taken throughout the island to study the presence of 70 EPs, and although they were lower than expected, there is concern that these types of contaminants must not reach the groundwater of the islands.

MAR projects can quickly yield positive results. An example of this is the aquifer of the Plana de Castellón (García-Menéndez et al., 2021), where almost 3 months after the start of water injection into the aquifer, the piezometric level increased by approximately 3.5 m. In addition, this aquifer, which has brackish water, as is also the case in Tenoya, observed positive changes in its hydrochemistry by including oxic and nutrient-rich water.

Moreover, a study conducted in Cape Town, South Africa, simultaneously tested the recharge capacity of an infiltration method and an injection method (which is the one proposed in this study), finding that recharge by injection is more effective than recharge by infiltration. The data showed that water storage in the aquifer increased by 6 Mm^3 with injection compared to the 4 Mm^3 provided by infiltration (Mauck and Winter 2021).

4. Conclusions

From the work carried out, it can be concluded that these technologies may be technically feasible and innovative in their application in the Canary Islands, a priori with an acceptable productive recharge capacity per device, possibly scalable after the experimental phase and extrapolable to other locations with similar conditions. However, it would be advisable to carry out a more exhaustive study over a longer monitoring period to determine the evolution of the aquifer and the possible fluctuations in the chemical conditions of the reclaimed water from the WWTP in operation before developing the pilot.

In addition, this work has important environmental benefits in terms of conservation and improvement of the status of the groundwater bodies in the area studied, as well as a contribution to knowledge and research on water management in volcanic terrain and islands. On the other hand, in economic terms, it can be a viable alternative, especially when compared to other similar storage methods.

In short, in the Canary Islands, there is an urgent need to close the water cycle because the pressures on the aquifer are constantly increasing, as it is a tourist area with a growing local population. Artificial recharge of the aquifer can therefore favour a quantitative and qualitative improvement in groundwater resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Noelia Cruz Perez reports was provided by University of La Laguna. Noelia Cruz Perez reports a relationship with University of La Laguna that includes: employment.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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