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Sites and Indicators of MAR as a Successful Tool to Mitigate Climate Change Effects in Spain

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Abstract: In this article, the authors will support Managed Aquifer Recharge (MAR) as a tool to combat Climate Change (CC) adverse impacts on the basis of real sites, indicators, and specific cases located Spain. MAR has been used in Spain in combination with other measures of Integrated Water Resources Management (IWRM) to mitigate and adapt to Climate Change (CC) challenges. The main effects of CC are that the rising of the average atmospheric temperature together with the decreasing average annual precipitation rate cause extreme weather and induce sea level rise. These pattern results in a series of negative impacts reflected in an increase of certain events or parameters, such as evaporation, evapotranspiration, water demand, fire risk, run-off, floods, droughts, and saltwater intrusion; and a decrease of others such as availability of water resources, the wetland area, and the hydro-electrical power production. Solutions include underground storage, lowering the temperature, increasing soil humidity, reclaimed water infiltration, punctual and directed infiltration, self-purification and naturalization, off-river storage, wetland restoration and/or establishment, flow water distribution by gravity, power saving, eventual recharge of extreme flows, multi-annual management and positive barrier wells against saline water intrusion. The main advantages and disadvantages for each MAR solution have been addressed. As success must be measured, some indicators have been designed or adopted and calculated to quantify the actual effect of these solutions and their evolution. They have been expressed in the form of volumes, lengths, areas, percentages, grades, euros, CO_2 emissions, and years. Therefore, MAR in Spain demonstrably supports its usefulness in battling CC adverse impacts in a broad variety of environments and circumstances. This situation is comparable to other countries where MAR improvements have also been assessed.

Keywords: Managed Aquifer Recharge; MAR; climate change; water management; IWRM; adaptation measures; indicators; Spain

1. Introduction

In a world of arising concern for the effects of Climate Change (CC), the search for practical solutions to mitigate undesirable consequences implies a global change of mentality in the management of water resources. Beyond overexploitation of water bodies, it is mandatory to build models that take into account the current effects of CC, especially in those countries with arid or a semiarid climate, such as the Mediterranean area, where the annual rain scarcity overlaps with punctual extreme precipitations. These accepted phenomena are indeed heightened according to the prevailing CC models.

The main manifestations of CC shown in this paper on which the Managed Aquifer Recharge (MAR) techniques can incise are an increase in the average temperature, a decrease in the annual precipitation, recurrent extreme weather and a rise in the sea level [1].

The key problems and impacts of CC whose figures are globally rising are the evaporation rate, water demand, fire risk, and run-off. On the other hand, decreasing figures are found, at least, in the water supply, wetland surface and hydro-electric energy production [2].

Managed Aquifer Recharge (MAR) can provide with a large array of technical solutions to mitigate those adverse CC effects by not only managing groundwater, but also showing an integrated vision of water resources and their associated wetlands, following the EU Water Framework Directive approach (2000/60/CE) [3]. This concept has been put into practice all over the world, facing different CC challenges, from building extreme run-off reservoir systems to fighting sea level intrusion. The monitoring of these devices shows a bunch of indicators of successful recharge and simultaneous local CC mitigation effects.

Some out-of-Spain models to assess the potential impact of future climate conditions on groundwater quantity and quality have been performed, e.g., in the Central Huai Luang Basin of Thailand. There, four different cases were developed to study the spreading saline groundwater and saline soils in this basin as a consequence of MAR activities, concluding that for all future climate conditions, the depths of the groundwater water table not only will increase, but also the salinity distribution areas will follow this trend by about 8.08% and 56.92% in the deep and shallow groundwater systems, respectively [4].

On the Spanish Mediterranean coast—an area with severe salinization over the last 40 years due to intensive exploitation of groundwater—piezometric levels and chloride concentrations have been monitored. Dry periods and their associated increases in pumping caused the advance of seawater intrusion. The sharp reduction in groundwater withdrawals over the last decade has pushed the saline wedge backwards, although the ongoing extraction and the climate conditions mean that this retreat is quite slow, and could be enhanced by means of MAR applications [5].

On the Southern Italian Mediterraneas coast, over four models were tested to foresee saline water intrusion threatening fresh groundwater resources. Among all the processes taken in consideration for the simulations, authors remarked the importance of a detailed statigraphic reconstruction and geomorphological settings. The results of the validated model indicated the strong link between surface water bodies (specially affected by CC impacts) and the coastal aquifer, with a slight salinization increase for the horizon 2050 [6].

In a recent study performed by the International Association of Hydrogeologists (IAH) considering inputs from a vast variety of countries with special focus on Brazil and South Africa, authors claimed the excellent groundwater drought resilience and how it provided a 'natural solution' for the deployment in CC adaptation, by means of 'strategic rethinking', conjunctive use, and quality protection. These actions should be applied on storage availability, supply productivity, natural quality and pollution vulnerability. They advised that though uncertainty remains over the long-term effects of CC on groundwater recharge, a higher impact on shallow aquifers is still expected. Nevertheless, they also remarked the necessity for more studies to be undertaken due to the current lack of definitive data [7].

2. Materials and Methods

The main objective of this paper was to collect figures and examples that could illustrate that MAR, as well as in combination with other techniques, could successfully contest the effects of CC by adaptation and even mitigation strategies.

The methodological approach used below pairs the problems and solutions together. Main CC impacts and risks were going to be matched with the available MAR techniques that could be used to mitigate them. Effects, impacts and corresponding MAR solutions were organized in 3 different columns in Figure 1.

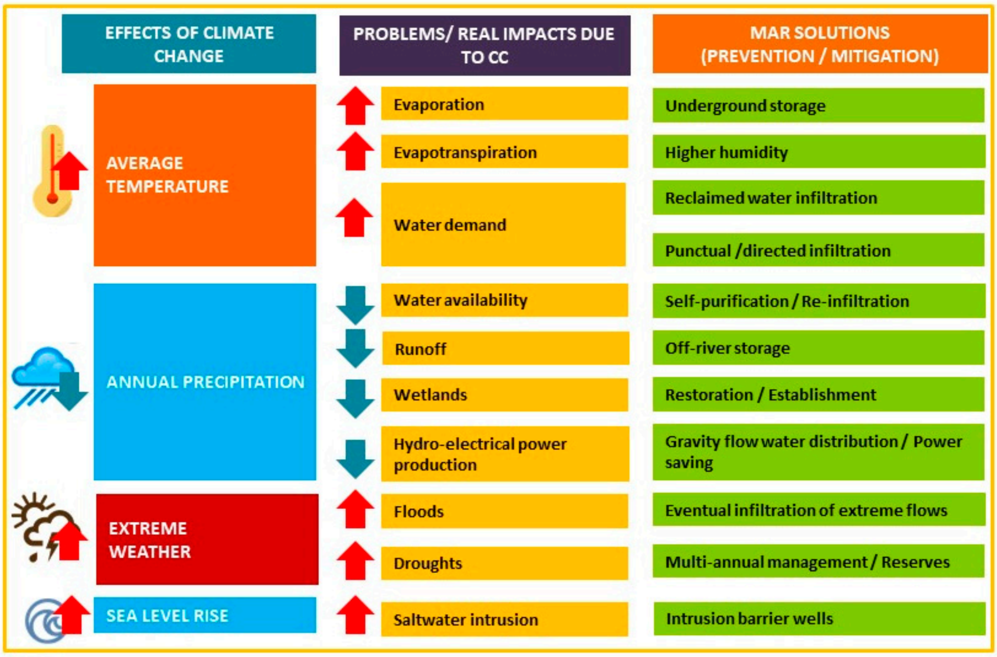


Figure 1. Relationships between the main manifestations of climate change (CC) and their main problems and impacts, and the technological solutions that can be implemented as adaptation measures.

3. Results

Results will be explained in the following pages, where some indicators will be proposed to measure the quantitative impact on CC mitigation as related to other usual techniques.

Examples of initiatives to combat climate change have been organised into four groups, as shown in Figure 1:

1. Examples of technological solutions to palliate rising temperatures (Section 3.1).
2. Examples of technological solutions to palliate decreasing annual precipitation rates (Section 3.2).
3. Examples of technological solutions to manage extreme phenomena (Section 3.3).
4. Examples of technological solutions to reduce the rising of the sea level and saline water intrusion (Section 3.4).

Spanish examples are located for every group (Figure 2).

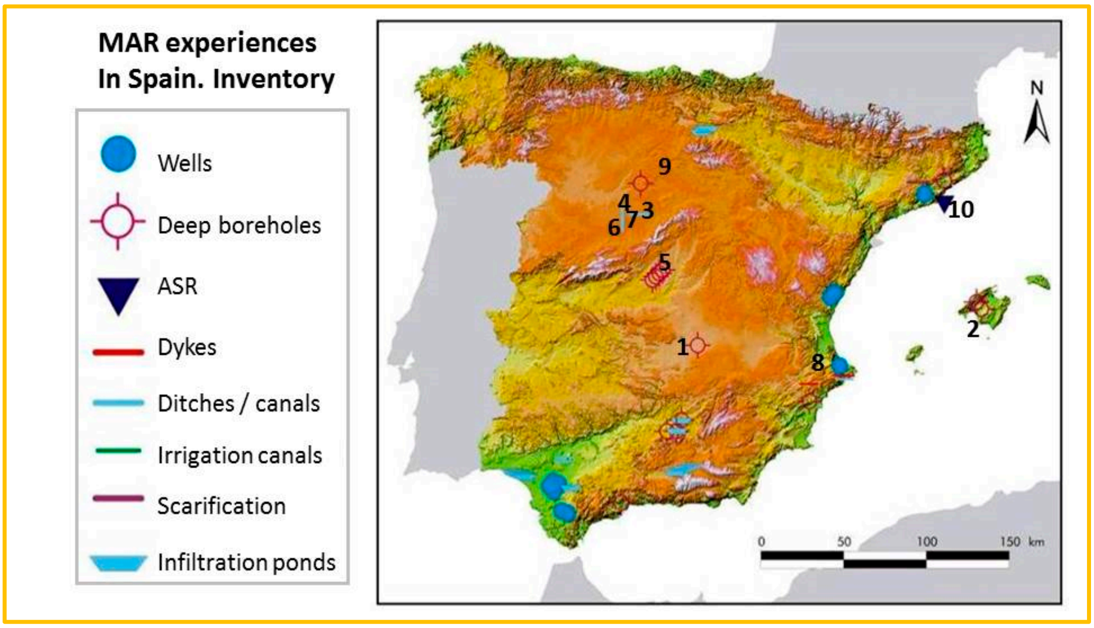


Figure 2. Map of Spain containing the Managed Aquifer Recharge (MAR) sites to fight CC adverse impacts studied and exposed. Numbers in the map follow in brackets after the header of the corresponding example in the next paragraphs.

3.1. *Examples of Technological Solutions to Palliate Rising Temperatures*

The International Panel for Climate Change (IPCC) in the 5th Assessment Report (2014) declared that the global temperature will rise more than 1.5 °C during the 21st century in all the possible scenarios and probably 2 °C in two of the highest emission sceneries [8]. Evaporation, evapo-transpiration and water demand are expected to follow this trend, but MAR has its own means to counteract those effects.

The indicators for each of the following examples have been gathered in Table 1.

Table 1. Selected Spanish MAR sites and indicators to track their relationship with CC adverse impacts.

MAR SITE (*)	CC IMPACT	INDICATOR/S
Guadiana Canal, Castilla-La Mancha (1)	PALLIATE RISING TEMPERATURE	Capability to recharge peak flows: Intermittent underground water storage. Total recharge in 48 supplementary hm^3/year
Parc Bit Majorca Island (2)	Palliate rising temperature	Lower surface temperature according to thermographic photographs
Gomezserracín, Castilla y León (3)	Palliate rising temperature	Increase in soil humidity during MAR cycles
Alcazarén, Castilla y León (4)	Strategic water storage/Palliate rising temperature	Increases of 0.4 hm^3 per year recharging reclaimed water
CYII Madrid (5)	Strategic water storage/Palliate rising temperature	Capability to recharge peak flows: Increases up to 5 hm^3 per year by recharging potable water excess
Santiuste, Castilla y León (6)	PALLIATE DECREASING PRECIPITATION RATES	Strategic reserve for drought periods +/−12–53% in water physical and chemical parameters

Table 1. *Cont.*

MAR SITE (*)	CC IMPACT	INDICATOR/S
Santiuste, Castilla y León (6)	Wetlands Restoration	5% recharge volume dedicated to alkaline lake restoration
El Carracillo, Castilla y León (7)	Gravity flow water distribution	Transport length without pumpage: 40.7 km of pipes and channels by gravity. Supplied irrigated area: 3500 ha
El Carracillo, Castilla y León (7)	Energy efficiency through Managed Aquifer Recharge	Saving in terms of kW-h is between 12 and 36% thanks to water level rise
Arnachos, Valencia (8)	MANAGE EXTREME CC PHENOMENA	Reduce precipitation peak thank to a high recharge capacity borehole (up to 1000 L/s)
Neila, Castilla y León (9)	Forested watersheds	Forest is capable of retaining and channelling 15%–40% of the volume of surface runoff
Santiuste, Castilla y León (5)	Multiannual management by means of Off-river storage	2.62 hm^3/year stored out of Voltoya River would allow groundwater extractions for irrigation during 3 years with no rain
El Prat de Llobregat, Cataluña (10)	REDUCE SEA LEVEL RISE AND SALINE WATER INTRUSION	Evolution of seawater intrusion by iso-chlorides lines evolution

(*) The positions of these MAR sites have been exposed in the Figure 2.

3.1.1. Underground Water Storage. Canal del Guadiana, Castilla-La Mancha (1 in Figure 2)

The high temperatures over 40 °C in August, that can be found in the historic record of the Castilla-La Mancha Region [9], and the shallow streams multiply the evaporation rate in summer. A net of wells close to the canal of Guadiana was built by the Guadiana River Water Authority (CHG) in Castilla-La Mancha (Figure 3), for rural development and mitigation of the overexploitation of the groundwater body (known as aquifer #23). This MAR system can increase the total storage volume by means of intentional recharge in about 48 supplementary hm^3 per year [10].

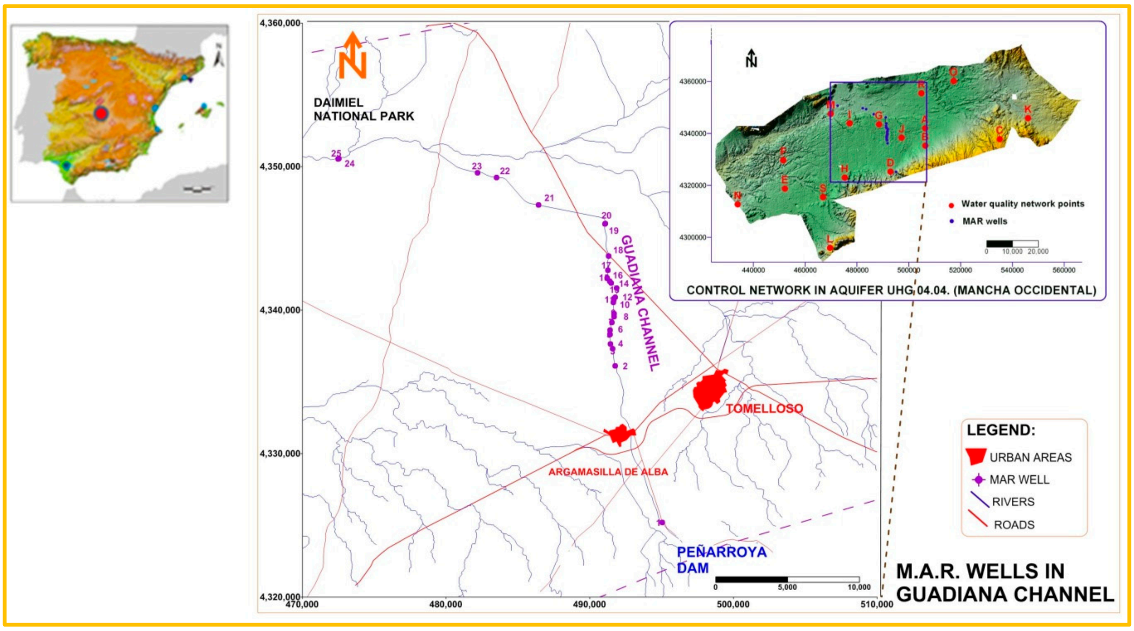


Figure 3. General sketch of the MAR system of wells near Canal del Guadiana for irrigation and environmental purposes.

3.1.2. Temperature Reduction. Parc Bit, Palma de Mallorca, I. Balears (2)

The Sustainable Drainage Urban Systems (SDUS) consisted in a group of building items that was integrated into the urban architecture [11], with the goal to increase the city water permeability by means of rising run-off infiltration into the aquifers under the town surface. At the same time, they could also combat Urban Heat Island (UHI) through the development of water stores and green areas within the city landscape.

A good example of this practice can be found in Parc Bit (Palma de Mallorca, Figure 4), where the vegetated roofs, fed by rain collection, were able to reduce the air temperature in the range of 1.5 to 6 °C. Thermographs were able to establish a clear and quick difference displayed in the pattern of colours when areas with or without a canopy were compared [12]. A square meter of green cover could evaporate more than half a litre of water per day.

Figure 4. Sustainable drainage urban systems (SUDS) to reduce the urban heat island (UHI). Model and development of green roof on the Parc Bit building, Palma de Mallorca, Spain. Example of thermography to track the UHI evolution.

3.1.3. Increase in Soil Humidity. Gomezserracín, Castilla y León (3)

Los Arenales aquifer in Gomezserracín provided an example of increased soil moisture and a rise in the phreatic surface brought about by underground storage through a system of canals and streams (Figure 5). Artificial recharge operations, initiated in 2003, resulted in an average rise in the phreatic surface of more than 2 m, even though it was a passive system since it did not require any electrical power to work. This additional storage in the unsaturated zone increased soil moisture by 15%–20% according to datasets obtained from the MARSOL ZNS-3 station [9–17], equipped with a set of sensors which captured measures in both, the saturated and the unsaturated zones. Humidity evolution has been the main assessed indicator after taking into account the natural precipitation. The costs, appart from the initial investment, were due to cleaning and maintenance, with an average of about 30,000 €/year, contributed by the irrigators´ association.

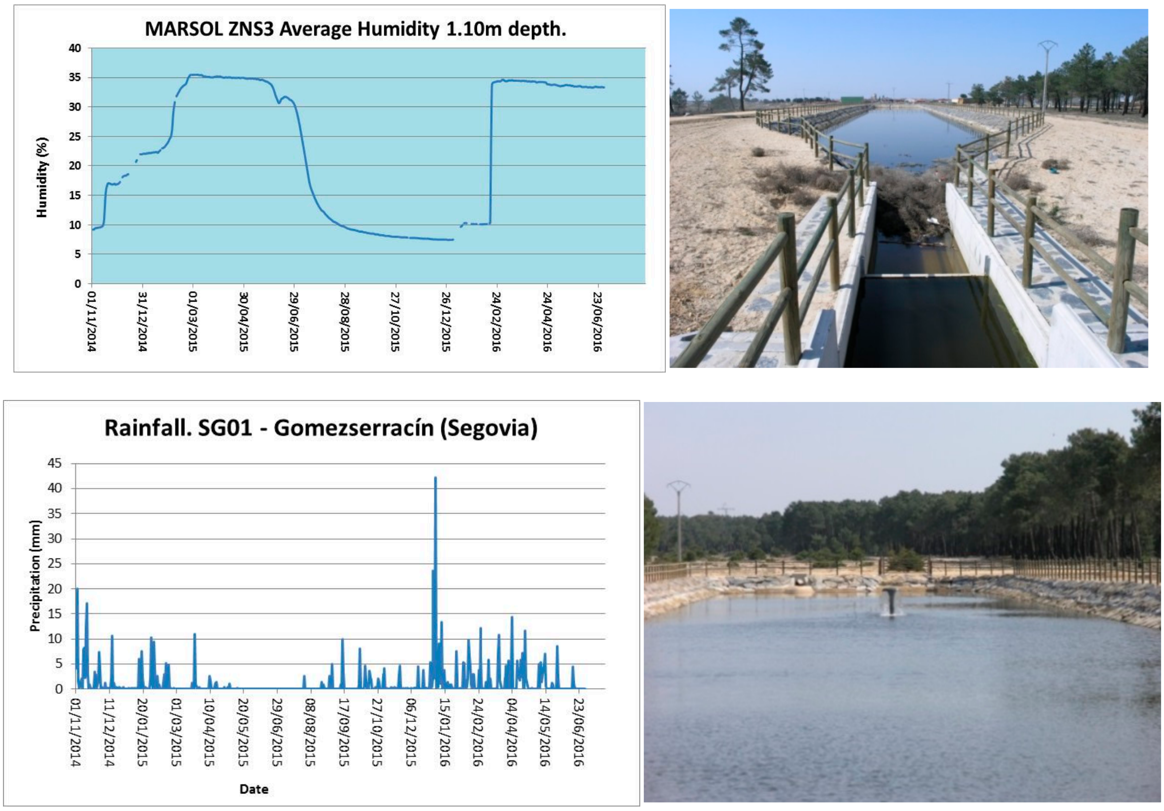
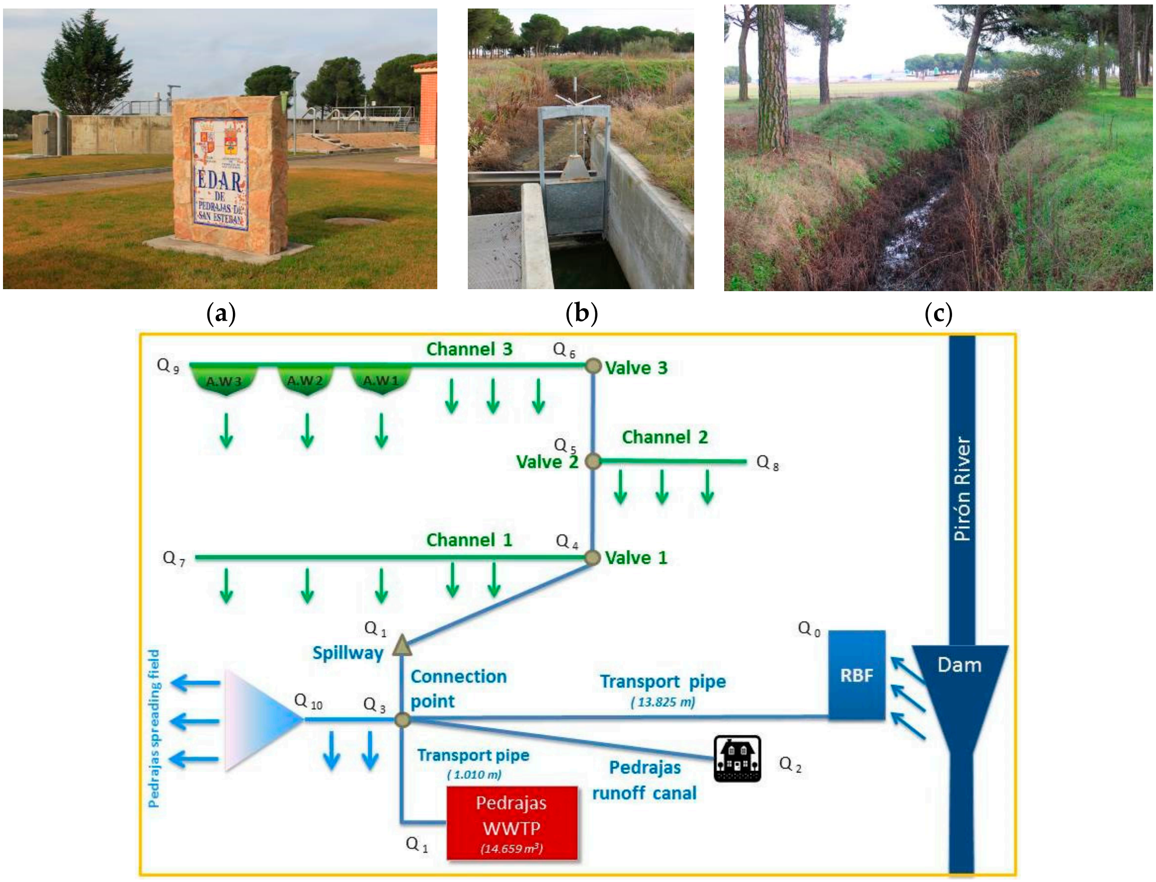


Figure 5. Infiltration ponds in the Los Arenales aquifer: Gomezserracín, soil humidity evolution from the so called MARSOL ZNS-3 station datasets (02/11/2014–30/06/2016) and natural precipitation evolution [9].

3.1.4. Reclaimed Water Infiltration. Alcazarén, Castilla y León (4)

The recharge system (Figure 6) began operating in 2012, with an estimated annual recharge of 0.6 hm^3 for the whole working period, with scarce variations, thus the main indicator remained constant [14–23]. In the case of Alcazarén, the recharge water came from an advanced secondary treatment at Pedrajas de San Esteban Waste Water Treatment Plant (WWTP). It was convenient to perform post-treatment actions on the treated water (filter beds, geofabrics, reactive filters, and tests with disinfectants or Disinfection By Products (DBP), thus that its quality was more appropriate to make MAR without causing damage to either the environment or the consumers' health. These waters were subsequently used for irrigation and agro-industry supply.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Alcazarén Area and its MAR components, Valladolid (Spain). Photos of some key points (**a**) Pedrajas waste water treatment plant (WWTP); (**b**). Connecting junction of water from WWTP, Pirón River abstraction and urban run-off channel; (**c**). Run-off canal from Pedrajas Village to the connection point; (**d**) General scheme.

3.1.5. Punctual Infiltration. Canal de Isabel II, Madrid (5)

Canal de Isabel II or CYII is the public enterprise in charge of water purification, supply and wastewater management in Madrid. This company has built a system of deep injection in a semi-confined aquifer in the aquifer under the city. Punctual recharge takes advantage of low surface need and high capability to recharge peak flows.

This MAR device was mainly used during drought alerts for potable water supply, increasing resources in the city of Madrid with up to 5 hm^3 per year [11]. Thus, the indicator remained about this figure along that time period.

3.2. Examples of Technological Solutions to Palliate Decreasing Annual Precipitation Rates

The impact of CC over the last decades has been connected to changes on a large scale in the hydrological cycle. Changes in the precipitation pattern were subjected to a significant variability in space and time. During the 20th century, precipitation had risen in inland areas and northern latitudes, while it had fallen between 10° S and 30° N from the 70s [16].

3.2.1. Self-Purification by Natural Biofilters and Nature Based Solutions. Santiuste, Castilla y León (6)

The Wastewater Treatment Plant (WWTP) of Santiuste pours the treated water into four lagooning purifications ponds, and then in the East MAR canal, with two different stretches: The first section works as a natural filter and as a MAR canal, and occupies more than one kilometre in length; while the second has a scarce filtering section, and extends for 1.5 km up to the mouth of the Sanchón artificial wetlands complex. Natural vegetation is respected in this stretch, as it acts as a biofilter, until it reaches the Sanchón spillway or is sent to the wetlands for post-processing actions. After the third (2b) artificial wetlands (AW), water returns to the East MAR canal with improved quality. Sunlight and plant growth play a crucial role in the purifying processes of the resulting water, combining one part from the Voltoya River and another from the treatment plant. Indicators assess the evolution of the main parameters, e.g., nitrate concentration was reduced by almost 30%, turbidity by 34%, and copper ions by more than 60% [9].

3.2.2. Wetlands Restoration. Santiuste, Castilla y León (6)

La Iglesia Lagoon is an alkaline wetland (salt-lake with basic salts of very high pH), which was rehabilitated by means of a solution specifically designed to take advantage of MAR facilities in the area. The recovery of the mineralization fundamental to maintain the characteristics of this type of water bodies, which was thus unique, was achieved through the interaction between the recharge water interacting with the biological and saline sediments deposited in the beach of the lagoon. This allowed the maintenance of a colony of endemic bacteria and the protection of vegetation of high ecological value. It was also an important refuge for aquatic birds. Finally MAR contributed in the preservation of minerals and biominerals considered "rare", thanks to about 5% of the total MAR volume being diverted to La Iglesia Wetland from the Santiuste West MAR Canal [17–22] by gravity (passive system). The amount of water used for environmental purposes has been adopted as the indicator for wetlands restoration.

3.2.3. Gravity Flow Water Distribution. El Carracillo, Castilla y León (7)

A "passive" MAR system is one that does not require electrical energy to operate. They generally function by gravity. Once the behaviour of the aquifer is known, it is possible to infiltrate the recharge water concentrated in a given area, relying on water resources being reused simply by gravity and the quality improvement by naturalization thanks to the aquifer. This technique makes it possible to reduce pipe layouts, with its consequent environmental benefits and cost savings. An example is the MAR artificial recharge at the head of the Carracillo, with distribution of the recharge waters from the storage area throughout the irrigable area, where most of the wells in the region are scattered. The volume of recharge water in the headwaters (East) is naturally directed through the aquifer to the discharge into the Pirón River and its tributary Malucas (West), and can be intercepted throughout the circuit by the irrigation and agro-industry wells, thus avoiding the laying of pipes.

The gravity distribution system (Figure 7) covers up to 40.7 km in length between canals and pipes from the dam to the final discharge area, serving an area of 3500 ha irrigated within 7586 ha of agricultural area [14]. Consequently, the adopted indicator is the length of the network divided by the number of irrigated hectares.

The system represents an important energy saving, which can be added to the savings involved in pumping water from shallower groundwater levels.

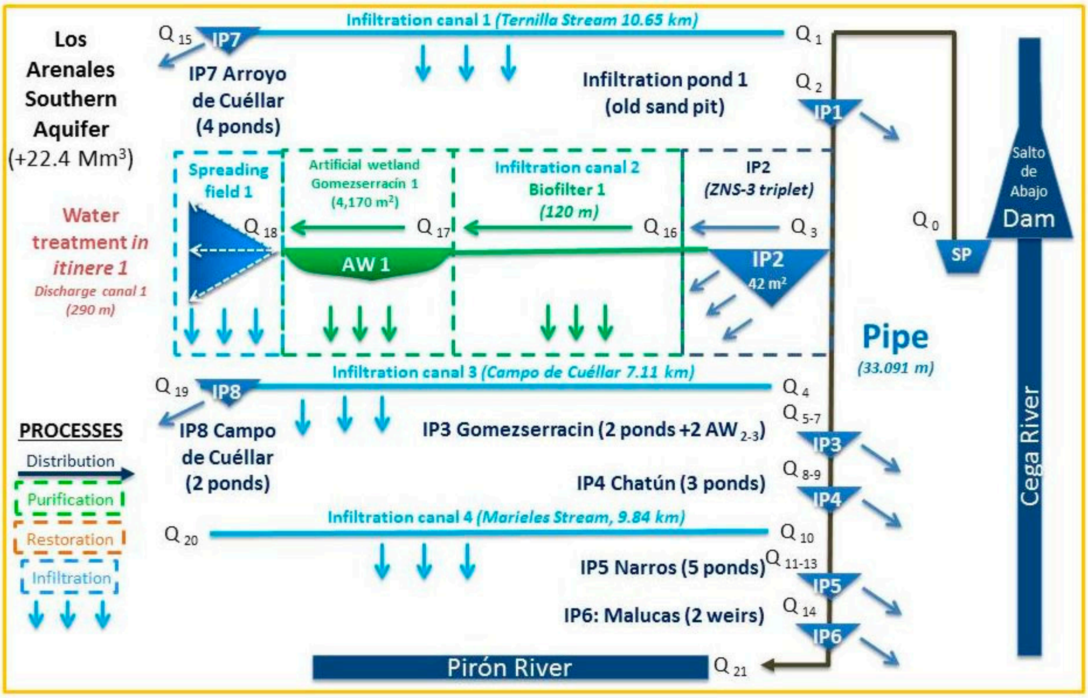
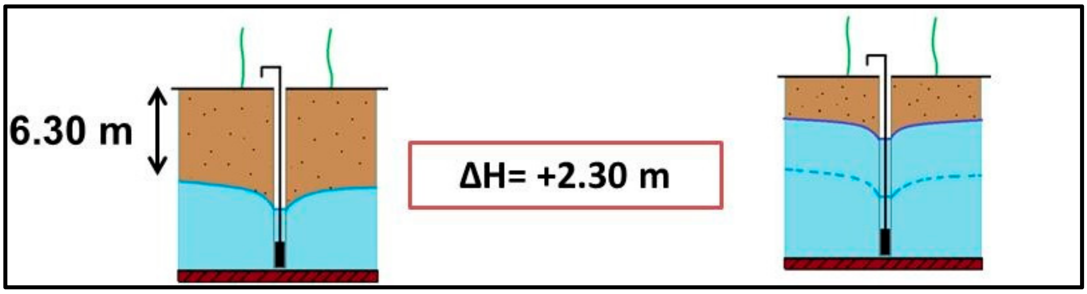


Figure 7. El Carracillo Area and its MAR sites. Devices, junctions, and functions, Segovia (Spain).

3.2.4. Energy Efficiency Increase through Managed Aquifer Recharge (El Carracillo, Castilla y León)

The recharge in El Carracillo contributes to the rise of the water table. Monitoring of the pumping costs of 314 extraction wells, with an average pumping of 9957 m^3 per well per annum, and the rise in the average phreatic level from 6.30 m to 4.00 m since 2003 to 2015 represented a rise of +2.30 m (Figure 8).



(**a**) (**b**)

Figure 8. Mock-up with the rise in water level resulting from artificial recharge operations in El Carracillo aquifer. Groundwater levels before (**a**) and after MAR operations (**b**).

The next task was to calculate how much a rise in water level of 2.30 m represented in energy terms. The saving for the irrigators' community, over a calculation of about 0.16 kW·h/m^3 as an average for water extractions, was between 12% and 36% depending on the area, the equivalent of 3000 €/annum as a maximum. This situation is very beneficial for irrigation and for shallow water ecosystems [9].

The volume of CO_2 emitted annually in the El Carracillo irrigation community had fallen by 10,780 kg, which was proportional to the rise in the phreatic surface, without taking into account upgrading, energy efficiency initiatives, etc.

The indicator adopted was either the cost savings or the reduction of emissions thanks to groundwater level rise caused by MAR actions.

3.3. Examples of Technological Solutions to Manage Extreme Phenomena

Extreme situations characterised by an abundance of water, such as floods, “cold drop” events, etc., GIAE [12] can be used, to a certain extent, for MAR. For this purpose, it was necessary to create a system to detain the fast-flowing water and channel it towards recharge devices.

3.3.1. Infiltration of Extreme Flows. Lliria, Valencia (8)

Since 1995, the Basic Civil Protection Guidelines for flood risk included safety procedures for preventing and limiting potential damage arising from this risk. An outstanding example was “Arnachos”, a 300 m deep borehole drilled in Losa del Obispo (Valencia) with an extremely high recharge capacity. This was located just a few metres from the irrigation pond of the Tarragó Irrigation Community (Figure 9). It enabled the extraction of a signification fraction of clean water from the irrigation pond in times of heavy rain. Therefore, this recharge system acted as a safety system, reducing the water excess during floods with zero electricity consumption.

Figure 9. Deep borehole “Arnachos” at Balsa del Campo, Valencia (UTM 685,744/4,391,256) located in the margin of an irrigation pond and used as both, a safety and recharge element. Photos courtesy of J.M. Montes and FEGA.

In 2014, it was used twice to reduce the peak-flow in a flood and to recharge the karstified aquifer with an infiltration rate of almost 1000 L/s for a period of 14 h (0.0504 hm^3), a significant amount of water that otherwise would have worsened the devastation caused by the flooding.

3.3.2. Forested watersheds. Neila, Castilla y León (9)

Many examples can be given of mechanical soil preparation for the purpose of increasing the infiltration rate: Channelling of river water to forests conditioned to store the water for a period and facilitate infiltration, as well as forests “organised” to receive “ordered” runoff and facilitate infiltration (Figure 10), etc. According to the DINAMAR project, the main share of artificial recharge in Spain comes from these kinds of devices and is estimated to be 200 hm^3 per year.

(**a**) (**b**)

Figure 10. Mechanical initiatives to minimise runoff, facilitate recharge, and subsequent plantation (**a**) and infrastructure to channel and level excess runoff water (**b**) Neila (Castilla y León).

An example of this sort was found in Neila, Burgos, where a canal had been constructed to channel water from a road towards a forest adequately prepared for this purpose. This forest was capable of retaining and channelling 15%–40% of the volume of surface runoff [10–18], therefore the indicator adopted is: Percentage of trapped water out of the total runoff.

3.3.3. Multi-Annual Management. Santiuste Basin (CyL) (6)

On certain occasions, conditioned by the potential storage volume of the receiving medium, multi-annual management actions may be performed on the recharge waters. This situation is possible either in areas of high volume available and any demand, or in areas of low potential storage volume and low demand.

In previous sections, situations of inter-annual water management have been described, including nodes of return to aquifers in topological schemes and strategic storage as a preventive measure of adaptation to hypothetical future adverse situations. In this same context, it is worth mentioning the multi-year management of reserves. This is a basic water management technique that considers water as a mining resource, renewable in years of favourable weather conditions, for use in years of prolonged drought.

For example, in the Los Arenales aquifer, Santiuste Basin (Figure 11), the storage of water during several winter periods, in addition to that previously existing when the aquifer was provisionally declared overexploited, could cushion short-term drought situations with almost no repercussions for farmers, as the system was passive too. According to data from the DINAMAR R&D project, the economic activity of the region could be maintained for a period of three years with zero rainfall during all this time, thanks to the reserves stored in the different underground basins that the aquifer presents [10–17].

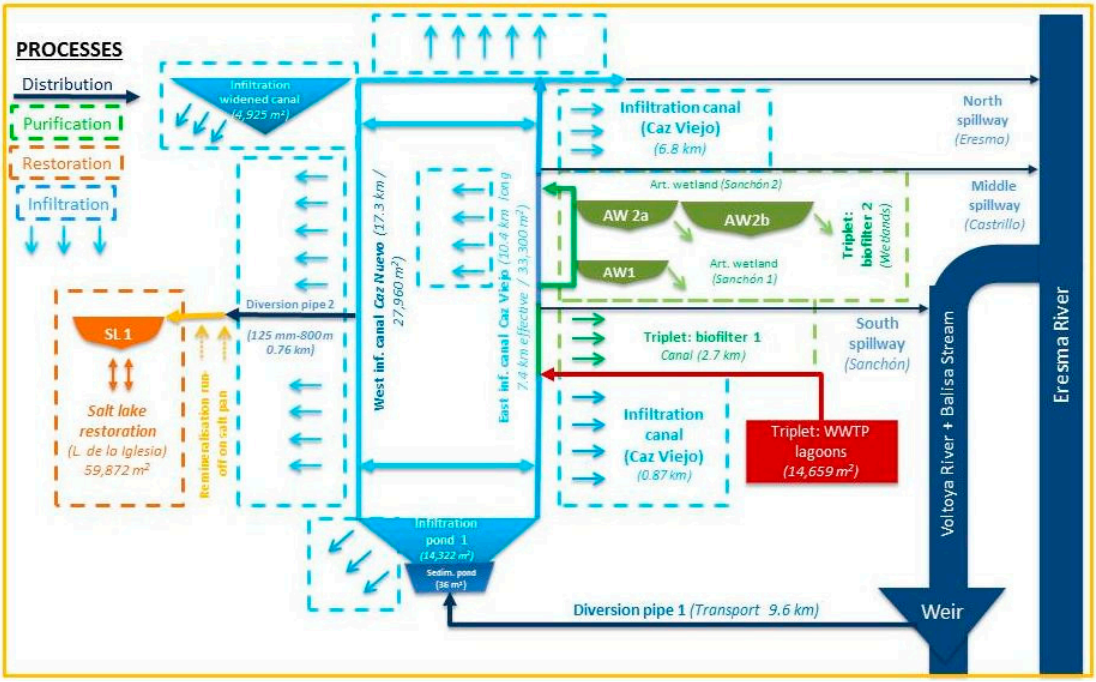


Figure 11. Managed underground water storage for use at annual intervals. Santiuste Basin. MAR devices and functions [15].

3.4. Examples of Technological Solutions to Reduce Sea Level Rise

Positive Hydraulic Barrier. El Prat de Llobregat, Barcelona (10)

One of the most emblematic examples of a water barrier against sea water intrusion is located in the surroundings of Barcelona city´s airport. It is a system of recharging wells injecting water from El Prat WWTP, a positive hydraulic barrier (Figure 12). According to the mathematical models the recovery of the preoperational state previous to the sea intrusion should take around 30 years [20]. The main disadvantage was the huge electricity consumption, thus the activity was eventually stopped during the global economic crisis affecting Spain from 2008.

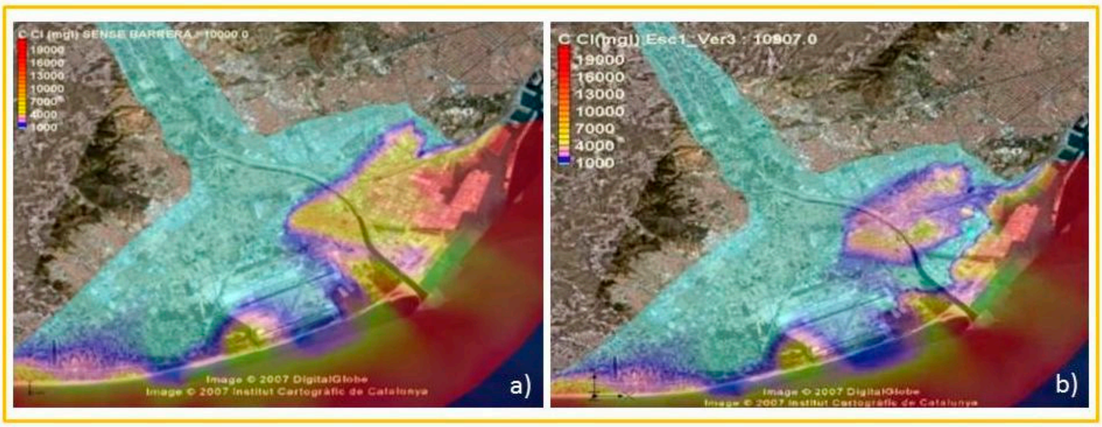


Figure 12. Intrusion barrier in the Llobregat River delta. Hydraulic barrier at Llobregat River delta. Iso-chlorides evolution graphic model for 2035 horizon: Evolution of seawater intrusion without (**a**) and with (**b**) operative recharges.

Specific Spanish MAR sites and proposal/examples of indicators to monitor and track their relationship with CC adverse impacts are exposed in Table 1.

4. Discussion

Analysing one by one some of the MAR solutions with a direct connection to CC impacts, some outcomes are obtained, according to the different groups established for disaggregated studies. These groups are underground water storage, temperature reduction, soil humidity increase, reclaimed water Infiltration, punctual infiltration, self-purification, off-river storage, restoration of key elements, ground-water distribution by gravity, savings/Lower emissions, infiltration of a part of extreme flows, forested watersheds techniques, multiannual management and intrusion barrier wells.

Table 2 summarizes the main pros and cons for MAR solutions regarding CC adverse impacts.

Table 2. Advantages and disadvantages of MAR technical solutions as mitigation measures of CC negative effects.

MAR SOLUTIONS	ADVANTAGES	DISADVANTAGES
Underground water storage	Water recharge can help to restore wetlands associated with overexploited aquifers, especially when winter extraordinary flows are used as a recharging source.	Run-off abstraction can change recharge into negative impact, considering downstream ecosystems
Temperature reduction	Broad array of possibilities in SDUS, from parking lots to roofs, from rain storage to high evaporation systems	Risk of accidental pollution through run off on contaminated areas
Soil humidity increase	Maintenance of micro-flora and fauna in the soil, increase in fertility, low infiltration with small investment and good purification	High soil humidity can facilitate flooding by water table rising or freezing in cold climates. Balance between unsaturated and saturated areas should be searched
Reclaimed water infiltration	Decreasing offer of primary sources (rain and run-off) and increasing offer of secondary ones (WWTP, desalination, storm reservoirs). Chance to change a split into a resource	Reclaimed water involves unbalance between recharging water quality and receptor aquifer quality, clogging during infiltration and legal limits to recharge (EIA) or to use (authorization)
Punctual infiltration	High potential to manage peak flows in constrained areas with filtering systems and possibility of deep recharge as a safety measure in open aquifers	Decantation processes can get clogged. Forced refill can reduce the availability of extreme flows from unexpected storms
Self-purification	Possibility of design according to characteristics of the spillage parameters, combining depth or development of vegetation that allow the development of physical, chemical and biological phenomena depending on draft, type of background, speed of flow, entry of light. Manageable characteristics also to accommodate different types of habitats	The mixture with poor quality waters can affect the infiltrating capacity of the aquifer by either clogging the unsaturated zone or compromising the possibilities and authorizations to use the final mixture. The development of certain vegetation can favour a greater infiltration through the roots or, on the contrary, encourage surface clogging by the formation of bacterial biofilms
Restoration	Slow infiltration into areas where sufficient surface is available for infiltration ponds allows temporary wetlands permanence requiring only a fraction of the total rechargeable volume and, at the same time, fulfils relevant ecosystem functions as a refuge for wild fauna and flora	The establishment of free water sheets may limit the use of reclaimed water due to possible health risks
Gravity flow water distribution	The greater the knowledge of the aquifer is, the greater is the established systems that take advantage of the hydraulic characteristics of the terrain	Detailed hydrology and geotechnics knowledge play a fundamental role in order to take advantage of the potential distribution of water along the aquifer by simple gravity. Precise studies are essential
Savings/Lower emissions	In this context, new lines of action are being considered to improve energy efficiency, such as the replacement of diesel engines by electric motors, the use of alternative energies to reduce pumping costs, such as solar panels, wind energy, and greater use of biomass	The improvement of the economic conditions allowing energy consumption can become a dangerous stimulus for the excessive increase in agricultural demand, thus, it is necessary to establish regulations for general resources management

Table 2. *Cont.*

MAR SOLUTIONS	ADVANTAGES	DISADVANTAGES
Infiltration of a part of extreme flows	High capacity to manage overfloods and peak flows in reduced spaces with the application of measures that decrease solid load. Ability to redirect flows to deep aquifers to avoid flooding in certain sectors of unconfined aquifers	Overfloods must be previously laminated to be partially infiltrated. The enhanced infiltration in the aquifer might reduce the soil capacity to absorb extreme precipitation by infiltration
Forested watersheds	Watersheds erosion control and promotion of forest hydrological restoration thanks to detention/retention devices to form soil and reduce slope. Development of deep soil botanical species with greater terrain stability (the retention of solids allows to increase the useful life of dams)	Water retention in the heading of the basin reduces downstream runoff, enhances soil formation and has a direct effect on associated wetlands
Multiannual management	Underground reserves do not require certain precautionary measures such as winter water releases, but might need to divert certain volumes to deep aquifers for exploitation in emergencies	Multi-year management implies a very good organization of uses with a great cohesive spirit among stakeholders. Despite their advantages over dams, they also require precautions against water table excessive rises
Intrusion barrier wells	Acceptable use of low-quality sources (high NaCl or NO_3 concentration) carefully combined for MAR	Collateral effects of pollutants in the recharged volumes on the aquifer's potential storage

Advantages and disadvantages should be considered before selecting the best fitted or a combination of techniques.

Regarding results, Figure 13 summarizes the relationship between CC current impacts and MAR solutions with their specific site mention and the assessed indicators of positive achievements against CC. Trends and evolutions of the different indicators are explained in each one of the references, but the figures exposed represent an accurate approach for the present MAR-CC binomial.

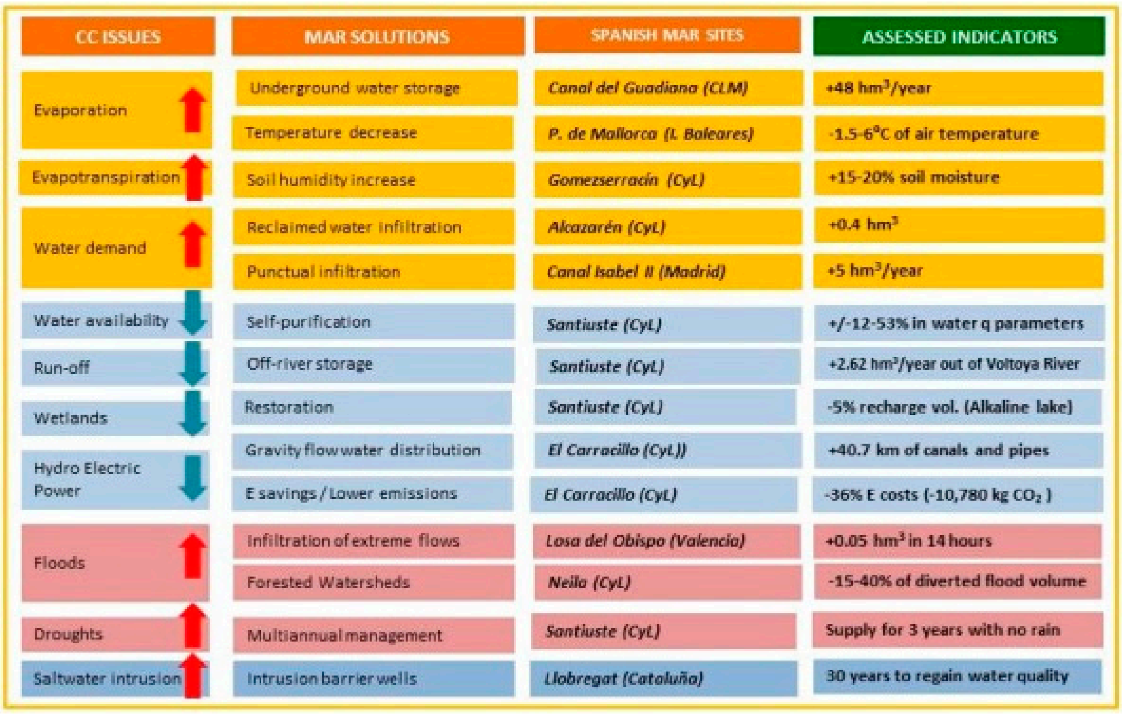


Figure 13. Relations between CC impacts and MAR solutions with their site locations and indicators of positive achievements.

These results have been compared with the referenced international parallel cases. All the studied demo-sites reflect a homogeneous evolution:

Most of the published articles pay special attention to modelling and saline water intrusion and groundwater salinity evolution, though they have scarce data and results about indicators to monitor most of the identified impacts.

Those sites affected by saline water intrusion and salinity increase do not show the groundwater resilience that the other MAR pilots expose, where indicators are showing a better reaction regarding water storage, soils humidity and extreme water related events response.

Monitoring water quality is being a pendant issue, as there are more indicators facing quantity constraints than quality issues.

Reclaimed water infiltration is a first-row topic under permanent revision. In the future and for the studied sites, this kind of MAR will not be an option but a priority.

Dykes play a key role regarding runoff capture and floods, extending the concentration time and enlarging the volume peak, therefore reducing the flood´s devastation capacity.

Wetlands are under permanent support. Most of the studied cases invest about 5% of available water for environmental purposes. A general regeneration is achieved to a certain extent in both, water availability and biodiversity.

5. Conclusions

Climate change effects and their associated impacts have been related to 10 successful MAR sites in Spain through a series of indicators (Figure 13), that let us assess the efficacy and efficiency of the MAR technique as a multifunctional technique that can simultaneously achieve several purposes.

The list of climate change effects in Spain has been accompanied by several fruitful cases of MAR. This success is economically sustainable as most of them are passive systems (do not require electricity to work). The data associated with these monitored cases have enabled the establishment of status indicators, whilst demonstrating the proficiency of MAR to face frontally CC adverse impacts, not only within the context of the case-studies in Mediterranean areas (Figure 13), but also in parallel circumstances all around the world.

The exposed examples affirm that management schemes featuring intentional aquifer recharge constitute an important set of climate change adaptation measures, while providing guarantees with respect to future water supply. These examples are aligned with other international cases consulted in the references, where despite isolated actions, the response to CC appears to be collegiated [24]. Some of the exposed technical solutions also serve to palliate the adverse effects of CC as mitigation measures. According to indicators, some progress is achieved in replenished aquifers where pumping costs save electricity due to a higher water level with an attached CO_2 emission reduction. The attention paid on water and anergy efficiency is also a general asset found in the whole MAR cases under study.

The exposed examples and their comparable potential may have a high practical value for MAR constructions, specially adapted to combat CC in Mediterranean countries [25] where droughts have dramatic effects.

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Abbreviations

The following abbreviations are used in this manuscript:

AW	Artificial Wetlands
MAR	Managed Aquifer Recharge
CC	Climate Change
NBS	Nature Based Solutions
SUDS	Sustainable Drainage Urban Systems
UHI	Urban Heat Island
WWTP	Waste Water Treatment Plant
MSCA	Marie Sklodowska Curie Action

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