MARSOL

Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought

MAR design and construction criteria

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

This report is part of the MARSOL (www.marsol.eu) FP7 founded EU project (Grant Agreement Number 619120).

The main objective of this deliverable is to provide a report stating a set of recommendations to bring up series of practical criteria as well as newly design for future development and implementation of MAR facilities, not only in parallel scenarios applying the same premises, but also is different environmental conditions, introducing some necessary changes.

This deliverable extends the information exposed in the previous deliverable 13-1 (MAR technical solutions) in which were displayed and explained most of the impacts detected and the technical solutions encountered to solve the different dysfunctions affecting MAR facilities.

The deliverable puts together the experiences from all the demo-sites and especially from Los Arenales and Menashe, due to the fact that these are the oldest and accumulate the larger experience among all of them. The exposed design criteria have been obtained from the experience in the eight demo-sites and also from the partner´s expertise deploying MAR plants elsewhere.

This report fulfils the requirements mentioned in the objective 6 of the WP13 (DoW, pg. 44) and the task 13-4 (MAR implementation guidelines). It represents a second part of the deliverable 13-1, where the state-of-the-art regarding technical solutions was exposed, and a vast series of inputs from all the demo sites increased considerably the existing degree of knowledge on this topic. Now, some specific construction criteria are provided, considering 21 out of the 25 different MAR structures inventoried all around the world (figure 4-2). The four pending facilities are reserved for future developments as they are beyond the project´s scope.

After this summary and the introduction paragraph, section three poses the technical-solutions binomials from the different demo-sites.

Section 4 recommends the design and construction criteria for the 21 sorts of MAR devices either operative in at least one out of the eight MARSOL demo-sites or with some other experiences conducted by the partners.

Lastly, Section 5 summarizes and collects the most important conclusive remarks, to finalise with references and two annexes.

2. INTRODUCTION

The MARSOL project aims at providing scientists, practitioners and end-users with an engineering-enabled set of technical solutions to improve Managed Aquifer Recharge (MAR) efficiency in areas where it is applied, and consequently, on general water management. This specific deliverable intends to report on newly developed designs and construction criteria obtained from the partners' experience in the eight different MARSOL demo sites and in other implementations.

MARSOL has built a bi-directional communication channel between partners and end-users. Behavioural data are collected by means of sensors in most of the demo-sites, in order to study how to increase the efficiency of the different devices and facilities. End-users provide hints about problems to be solved by technical solutions, being the social participation a very important source of inspiration to accomplish improved activities. It has become a looping process where feedback brings challenges to be solved in a later stage.

MARSOL´s Work Package 13 tries to summarize and evaluate technical solutions for different MAR scenarios. Specific technical solutions to meet seasonal, long-term or emergency demands are being elaborated, in order to achieve a sustainable water supply through aquifer storage. The specific objectives of this work package are:

- ✓ To mobilize industry and promote innovative solutions for water-related challenges by means of tackling issues of real innovation, practical importance, relevance and viability regarding MAR.
- ✓ To demonstrate that MAR represents, in some cases the only strategic solution to face water scarcity and extreme water related events, especially droughts *("the key is the storage")*.
- ✓ To present the current state-of-the-art for technical solutions at existing MAR sites.
- ✓ To propose effective strategies to integrate MAR techniques and associated designs into water system expansion plans to meet water supply needs.
- ✓ To deploy new technologies at the MARSOL DEMO sites.
- ✓ To prepare guidelines for the selection of appropriate MAR technical solutions and constructions under diverse boundary and environmental conditions.

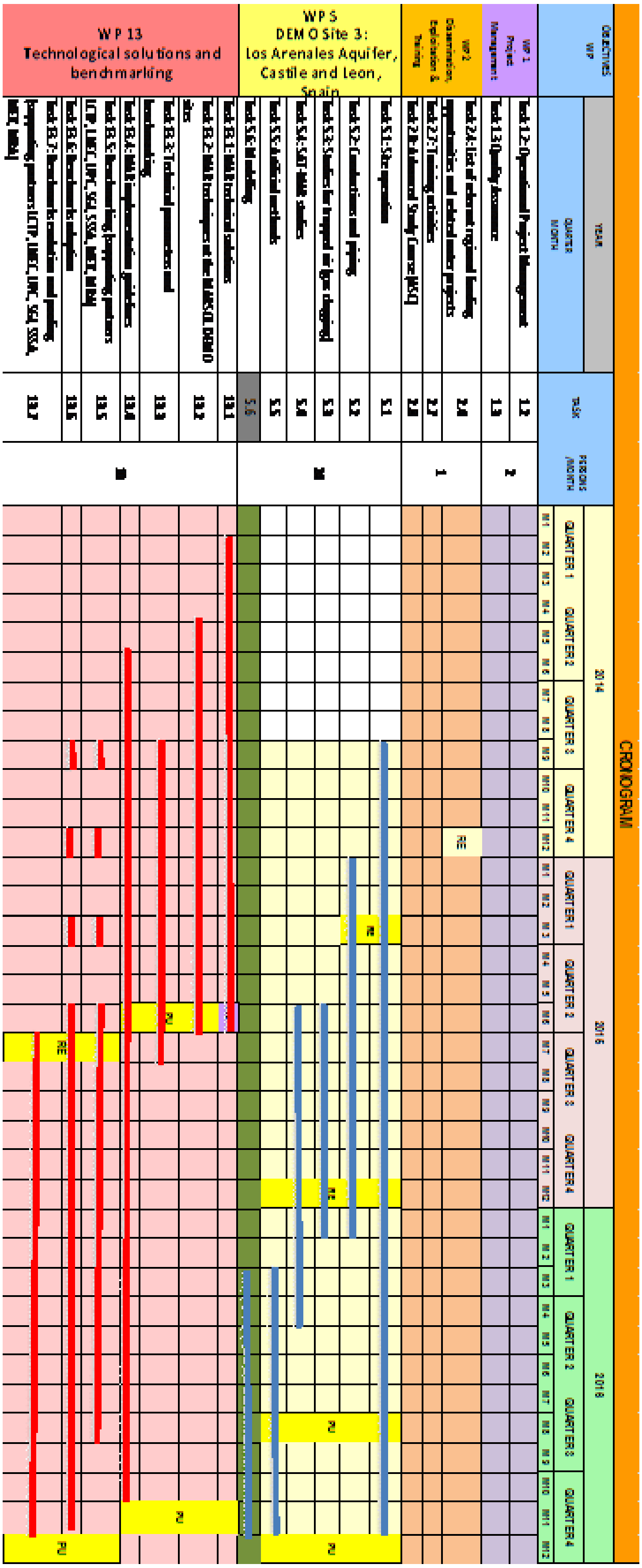
In order to fulfil the WP13's objectives, it is essential to:

- ✓ Summarize and analyse the technical solution currently active in MAR sites, to define the background techniques and their impact on water availability.
- ✓ Analyse the technical solutions at the MARSOL DEMO sites and evaluate their performance in terms of advantages and shortcomings towards benchmarking.
- ✓ Develop new designs and propose construction criteria, testing protocols for different exemplary MAR schemes by means of indicators and benchmarking.
- ✓ Develop technical guidelines, in a practical perspective, for the implementation of MAR under various boundary conditions, which is main target of this deliverable.

This deliverable relates, in special, to tasks 13.2 (MAR Techniques at the MARSOL demo sites) and 13.4 (MAR implementation guidelines) lead by Tragsa Group and the inputs received from closer partners regarding design and construction criteria, in special from MRA and TARH colleagues.

Table 2.1 exposes a timetable with the planned dedication for this WP leading partner within the whole project.

Table 2-1: Proposed timetable for WP13 and other related WPs where Tragsa Group participates.



3. TECHNICAL-SOLUTION BINOMIALS SUMMARY

3.1 Main sort of impacts affecting each MARSOL demo-site

The majority of Southern Europe countries face major problems related to water shortage caused by excessive agricultural irrigation. This situation has been aggravated by climate change adverse impacts, being water scarcity the main impact affecting MARSOL demo-sites.

Precipitation in the Mediterranean areas is significantly varied, both in terms of total annual water amount and of seasonal distribution. This fact, combined to the excessive water consumption by agricultural irrigation causes a high rate of exploitation on these aquifer areas.

Agriculture, industry and water supply uses have put pressure on water resources and these stresses are likely to be exacerbated by the climate change scenario. Water demand increase while shrinking water supplies are accompanied by droughts and lower precipitation cycles. In some areas, climate change increases runoff causing flooding.

In coastal regions and islands (such as Llobregat or Malta South demo-sites) an important dysfunction affecting some specific facilities due to marine intrusion is causing the inland penetration of salt groundwater and their negative consequences.

MAR may also be a solution for contaminated aquifers. This particular impact may vary depending on the pollution source, being the most usual nitrates from the agricultural activity (for example in Portugal) or mining and other industries, as well as organic pollution.

Below, table 3-1 shows the different impacts classified according to some established categories and their presence in the eight MARSOL demo-sites.

Table 3-1: Main impacts on the aquifer area detected in each demo site, and grouped according to some established categories.

PROBLEMS	Main impacts on the aquifer/s	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
Scarcity (Overexploitation)	Quantitative issues because of overconsumption	X	X	X		X	X		X
Scarcity (Climate Change)	Drought, rising temperatures trend, lower precipitation cycles...	X				X	X	X	
Salinity (Seawater intrusion)	Associated to coastal aquifers	X							X
Heavy metals (Mining, farming, industry)	Metals from agrochemicals, urban, industrial sources: Pb, Fe, Al, Cr, Cd, Hg….	X							
Agriculture contamination (mainly N)	Agriculture diffuse contaminants: N, P K…	X	X	X					

Organic pollution (agrochemicals and antibiotics)	Toxic pollutants as pesticides and antimicrobials	X	X	X					
Wastewater discharge	Insufficiently treated effluents			X					
Wetland desiccation	Deterioration by water Table decline, Run-off shortage….			X		X			
Floods	Flooding events caused by climate change, extreme rain…							X	
Others	*To be specified along the rest of the project*								

In summary, Mediterranean region should establish MAR technique as a key factor to combat the exposed impacts and to achieve a more sustainable water development.

3.2 Problem-Technical solution binomials. Brief summary and lists of activities to comply needs

Different methods, activities and key studies to solve impacts affecting MAR facilities were deployed in the deliverable 13-1 (MARSOL, 2015c). A brief list of the technical solutions already developed has been exposed downwards, either implemented in the demo sites or taken from hydrogeological literature and partner´s expertise. The set of "tech-sols" exposed in the mentioned report (MAR Technical Solutions Review and Database) has a corollary containing 73 techniques classified according to five categories:

1. Applied to water from its original source (quantity).
2. Applied to water from its original source (quality).
3. Applied to the receiving medium (in both soil and aquifer).
4. Applied to management parameters plus cleaning and maintenance operations.
5. Applied to the combination of all of them (integrated system).

And within these initial groups, activities have been classified according to the following 15 different types of operations.

- 1.1. Water quantity aspects (T.S. 1 to 5).
- 2.1. Pre-treatment-treatment (T.S. 6 to 12).
- 2.2. Surface facilities (T.S. 13 to 16).
- 2.3. Deep injection (T.S. 17 to 19).
- 2.4. Receiving medium (T.S. 20 to 24).
- 2.5. Others (T.S. 25).
- 3.1. Previous studies (T.S. 26 to 27).
- 3.2. Surface facilities (T.S. 28 to 35).
- 3.3. Injection facilities and piezometers (T.S. 36 to 41).

3.4. Operative aspects (T.S. 42 to 46).
4.1. Operation (T.S. 47 to 53).
4.2. Maintenance (T.S. 54 to 56).
4.3. Decision support systems (T.S. 57 to 63).
4.4. Management (T.S. 64 to 70).
4.5. Reuse (T.S. 71 to 73)

The annex 1 exposes the relations or binomials between the detected impacts and the solutions applied in each demo-site, being the starting point to put together the next set of "good practices" (table 3-2).

Tables 3-2: Lists of technical solutions as a response to main impacts on the aquifers detected in each demo site and grouped according to some established categories.

RECHARGE WATER (QUANTITY)

1-Preselecting: selective criteria for the origin of recharge water when several sources are available
2-Temporary storage of MAR water in surface reservoirs
3-Control of the flow velocity of MAR Water (stopping devices…)
4-Manage/avoid operations during specific events/periods, e.g. freezing weather, heat waves…
5-Security structures for overflow events, run-off tramps, spillways, etc.

RECHARGE WATER (QUALITY)

*6-**TECHNIQUES OF GENERAL APPLICATION:** Pre-treating of water for MAR in origin: (WWTP, membranes, mud lines, filters, packets…)*
7-Pretreating of water for MAR in the heading of the structure: Filtering beds, decantation/stagnation structures, deairation, etc.
8-Pretreating of MAR water using unsaturated zone as a pre-treatment natural filter (in absence of persistent substances, micropollutants and emergent compounds).
9-Treatment structures intercalated along the construction for surface facilities, e.g. control of pH by means of mudstone gravel filters
10-Pretreating by means of Disinfection By Products (DBPs) technique, e.g. Cl, I, O_3, H_2O_2, UV rays, etc.
11-Chemical additives to eliminate clogging layers
12-Combination of different MAR facilities to improve the MAR water quality, e.g. a "triplet scheme" (WWTP, green biofilter, artificial wetland)?
*13-**SURFACE FACILITIES**: Design and preservation of slope (rubble works, gabions...)*
14-Limitation/control of the water layer thickness
15-Denitrification processes/additives (e.g. anammox)
16-Mechanisms to force the mixture of the different layers of MAR water, e.g. for canals let the water jump over or below stopping devices alternatively
*17-**DEEP INJECTION FACILITIES**: Employ of anticorrosion materials in the MAR devices*
18-Changes in the depth of the pump for wells/ boreholes

19-Induced changes in water quality for irrigation. Fertilizers…
*20-**RECEIVING MEDIUM**: Avoid aeration on AR waters: communicating vessels, open/buried structures, velocity control*
21-Deaeration techniques: piezometers, increase distance between injection-extraction points…
22-Structures for isolation from atmosphere/sunlight
23-Avoid natural salinization: Induced recharge, e.g. barriers in salty areas
24-Recycling effect of water in the MAR system
*25-**OTHERS**: Specific fishes/exotic species introduced to reduce clogging (e.g. medaka)*

RECEIVING MEDIUM (IN BOTH SOIL AND AQUIFER)

*26-**PREVIOUS STUDIES**: The knowledge of the environmental conditions for the receiving medium might be considered sufficient?*
27-Regarding the selection of the site, are there "natural fences" to avoid water to leave the system?
*28-**SURFACE FACILITIES**: Changes in the receiving medium design. Furrows in the bottom, width, shape...*
29-Changes in the receiving medium design. Geofrabrics in the bottom/slopes (specify)
30-Inverse pumping in wells pits close to a MAR canal or pond
31-Backwashing in geofabrics, membranes and filters
32-Use of jet type cleaning techniques
33-Chemical cleaning (use of chemical additives)
34-Operations in the bottom: Algae drying, natural bed drying, cryotreating, cracking (cake)
35-Mechanical cleaning (scarification or silting zones and cleaning /replacement) (specify)
*36-**INJECTION FACILITIES AND PIEZOMETERS**: Alternate normal and inverse pumping and frequency*
37-Mechanical cleaning (wall brushing, scratching...)
38-Chemical cleaning (use of chemical additives) techniques for the regeneration of recharge wells
39-Selection of casing materials for wells according to groundwater characteristics (quality, quantity, durability...)
40-Employ of water level control automatic systems (alarm systems, buoys…)
41-Employ of clogging preventive systems, e.g. cathodic protection…
*42-**OPERATIVE ASPECTS**: Use of dual systems allowing cleaning of one of them whilst the other is operating*
43-Cleaning of the vegetation in the MAR facilities
44-Specific plantation during any season
45-Cleaning techniques frequency
46-Use of Basic Cleaning Vehicles (BCVs)

MANAGEMENT PARAMETERS AND EX SITU TECHNIQUES (INCLUDING MANAGEMENT, GOVERNANCE...)

*47-**OPERATION**. Management parameters and ex situ techniques related to water management, governance... INCLUDING pumping out the recharge water in order to release the aquifer storage for the next recharge cycle*
48-Selection of the most appropriate period and place to MAR water / obligation due to administrative concessions
49-Initiate 'soft' MAR cycles (start gradually)
50-Input flow and flow water speed control (automatic, manual)
51-Dual systems: duplicated MAR facilities to alternatively manage MAR and cleaning activities
52-Alternative sources of MAR water and management
53-Monitoring chemical properties of MAR water during recharge cycles
*54-**MAINTENANCE**. Specific protocol for clogging control*
55-Protocol for proper hydro-mechanical aspects in space and time. e.g. pressure inside a pipeline circuit
56- Specific cleaning and maintenance programs or decisions made "on the go"?
*57-**DECISION SUPPORT SYSTEMS**. Integrated system design: all elements are interconnected*
58-Promote participation of farmers or other social agents or stakeholders in water management
59-Limit fertilizers use
60-Decrease untreated spilling in the area
61-Protected perimeter around the MAR facilities
62-Use of protection devices for fauna and people in MAR facilities
63-Public use regulation
*64- **MANAGEMENT**. Early adoption of the Best Available Techniques (to what extent new BATs are tested prior their application?)*
65-Design and adoption of a proper Watching and Control Program
66-Construction of dams specifically designed for MAR
67-Construction of WWTP specifically designed for MAR
68-For those devices constructed due to a R&D specific project, is there any guaranteeing mechanism to operate the system after the end of the project
69-Are there already specific operative guidelines?
70-Use of sensors to monitor turbidity, dissolved oxygen, temperature… either inlayers or installed in surface facilities
*71- **REUSE**. The wells used for MAR were specifically designed or previous wells/shafts were used (change of use)?*
72-Use of existing natural previous elements to improve MAR efficiency, e.g. River Bank Filtration (RBF direct or inverse), use of dolines, sinkholes…
73-Use of pre-existing artificial previous elements for MAR, e.g. rivers dams, meander scarfs…

Set of “tech Sols” or SMARTS (Sustainable Managed Aquifer Recharge Technical Solutions) currently under development. Some working groups and action groups supported by the European Commission develop lines of action related to the tech sols exposed. Some of their lines of action are:

- *Existing regulatory requirements for the recharge water quality*
- *Carry out batch experiments to analyse the potential negative effect of subproducts Derived from DBP technique applications.*
- *Combination of green biofilters with lagooning WWTP, in order to increase MAR system´s efficiency (continuous water source with annual operation permissions). Reusing rather than spilling.*
- *Evaluation of hydrogeology characteristics: areal extent, aquifer thickness and depth, stratigraphy, geochemical compatibility between recharge and native groundwater, etc.*
- *Wells inventory (groundwater withdrawal) in the influence area and integrated effect on MAR.*
- *Conduct a feasibility assessment: cost-benefit analysis increases the success of any MAR experience.*
- *Design an alert system service: Alert messages directed at selected users. Monthly report with relevant data and basic operation statistics.*
- *Disseminate some encouraging examples and successful cases from other experiences around the world, to provide new insights and outcomes.*
- *Create a specific MAR Network for each MAR experience, involving different stakeholders, such as policy-makers, technicians, end-users, interested citizens, etc.*
- *Combination of different MAR water sources in an integrated system applying the premise: “Dilution as a solution to pollution”. This premise should only be applied in circumstantial circumstances.*
- *Reuse of abandoned structures, such as quarries, sand pits, old mines… for MAR surface systems (multi-functionality).*

4. MAR FACILITIES DESIGN AND CONSTRUCTION CRITERIA

Based on the global inventory for MAR facilities, which distinguishes 25 types of MAR devices, it is important to conduct and disseminate their most successful design and recommendation criteria, with the aim of responding a question: *"How to improve MAR efficiency?".* In this sense, authors have been able to obtain some technical advices for 21 of the exposed sort of MAR plants, despite only 15 out of 25 are present in the *Marsolian* demo-sites. The data base on technical solutions has been tailored to include all the relevant information from the MAR sites (attached as annex 1). Each number fits those in figure 4-2.

1-Infiltration ponds/ Wetlands
2-Channels and infiltration ditches
3-Ridges/ soil and aquifer treatment techniques
4-Infiltration fields (flood and controlled spreading)
5-*Accidental* recharges by irrigation returns
7-8-9- Reservoir dams, permeable and perforated
10- River bed scarification
12- Drilled dams
13- Qanats (underground galleries)
14- Open infiltration wells
15- Deep wells and well-boreholes (about 50 m or more)
16- Drilled boreholes
18- ASR
19- ASTR
20- River bank filtration (RBF)
21- Interdune filtration
22- Underground irrigation
23- Rainwater harvesting in unproductive terrains
25- SUDS.

The pendant rest remains as an "open line of action" for future stages. It is expected to bring up recommendations regarding design and operational aspects of the next group:

- 6- Bofedales wetlands. Usual South American sort of wetlands which are currently used for MAR in some specific areas, especially in Colombia (see MARSOL, 2015c).
- 11- Sub-surface/ underground dams. They are "hidden" structures to dam groundwater, frequently in narrow river channels filled with alluvial materials. There are abundant examples in the hydrogeological literature (Gale, 2005).
- 17- Sinkholes, collapses. In some part of the world collapses related to MAR activities are appearing but it is not clear whether they are a cause or an effect. There are also some cases, for example for Majorca Island (dina-mar, 2010).
- 24- Accidental recharge from pipes and sewer systems. This measure, usually integrated into MAR systems, can rather be considered an *"anti-MAR".* It is rather a pure accidental recharge which eventually happens with poor water quality and even harmful spills. In that case, natural processes in vadose zone help to improve that quality as water flows down.

Figures 4-1: Types of MAR construction not present at MARSOL demo-sites or with scarce expertise (6- *Bofedales*; 11- Sub-surface dams; 17- Sinkholes & 24- Accidental recharge from sewers.

4.1.1 MARSOL existing facilities in the demo-sites

The figure 4-2 summarizes the MARSOL inventory for the different existing MAR devices and their presence in the different demo-sites.

Nº	SYSTEM	MAR DEVICE	LOGO	FIGURE	PHOTO	LEGEND	1: Lavrion, Greece	2: Algarve and Alentejo, Portugal	3: Los Arenales, Spain	4: Llobregat River, Spain	5: River Brenta, Italy	6: Serchio River, Italy	7: Menashe, Israel	8: South Malta, Malta
1	DISPERSSION	INFILTRATION PONDS/ WETLANDS				Artificial wetland to recharge in Sanchón, Coca, Arenales aquifer		✓	✓	✓				
2		CHANNELS AND INFILTRATION DITCHES				Artificial recharge channel of the Basin of Santiuste, Segovia, Spain, operative since 2002.			✓					
3		RIDGES/ SOIL AND AQUIFER TREATMENT TECHNIQUES	SAT			Furrows at the bottom of a infiltration pond in Santiuste basin (Arenales)	✓	✓	✓	✓	✓			
4		INFILTRATION FIELDS (FLOOD AND CONTROLLED SPREADING)				Infiltration field in Carracillo, Arenales aquifer	✓		✓		✓			
5		ACCIDENTAL RECHARGE BY IRRIGATION RETURN				Artificial recharge by irrigation return. Extremadura, Spain. Photo: Tragsa		✓			✓			
6		BOFEDALES WETLANDS				Bofedales (Colombia)								
7	CHANNELS	RESERVOIR DAMS AND DAMS				Artificial recharge dam in Arenales. Segovia, Spain.			✓					
8		PERMEABLE DAMS				Permeable dam in Huesca, Spain. Photo: Tragsatec.								
9		LEVEES				Levees in Santa Ana river, Orange County, California, USA. Photo: A. Hutchinson.								
10		RIVERBED SCARIFICATION				Scarification at Besós riverbed, Barcelona, Spain. Photo: J. Armenter.								
11		SUB-SURFACE/ UNDERGROUND DAMS				Sub-surface dam in Kitui, Kenya. Photo: Sander de Haas.								
12		DRILLED DAMS				Drilled dam. Lanjarón, Granada, Spain. Photo: Tragsatec.								
13	WELLS	QANATS (UNDERGROUND GALLERYS)				Qanat at Carbonero el Mayor, Segovia, Spain. Photo: E.F. Escalante			✓					
14		OPEN INFILTRATION WELLS				Passive infiltration well. Santiuste basin		✓	✓					
15		DEEP WELLS AND BOREHOLES				Artificial recharge well. Menashe. Israel. Photo: EFEscalante								✓
16		BOREHOLES				Borehole in Israel. Photo: EFEscalante								
17		SINKHOLES, COLLAPSES...				Sinkhole called"El Hundimiento". Alicante, Spain. Photo: DINA-MAR								
18		ASR	ASR			ASR device in Scottsdale, Arizona, USA. Photo: DINA-MAR					✓		✓	
19		ASTR	ASTR			ASTR device in California, USA.				✓				
20	FILTRATION	RIVER BANK FILTRATION (RBF)	RBF			MAR RBFsystem in Villeguillo, Arenales, Spain		✓				✓		
21		INTERDUNE FILTRATION				Interdune filtration in Carracillo Eastern site. Arenales, Spain			✓					
22		UNDERGROUND IRRIGATION				Underground irrigation in Andalucía, Spain. Photo: Tragsa.								
23	RAIN	RAINWATER HARVESTING IN UNPRODUCTIVE				Rainwater harvesting in unproductives for MAR techniques.			✓					
24	SUDS	ACCIDENTAL RECHARGE PIPES AND SEWER SYSTEM				Artificial recharge from sewer system in Arenales, Spain			✓					
25		SUSTAINABLE URBAN DRAINAGE SYSTEMS				SDUS. Gomeznarro park. Madrid, Spain. Photo: E.F. Escalante.								

Figure 4-2: MARSOL inventory for the different existing MAR devices. Summary and MAR schemes catalogue grouped by typologies (Modified from Fernández and San Sebastián, 2012, inspired on Gale, 2005). Clicks indicate the different typologies available in each demo-site.

4.2 Recommendations for newly developed MAR designs

Managed Aquifer Recharge or *artificial recharge* implies not only a system of water storage, but also a method of combating marine intrusion, renew stored water by pumping, a recovery and restoration system of wetlands, a method of controlling erosion and desertification, an effective method for the purification of the water, etc. That is why its design goes beyond a classical storage infrastructure design.

There are many possible variations on existing devices. In all cases, each one must fit the environmental conditions and characteristics of the area where it is intended to be located in order to achieve maximum efficiency and effectiveness. Consequently, most of the designs must be “tailor made” despite sharing some common features.

The previous classification distinguishes six MAR facilities major groups:

1. Surface systems: dispersion (canals and filtration)
2. In channel modifications
3. Deep systems: wells (boreholes, wells…)
4. Filtration systems (RBF, inter-dune filtration)
5. Rainfall (Rainwater harvesting in unproductive terrains)
6. Sustainable Urban Drainage Systems (SUDS) as a group of water harvesting elements applied in urban hydrogeology and architecture.

While for surface systems, such as dispersion and in-channel modifications, the water infiltration is produced through the unsaturated zone towards the aquifer. In the case of systems of MAR wells, they carry out a direct deep injection on both, the saturated and the unsaturated zones, reducing the interaction processes along the vadose zone. These variations involve large differences in the design of these devices. Also, the quality standards to meet the required/ recommended water quality demand for MAR, with or without interacting with the vadose zone, are different.

Other characteristics, pros, cons and environmental aspects for each of the inventoried MAR devices are detailed in Annex II, including conditioning factors and constraints for each MAR type of facility. This annex provides selection criteria for MAR zones that should be considered previous to the implementation of any plant for MAR.

Recommendations are exposed in parallel (same order) to the MAR devices presented in the figure 4-2.

4.2.1 Infiltration ponds/ Wetlands

Infiltration ponds are the more numerous MAR systems in MARSOL demo sites and in the world. They are essentially shallow depressions designed to infiltrate temporal storage water through the soil (in general from both, walls and bottom) into the aquifer. They present relevant design variations but hold some common requirements, such as designs to avoid problems caused by the clogging or silting on the soil surface.

Clogging is caused by many factors, and perhaps the most relevant is the suspended solids deposition. Clogging reduces the infiltration rate taking advantage of natural topography (irregular distribution minimum in ridges and maximum in valleys). Original water quality and climate also play an important role in its development.

It is important to consider a set of premises for any infiltration pond´s designing:

1. Location in relation to the aquifer (distance to hydrogeological thresholds, to areas with maximum thickness of the aquifer below…)
2. Morphology: bottom and walls of the pond
3. Hydrological characteristics of the area
4. Depth of the water table
5. Quality of the recharge water
6. Time of residence of the water across the vadose zone and in the aquifer until its drainage by rivers…
7. Location of pumping wells around the infiltration ponds (number of wells, distance from the ponds and between the wells, pumping depth, hourly discharge…).

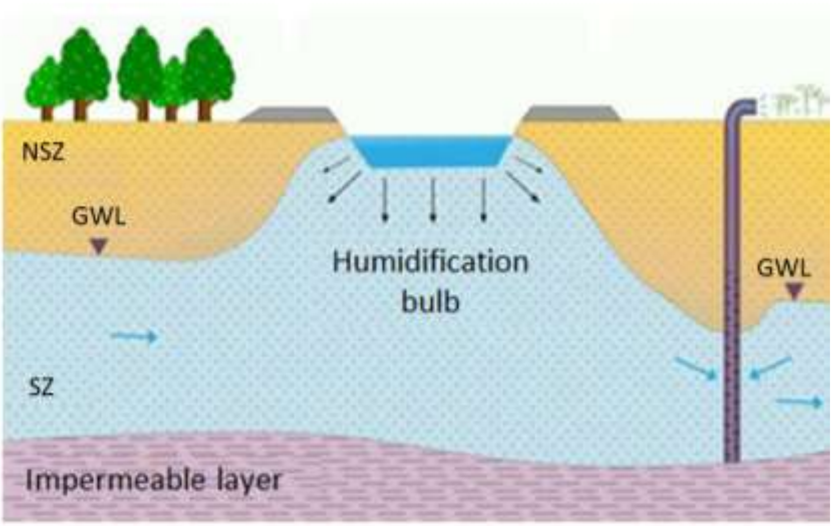


Figure 4-3: Infiltration pond/wetland scheme.

1. LOCATION

First of all, a good selection of the location is a major factor that will determine the future infiltration pond success. It is recommendable to locate this MAR facility in a single watershed or over a threshold if the intention is to perform an artificial recharge in two basins at the same time. It is also usual to set an infiltration pond over high thicknesses of unsaturated zone´s sediments.

Infiltration ponds are dependent on permeable soils and unconfined aquifers with a relatively shallow water table (to reduce soil moisture losses). Transmissivity must be high enough to promote a centrifugal flow from the humidification bulb.

In order to obtain a maximum aquifer recharge volume, it is necessary a large infiltration surface, involving the occupation of large plots of land. This is perhaps the biggest constraining factor to place these devices, especially in areas where the terrain availability is scarce.

The proximity of the water source intended to be taken during the recharge should be as close as possible from the chosen location and a certain guarantee of supply along each MAR cycle. This closeness will lower the construction and maintenance costs of the infiltration ponds in the future, apart from reducing investment costs in water transport.

2. MORPHOLOGY: BOTTOM AND WALLS

Ponds are a depression in the ground, either natural or artificial, and either pre-existing (sand pits, quarries, drained wetlands… or constructed "à la carte") with sloping walls and the bottom as levelled as possible in order to promote a homogeneous infiltration, although it is usual to dig furrows to facilitate cleaning operations.

Several external embankments have been tested along MARSOL project, with initial 1/1 or 3H/2V slopes. The landslides in detrital aquifers caused a change and new tests, to seek the most stable slope for sandy aquifers avoiding, when possible, artificial erosion protection (stones, gabions…) expenses. Finally, the technical criteria more applied has been 2H/3V and 2H/1V in order to achieve a greater stability and for areas where the availability of land allows this type of slopes. In rocky aquifers and ponds dug in alluvial formations, it is usual to hold a 1/1 slope.

Both, the bottom and the walls of each infiltration pond must have high infiltration capacity and eventually slopes are covered in geofabrics to retain landslides, and eventually the infiltration across the walls is minimized. A previous calculation is recommended to make an appraisal on maintenance geofabrics costs to choose the best and most economic option.

If the aquifer or receiving medium has materials less permeable than it is desirable, a sand layer is usually placed upon the bottom and walls, in order to delay obstruction processes and to extend in time artificial recharge periods or cycles. This cover must be replaced when it becomes clogged.

One of the main problems is the reduction in the infiltration capacity, due to clogging phenomena, which occurs at the surface up to a certain depth because of several processes. However, clogging layers can also get formed at depth where soil is denser or finer (*e.g.* in Los Arenales it has been detected a clogging level caused by calcite precipitation between 50 and 75 cm deep, what makes the cleaning actions more expensive. The heating of cold water while it is crossing the vadose zone appears to be the cause of this carbonated layer.

The construction or furrows, ploughing or scarification of the infiltration pond bottom promotes higher volumes of artificial recharge, due to the fact that the area of the receiving medium is increased and the suspended solids and clogging fraction in the water deposits, preferentially in the most depressed parts with scarce settlements in the ridges. The furrows distance is decisive. Experiments conducted in Los Arenales along the whole project have provided figures for a recommendable distance between furrows of 80 cm in order to achieve the biggest infiltration rate, at least for sandy aquifers, with a groundwater level close to 5-6 m depth. These results could vary in different environmental conditions.

Figure 4-4: Infiltration pond in Santiuste basin, Los Arenales (Spain).

3. HYDROGEOLOGICAL CHARACTERISTICS

The target aquifer to be recharged by means of infiltration ponds should be shallow and unconfined since the recharge takes place from the surface. High storage coefficient and medium-high transmissivity are also desirable characteristics. Alluvial formations, sand dunes or detrital systems are generally the most suitable. However, aquifers with a high transmissivity can permit rapid dispersal of the *"MARed"* water and, as a result, only limited water quantities might be recovered.

4. WATER DEPTH RECOMMENDATIONS FOR THE INFILTRATION PONDS

The depth of water in the pond is a crucial factor, since excessive weight compact the bottom, compress the sand grains and decreases the infiltration rate. However, shallow depths do not induce the necessary pressure to enhance and force the infiltration capacity. Higher values obtained in experimental laboratories and hydraulic calculations (modelling) have been water heights nearby 80 until 140 cm for sandy aquifers. On a direct mudstone bottom infiltration pond this measure can reach up to 400 cm (Martin & Dillon, 2002, Martin, 2013).

Figure 4-5: Infiltration pond in Carracillo District, Los Arenales demo-site (Spain).

5. MAR WATER QUALITY

Water quality determines, to a large extent, infiltration pond design and maintenance requirements. If the water comes from a high quality source, clogging caused by mechanical, physical, chemical or biological processes will have a lower impact than e.g. treated wastewater as the recharge source.

Due to water stagnation in the pond, eutrophication problems can appear at the bottom produced by bacterial growth. A correct design in terms of depth is an effective method to reduce these problems. In order to avoid anaerobic conditions, the depth may not exceed 4 meters. In general, it is desirable to construct a pre-treatment system by decantation. There are different choices such as multiple steps ponds, gravel, grit and sand filters (even interspersed inside the conductions), reactive layers, divided ponds, etc. These measures promote suspended solids settlement before they reach the infiltration pond.

6. TIME OF RESIDENCE OF THE RECHARGE WATER

The time of residence of the water in the aquifer will depend on the final use. Urban supply requires, usually, higher quality and greater residence time. In case the return of water to the recovery point occurs too quickly, this type of facility may be inadvisable, or it would be necessary to intersperse stopping devices as underground dikes to delay the natural water flow, with the consequent increase of the costs. Once the natural conditions have been modified, it is important to remind the necessity to have pumping capacity to renew the recharged water and to leave some of the storage capacity available for the next recharge cycle.

MARSOL EXAMPLE: INFILTRATION PONDS IN EL CARRACILLO DISTRICT, LOS ARENALES DEMO-SITE (SPAIN)

1- West infiltration pond description

This infiltration pond was built semi-dug in the ground and its capacity is 8,455.70 m^3. The fill slope downstream is covered with a topsoil layer mixed with shrubs and herbaceous species of the surrounding area. The pond inner slope was covered with riprap between 30 and 60 cm. A ramp was built on the pond embankment with a slope of 0.10 m/m. It serves as an access to the pond bottom with the aim of cleaning and maintenance activities.

The most remarkable pond geometric characteristics are outlined below:

Table 4-1: Geometric characteristics of the West infiltration pond at El Carracillo (Los Arenales).

Crown height	813.00 m
Background height	810.00 m
Water height	811.30 m
Inner embankment	2H / 1V
External embankment	3H / 1V
Pond surface bottom	6,183.70 m^2
Surface maximum water sheet	6,994.45 m^2
Surface inner slopes	2,224.24 m^2
Surface external slopes	854.60 m^2
Reservoir volume	8,455.70 m^3
Coronation road width	2.00 m
Coronation road length	376.00 m
Total cuttings volume	13,895.00 m^3
Total embankments volume	1,606.95 m^3
Total infiltration pond area occupation in plant	10,197.45 m^2

Water gets to the infiltration pond across a heatsink valve 900 mm Ø. The inlet pipe is a polyethylene pipe PN6 400 mm Ø to conduct a flow rate of 170 L/s.

Figure 4-6: West Infiltration pond in Carracillo District, Los Arenales demo-site (Spain).

2- East infiltration pond description

The infiltration pond capacity is 9,275.20 m^3 and was built completely dug into the ground. The pond inner embankments are also covered with riprap between 30 and 60 cm. As for the previous case, the pond has an access ramp with a slope of 0.10 m/m for heavy machinery.

The most remarkable pond geometric characteristics are outlined below:

Table 4-2: Geometric characteristics of East infiltration pond of Carracillo.

Coronation height	803.30 m
Background height	801.30 m
Water height	802.80 m
Inner embankment	2H / 1V
External embankment	2H / 1V
Pond surface bottom	5,760.40 m^2
Water sheet surface	6,714.10 m^2
Inner embankments surface	1,788.57 m^2
Reservoir volume	9,275.20 m^3
Total cuttings volume	16,044.38 m^3
Total infiltration pond area occupation in plant	7,360.15 m^2

A sink valve speeds down the water velocity when it gets to the pond. The inlet is a polyethylene PN6 400 mm diameter pipe designed to transport a 160 L/ s flow rate.

Figures 4-7: a & b. East Infiltration pond in El Carracillo District, Los Arenales demo-site (Spain).

4.2.2 Infiltration canals (=channels) and ditches

Infiltration channels and ditches are artificial recharge devices included in the surface systems group. Unlike infiltration ponds, channels have lower needs regarding soil availability but they have a barrier effect. Moreover, infiltration channels are less sensitive to silting and eutrophication problems, as a uniform flow is maintained through the system.

The main difference between both devices is that channels are usually installed to conduct water through extended permeable areas or to guide it to specific infiltration spots. Ditches are retaining runoff structures that significantly reduce slope erosion, increase natural infiltration and recharge the underlying aquifer. Another difference is that ditches are usually installed in series, while channels tend to follow a continuous path.

CHANNELS

Channels layout design requires a previous advanced knowledge of the aquifer hydrogeological characteristics and groundwater behavior, such as flow direction, unsaturated zone thickness, storage capacity, transmissivity, rock massif characterization, etc.

The main lines of action to increase the infiltration rate and total infiltrated volume in the channels bottom and walls are focused on the channel morphology itself (DINA-MAR, 2010). They also focus on flow regulation and silt filtering in the artificial recharge water (Fernández et al., 2009). In order to accumulate silting, some canals have a single furrow construction along the deepest line of the channel to make cleaning easier and cheaper. Another option is the use of geofabrics in order to replace and clean them when they get covered in clogging, what makes maintenance operations easier (Fernández & Senent, 2012).

The surface "furrows" or grooves ploughed at the bottom of the recharge structures are usually covered with a waterproof membrane or specific geofabrics. The result is that walls are still sparsely silted, while most of the viscous processes are addressed on the bottom (groove), with muddy deposits due to the effect of gravity, currents, rain and waves (Peyton, 2001).

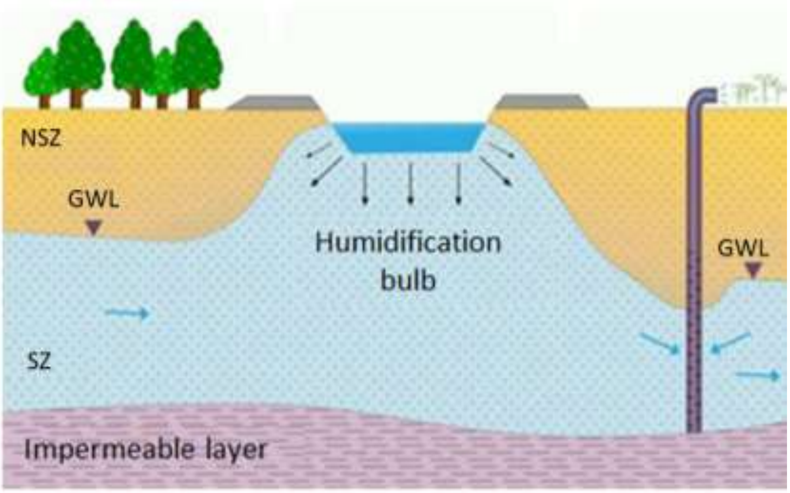


Figure 4-8: Infiltration channel scheme.

MARSOL EXAMPLE: INFILTRATION CHANNEL IN SANTIUSTE BASIN, LOS ARENALES DEMO-SITE (SPAIN)

Artificial recharge devices in Santiuste Basin consist, mainly, on infiltration ponds and canals, with occasional wells. The main reason to choose this sort of MAR device is the scarce land availability. There is a demand for arable land occupation, since agriculture is the driving force of the region´s economy. Topography, drainage and the specific geology of the area are other important factors in the election of the best MAR facility.

The channel layout takes advantage of a favourable average gradient of 0.28%. Therefore, the channel runs 20% of its length by the dry ancient river bed called *La Ermita* stream.

The design of the canal pursues to obtain as much as possible infiltration surface or area of interaction between “MAR water” and the soil. With this objective, small dams or stopping devices were interspersed along the canal at distances close to 150 meters, favouring the final infiltration volume. These dykes are made of precast concrete and its management has been transferred to the Irrigation community with technical advice. The crosses of the canal with roads, ways, etc. are also made of precast concrete devices.

According to the study for artificial recharge in the area ["Study of solutions for aquifer recharge of Santiuste de San Juan Bautista (Segovia)"] the infiltration surface necessary to infiltrate a maximum flow rate of 1 m^3/s was estimated as 21,600 m^2. This type of calculation is basic to make the MAR canal design and dimensioning decision.

It is common to apply a trapezoidal shape in sandy aquifers. In the case of the example and after eventual landslides, the final design has 1.00 m base width, 1.50 m height, 4.0 m wide at coronation and 1/1 embankments. Along the channel, stopping devices were built in precast concrete. Most of them are equipped with a gate between 0.50 and 1 m high from the bottom of the canal in static situation.

Taking as a calculation value an average draught of 0.75 m, the value obtained of the wetted perimeter is 3.12 m. The necessary channel length within these conditions is 21,600 m^2 / 3.12 m = 6,293 m. However, a channel length of 10,671 m was projected to achieve greater homogenization of infiltration process throughout the aquifer and rectify deficiencies to be produced by clogging and vegetation coverage.

A service road next to the canal was built for inspections, watching and maintenance. The standard cross-section has 2 m tall and 4 m wide 0.50 m above the gutter coronation and agricultural lands, acting as a little dam to avoid possible flooding. It was built with material extracted from the channel excavation itself.

Figures 4-9 a & b: Infiltration channel in Santiuste with recharge water (a). Infiltration channel double precast stopping device in Santiuste basin (b) (Los Arenales demo-site, Spain).

There are three different types of concrete-made stopping devices installed along the MAR canal.

- Stopping devices along the infiltration channel (to speed down the water flow).
- Damming devices (to decrease the flow velocity and retain a certain amount of water).
- Stopping and damming devices (forcing the infiltration capacity beneath the retained water).

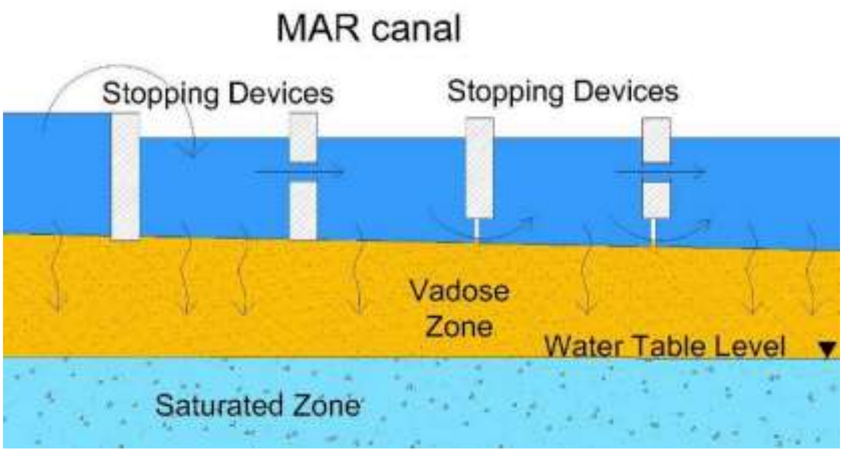


Figure 4-10: Stopping devices scheme to force the mix.

These little impermeable dams are made of precast H-125 concrete elements, 0.20 m thick, supported on the floor, to avoid differences in the pieces' settlement. The works were completed with gabions protection of 2 m length upstream and downstream of each device or in the canal bottle-necks, making the transition from a trapezoidal section to a rectangular one. Its overall dimensions, once assembled, are 4.80 x 2.00 x 1.90 m. Some of them have a lock gate of 1.00 m height that regulates infiltration.

The water flows across the canal with permanent mixture, avoiding thermal or chemical stratification thanks to the combination of gates and stopping dams placed at various altitudes to force the mixing of running water pursuing homogeneity (figures 4-09 to 4-11).


Figures 4-11 a & b: Elements (stopping devices) in the MAR canal. The locks (gates) are raised so the water flows either across the halfway drilled holes (a), underneath (b), or jumping over the slab so as to achieve a running water homogenization.

INFILTRATION DITCHES

They present a linear morphology and a semi-circular section and are usually located following the contour lines with a double target, increasing infiltration and reducing erosion.

Ditches are mainly used in hillsides with steep slopes to reduce water erosion. They are usually built perpendicular to maximum land slope, with a parallel traced to contour lines, leaving a small earth bund in a margin constructed with the dug material and usually stabilised by planting. They regularly have a spill over channel to prevent the ditch destruction in case of heavy rain episodes. Ditches enhance artificial recharge due to surface water retaining and residence time increasing.

The proper operation is directly related to its maintenance, since sedimentation processes reduce their infiltration capacity and thus their effectiveness and lifespan.

Figure 4-12: Image of a recharge trench along the contour lines to capture rainwater (Source: WCT).

Design criteria for infiltration ditches

The infiltration ditches design is one of the most important and complex issues, since it requires to know not only the hillside slope, but also soil characteristics (soil type and organic matter content), precipitation intensity, period of return, runoff coefficient, soil infiltration rate and even the substrate hydrogeological characteristics.

Some of the most important parameters to consider in their design and implementation are:

$$Vai = Vcz + Vin$$

V_{ai}= Surface runoff volume (m^3)
V_{cz}= Intake volume (m^3)
V_{in}= Infiltration volume (m^3)

$$Vai = P \times S \times e$$

V_{ai} = Surface runoff volume (m^3)
P= Rainfall (volume in 1 hour)
S= Runoff Surface (m)
e = Runoff coefficient

$$Vcz = b \times h \times l$$

V_{cz}= Water collected volume in the ditch (m^3/h)
b= Ditch bed (m)
h= Ditch height (m)
l = Ditch length (m)

$$Vcz = b \times v \times l$$

V_{cz}= Infiltration volume (m^3/h)
b= Ditch bed (m)
ν= Ditch infiltration velocity (m)
l= Ditch length (m)

$$d = \frac{b \times (h + v)}{P \times e}$$

d= Distance between ditches

Consequently, narrow deeply ditches are usually constructed on hillsides with steep slopes, while, in slight slopes, ditches can reach several meters wide. It is advisable to build the ditches following the contour lines if the inclination of the slope where they will be installed is between 2% and 45%.

The higher the slope of the hillside is the greater water velocity and runoff. Therefore, on hillsides with steep slopes, the distance between trenches should be less, to allow water surface runoff infiltration.

Another important design factor is soil type, since the infiltration capacity varies depending on the structure, texture, clay content, organic matter, etc. Therefore, the thicker the soil is the higher the infiltration rate and lesser the distance between ditches.

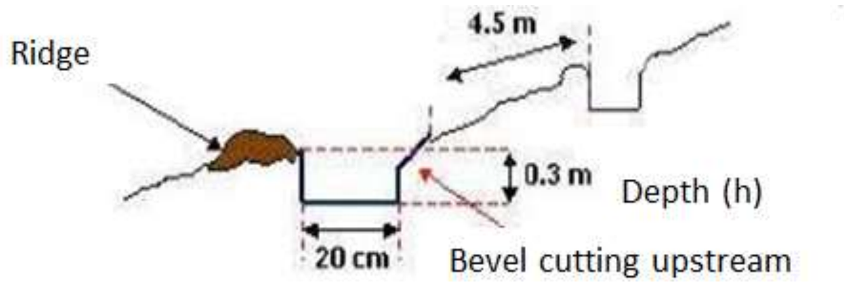


Figure 4-13: Example for a usual infiltration ditches scheme. Ditch dimensions: 0.2m width x 0.3m height. Distance between ditches: 4.5 m uphill.

The amount of water that every ditch must capture is another element to consider. Some required parameters for hydrological modeling are the peak flow, basin area, rainfall intensity or period of return.

Infiltration ditches must include an overflow channel to drain the excess water. The water that cannot infiltrate into the soil during periods of heavy rain is channelled through the overflow channel, to the nearest ditch. If necessary, infiltration ponds or wells to store this excess coming from the ditches are constructed.

4.2.3 Ridges/ soil and aquifer treatment techniques SAT

Water reuse is becoming a growing option regarding MAR applications, and the soil and aquifer treatment techniques (also called SAT) are positioned as an important alternative to consider, because they transform a problem (sewage removal) into a new resource (groundwater storage).

It is worth mentioning that SAT techniques are generally considered a form of reclaimed water reuse, but the term is, originally, much broader. In its Dutch connotation, it is understood as a set of actions to apply on water or on the receiving medium to increase the infiltration rate into the aquifer through interventions on the ground (S), in the aquifer itself (A) and in the water recharge (A´) (Krul & Liefrinck, 1946).

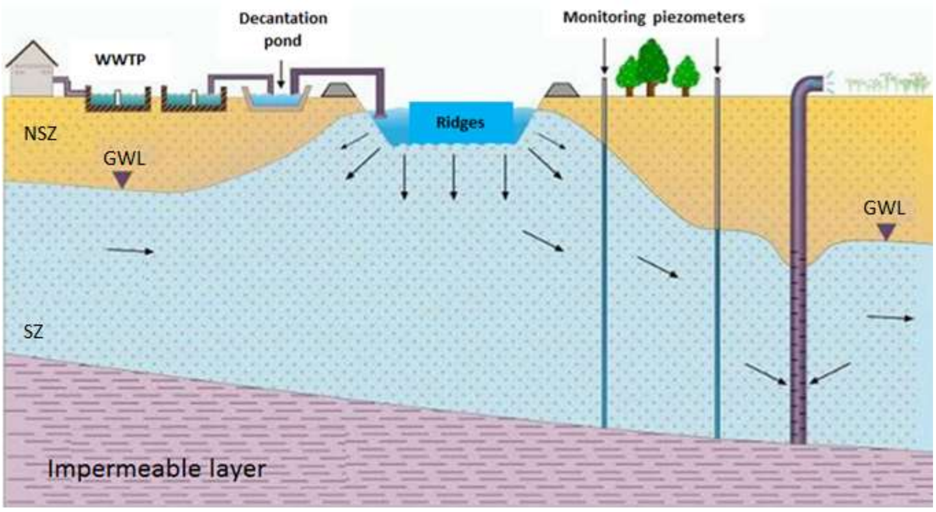


Figure 4-14: Example for S.A.T. Techniques application scheme.

These techniques can infer in the receiving medium (environment characterization), in the artificial recharge devices (engineering structures) and in the recharge water (especially during its pre-treatment phase), including multiple combinations. The application of these practices also extends to latter stages, where it is necessary to carry out cleaning and maintenance activities, aquifer evolution monitoring and correcting actions (Fernández-Escalante, 2005).

Some authors have concentrated their efforts in the study of actions to improve MAR water previous contamination and general treatment, either focused into the attenuation of any specific compound, such as, e.g., dissolved organic matter (Leenheer, 2002) or turbidity (De los Cobos, 2002), concluding that pre-treatment is the most effective measure to improve MAR systems effectiveness, statement defended by Bouwer, 2002, (as much as decreasing MAR constraints).

As general rules of SAT techniques application for all MAR methods and devices, the following suggestions must be analysed in each specific case:

1. Proper treatment of artificial recharge water and/or employment of good quality water for this purpose (Pérez-Paricio *et al.,* 2007).
2. Minimize aeration of the water and *Lisse* effect (barrier effect hampering the recharge water downward movement caused by the air-bubbles trapped into the aquifer (Krul & Liefrinck, 1946).
3. It is recommended to recharge at slow speeds avoiding water shaking and cascading effect, in order to prevent the excessive aeration of the water (Pérez-Paricio, 2007).
4. Minimize the corrosion of the structures and oxygenation of the water, controlling the oxidizing conditions, e.g. recharging only with water which temperature is higher than the temperature of the aquifer where carbonate precipitates, etc.
5. Control of certain parameters avoiding exceeding the quality standards of the recharge water according to the law of every country.
6. Proper design of the structures with warning and alarm systems when the *depth of alert* is exceeded.
7. The extra oxygen supply causes a decrease in the infiltration rate and accelerates the precipitation of iron and manganese; while losses of CO_2 accelerate the precipitation of carbonates in the receiving medium.

Some actions are questionable for different authors.

MARSOL EXAMPLE: FURROWS EXPERIENCE IN INFILTRATION PONDS IN LOS ARENALES DEMO-SITE (SPAIN)

Considering the experience in Los Arenales aquifer (Spain), several sorts of tillage were accomplished with diverse furrows harrowing (from 60 to 100 cm) and a turn over close to 20 cm (in Fernández-Escalante *et al.,* 2009). After that, little changes were done regarding furrows path and separation, and they were ploughed following the water stream direction and with a broader harrowing (from 40 to 140 cm).

In a second experience (2014 Sep. 29th) different furrows were practiced in other sectors of the Santiuste basin infiltration pond, in six parcels with a different furrow width (40, 60, 80, 100, 120 & 140 cm) apart from one plot of land ploughed with a “roman” ploughing tool. Highest infiltration rates were found for distance between furrows of 80 cm. The description of this experiment can be found in MARSOL 2015a and 2015b (deliverables 5-1 and 5-3).

Figure 4-15: Furrows experience in Los Arenales demo-site (Spain).

The disks ploughing tool is preferable to the mouldboard, as the first one induces a lesser pulverization rate in the superficial layer.

4.2.4 Infiltration fields (flood and controlled spreading)

This artificial recharge device type is an ancient form of water resources management, widely used in arid and semiarid areas.

Water diversion for flood or "Water Spreading" is a technique that involves forcing the water to flow out of its natural riverbed, for example through canals and levees systems towards arable lands.

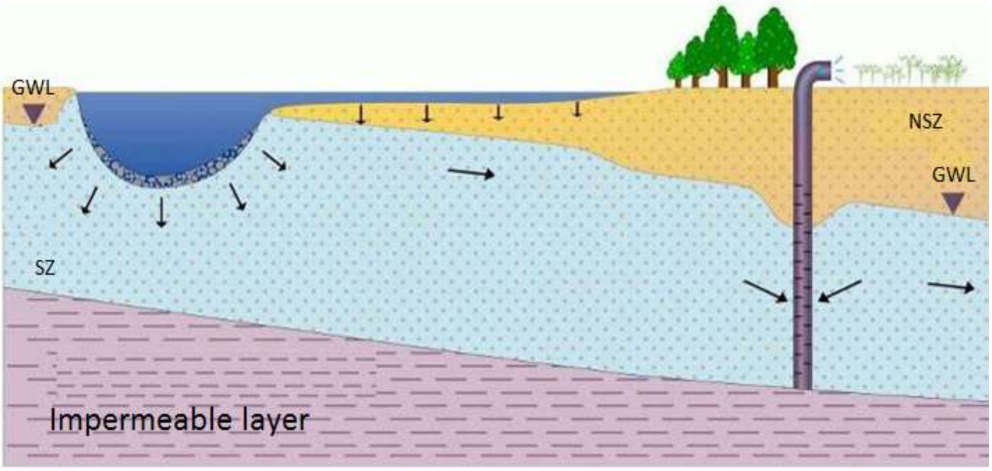


Figure 4-16: Infiltration field diagram.

This network implementation frequently needs extensive flat and permeable plains (alluvial plains) to induce an “artificial flood”.

The diversion through water channels from a river allows the controlled spreading of the water sheet over a large area. This sheet moves over the surface at very low speed, minimally altering the soil surface. To control the water depth, banks or ditches must be installed on the flood plain margins, preventing the flood of areas with different uses.

The soil infiltration capacity depends on their characteristics, such as texture, structure, organic matter content, etc. Thus, in this type of MAR system, the highest infiltration values occur in soils where vegetation is retained and the surface coating remains intact.

These flooded lands work temporarily as wetlands and show significant and simultaneous ecological functions, such as a habitat for wildlife, improving water quality and soil fertility through biogeochemical transformations, flood control by lamination in the diversion dam, etc.

Infiltration fields are usually designed in sections or divisions which cause irregular water dispersion during the rainy season. The first section of the field or area receives more water than the second, and this more than the third and so on. This creates a problem due to heterogeneity in the infiltration rate and lack of control of the actual volume of water absorbed in each area. For this reason, it is recommended that each section has a different size and also the channel meets only once every infiltration zone.

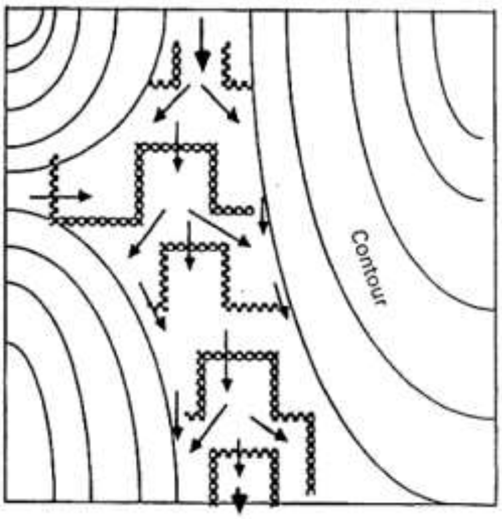


Figure 4-17: Schematic design of the barriers used to spread runoff water on the floodplain for watering the Nabatean farms in the Negev desert. Taken from Evenari and Koller, 1956.

Proper maintenance of these devices is essential to achieve maximum performance and to avoid possible flooding from ruptured channels. It is convenient to create a local organization to carry out an appropriate preservation of the devices.

Due to flooding, large sediment accumulations concentrate on the surface, which can be profitable for agriculture in the area, but it can significantly reduce the artificial recharge volumes requiring again intense maintenance activities (Esfandiari-Baiat and Rahbar, 2004).

4.2.5 "Accidental" recharge by irrigation return

Excess irrigation water from canals and fields have historically caused water logging and salinization problems. However, when over-irrigation is properly managed, this incidental recharge could indeed be a technique of artificial recharge, by means of infiltration and percolation into the underlying aquifer.

According to the International Institute for Water Management (2002), it is estimated that approximately 60% of the water applied to rice paddies is utilised by the plant, while the remaining 40% seeps into groundwater or is lost by evaporation. This activity represents a significant volume for artificial recharge either intentional or accidental.

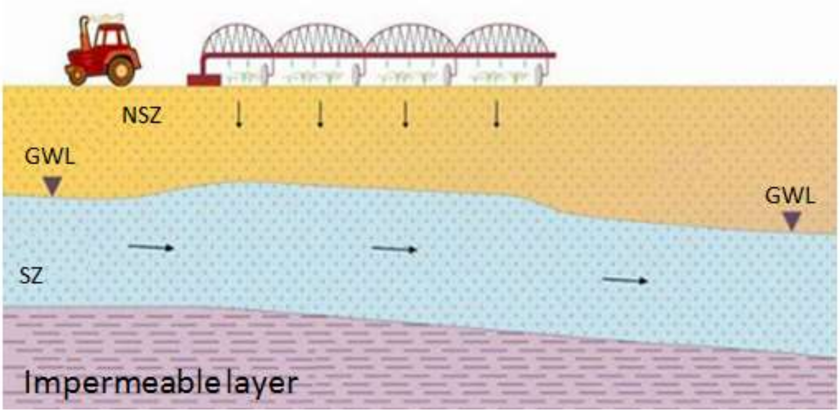


Figure 4-18: Scheme for accidental recharge by irrigation return, when the water volume exceeds the necessity of the plants. This option can eventually be intentional.

Certain changes in the irrigation canals morphology enable to increase natural groundwater recharge. Among the different irrigation types commonly used, the surface ones are obviously best suited for artificial recharge, and especially, furrow irrigation.

On the other hand, micro-irrigation and drip irrigation are not recommended, as well sprinkler irrigation. The more effective irrigation is the less water gets infiltrated and evaporated.

Table 4-3: Types of irrigation and their suitability for artificial recharge.

TYPES OF IRRIGATION	SUITABLE FOR ARTIFICIAL RECHARGE
SURFACE	YES (FURROW AND SURFACE)
SPRINKLER	NOT (CRITERIA DESIGN)
DRIP	NOT (SCARCE WATER VOLUME SUPPLIED)
UNDERGROUND	YES

In most cases, part of the plant´s water needs is supplied by rainfall and the remaining part by irrigation. Then, the irrigation water need (IN) is the difference between the crop water need (ET crop) and that part of the rainfall which is effectively used by the plants (Pe).

In formula: IN = ET crop - Pe.

When rain water [(1) in Figure 4-19], falls on the soil surface, some of it infiltrates into the soil (2), some stagnates on the surface (3) and some flows over the surface as runoff (4). When the rainfall stops, some of the water stagnating on the surface (3) evaporates to the atmosphere (5), while the rest slowly infiltrates into the soil (6). From all the water that infiltrates into the soil ((2) and (6)), some percolates below the root zone (7), while the rest remains stored in the root zone (8). The effective rainfall (8) is the total rainfall (1) minus runoff (4) minus evaporation (5) and minus deep percolation (7). Only the water retained in the root zone (8) can be used by the plants, and represents what is called the effective part of the rainwater (FAO, 1986). Deep percolation water contributes to the recharge of the underlying aquifer (7) and the final amount varies depending on the type of crop, soil characteristics, irrigation water system and climatic conditions.

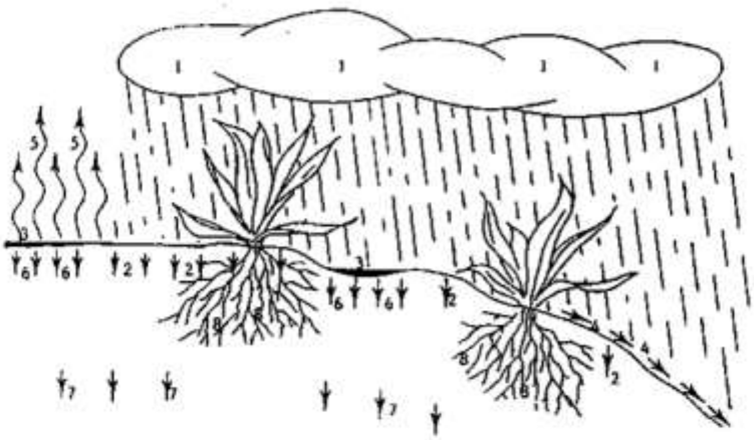


Figure 4-19: Effective rainfall (Taken from FAO, 1986 and 2000).

Reclaimed water used for irrigation may be considered as a reuse and recovery water system. However, this might provoke problems in the groundwater quality in case of an inappropriate treatment has taken place. Nevertheless, the use of wastewater combined with “SAT techniques” usually improve its quality and allows its use for irrigation or other uses, such as, overexploited aquifers recovery, wetland regeneration, etc.


Figures 4-20: Irrigation ponds of reclaimed water in Majorca island, Spain.

MARSOL EXAMPLE: FORESTED INFILTRATION AREA IN BRENTA DEMO-SITE (ITALY)

The pilot area of Schiavon represents an accidental recharge example on the underlying aquifer. The fast-growing trees cultivation can turn out economic benefits for land owners (e.g. trees for paper production and biomass energy generation) and in the meantime, provides environmental services (ecological enhancement and water quality as well as quantity improvement).

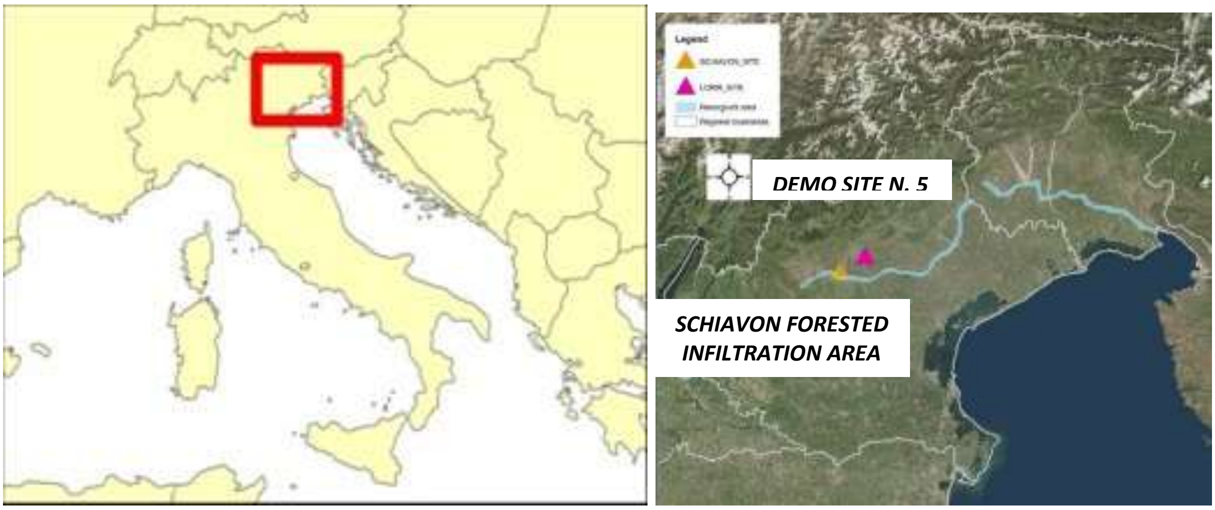


Figure 4-21: Brenta demo-site, Venice (Italy). Taken from MARSOL WP7 Brenta demo-site presentation exposed at Workshop on Financial and Economic Analysis of MAR solutions, 2016 June.

Fast growing trees (such as *Platanus hispanica, Ulmus minor, Paulownia tormentosa*) are planted on both sides of the furrows with a density of about 5,000 trees/ha. The vegetative cycle entails 5 years, after which they are harvested and chipped.

The total area of Schiavon FIA is 1.4 ha. This pilot area uses furrow irrigation to ensure infiltration into the aquifer at a rate estimated between 20 and 50 l/s/ha. The distance between furrows is 7 m from each other. Furrow dimension: 0.7 m-deep, 0.7 m-wide on top and 0.3 m-wide on bottom. The furrows are fed by drainage channels connected to the irrigation ditch of the local irrigation network.

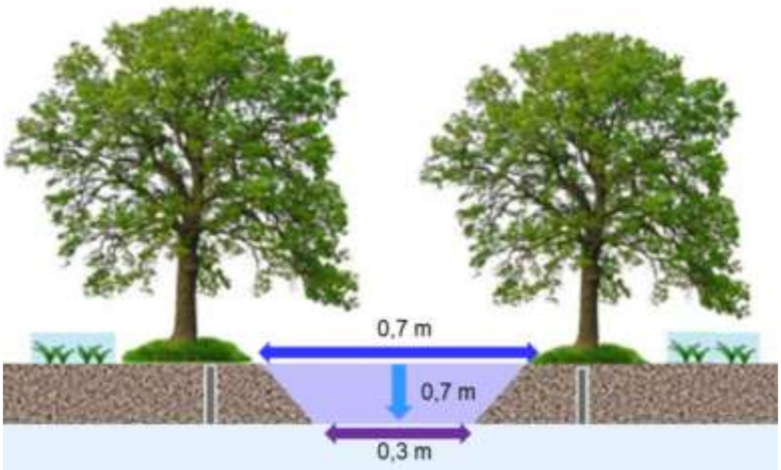
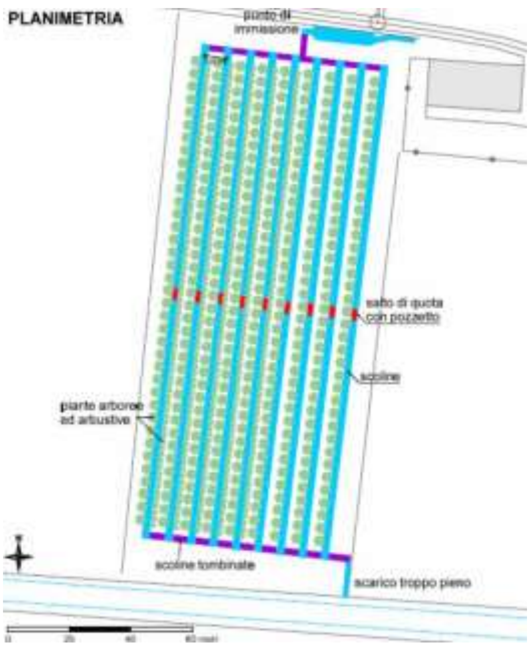


Figure 4-22: Criteria design of furrows in Brenta FIA, Italy. Adapted from WP-7 Demo Site Brenta Vicenza, MARSOL Deliverable 7-1.

The system operates continuously during the winter non-irrigation period (ensuring that ecological flow of rivers is maintained) and, on an intermittent basis, during the irrigation period in summer, totalling 194 operating days per year.



Figures 4-23: a & b. Schiavon pilot site graphical representation (a) and prospecting works in FIA (b). Both taken from MARSOL deliverable 7-1; Brenta demo-site.

OTHER EXAMPLE: AZARBES (SPAIN)

"*Azarbes*" are aquifer recharge examples employing excess of irrigation water. They usually consist of uncoated trapezoidal ditches forming a branched network that collects the irrigation water excess leading it to other downstream end-use points. Some of the water can be used to recharge aquifers, infiltrating directly from the ditch or other system such as an open infiltration/injection well for MAR.

Figure 4-24: Azarbe example, Valencia, Spain.

Azarbes are important networks because they prevent waterlogging and subsequent salinization. Construction, operation and maintenance are subject to the same criteria and conditions than distribution networks, but they require a frequent cleaning owing to the usual reeds and cattails proliferation.

4.2.6 Reservoir dams and dams

Check dams vary considerably in size and construction depending on the catchment size, topography and available resources for construction. These devices restrain surface runoff within the confines of the stream and facilitate infiltration upstream of the dam.

Check dams is a broad-spectrum term which includes small scale reservoir dams and regular dams. The first ones are built in the riverbed to intercept flows in ephemeral channels and store water during a flood; while the second ones are constructed into permanent flow channels and their activity is distributed all throughout the year. In both cases the stored water tends to be extracted from the aquifer or from the river bank through wells or galleries.

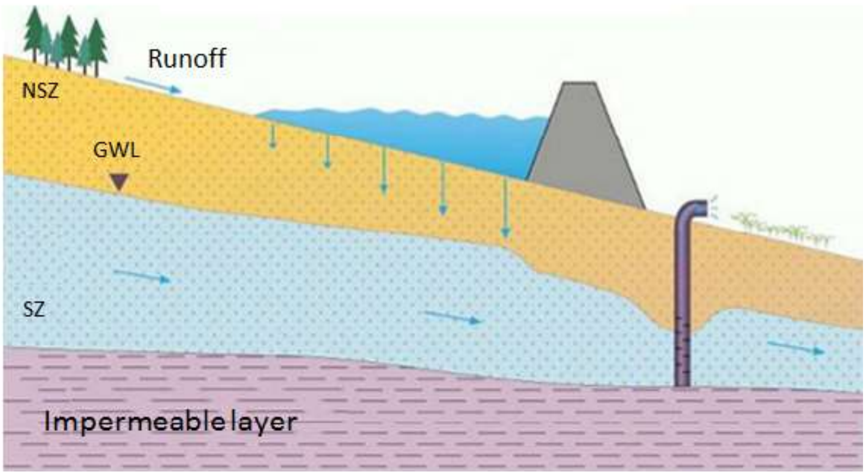


Figure 4-25: Reservoir dams/ dam's scheme.

RESERVOIR DAMS

They can be constructed in ephemeral (seasonal) gullies or streams and must be underlain by permeable river bed and a permeable rock or alluvium. They are designed based on channel cross-section (usually no more than 3 m in height). The excess of water spills over across a spillway in the dam coronation, with an adequate freeboard so that the structure is not over-topped in an uncontrolled manner. Unrestrained overflows are the main cause of dam failure. They must be built with impermeable materials such as stone, brick or concrete to avoid losses by filtration.

In regions where rainfall is intermittent and discontinuous, with heavy storms or high gradient, the surface water runs at high speed reducing the infiltration rate capacity and creating intense erosion processes. The construction of these dams reduces the mechanical energy of the surface runoff and increases the water residence time in the basin, enhancing a natural infiltration in the ground.

DAMS

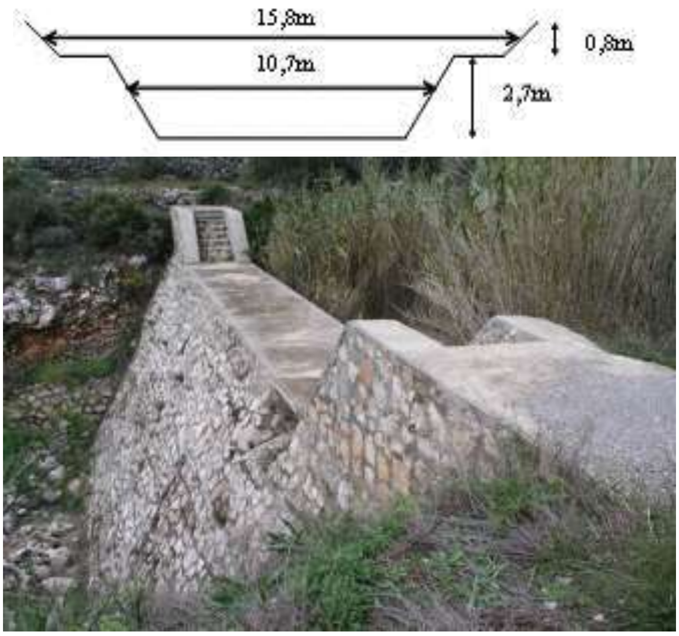
Rivers and streams that maintain uniform flow throughout the year allow the installation of “dams”. It consists of a series of barriers arranged transversely to the river, without completely blocking the water flow. These barriers reduce the water speed in the stream-bed, favouring infiltration and recharging the underlying aquifer. Therefore, shallow unconfined aquifers with high storage capacity and permeability are preferred.

Annex 2 widens this information about the selection criteria for each specific MAR system.

EXAMPLE: SELECTIVE REINFORCED CONCRETE DAM “BARRANCO DE LANA MAYOR“, HUESCA (SPAIN)

Reinforced concrete is the chosen material for dam foundations and the dyke construction. It has a trapezoidal shape and a 3.5 m (2.7 + 0.8) height. It comprises a first bucket of 10.7 x 2.7 m with a drainage capacity of 146.97 m^3 / s, which corresponds with the peak flow for a return period of 50 years. The second bucket is 15.8 x 0.8 m^2 and allows the flow of 31.4 m^3/s, i.e. the calculated peak flow for a 100 years´ period of return (figure 4-26 a).

Another peculiarity of this devices is the way they help to develop flora and fauna typical from wetter and deeper soils in hillsides where the steep slope would not permit this kind of habitats. That is an environmental fact to be considered as much as its counter-erosion effect in arid climates.



Figures 4-26 a & b: Dam diagram (a) and example for a dam specific for MAR and lamination in Alicante province, Spain.

There is a long experience in the Sahel in the use of this type of dykes and dams to manage recharge in aquifers under oasis using water resources from an intermitent stream (oued or wadi). As a matter of fact there is a a demonstration project funded by European Commission through Sustainable Water Integrated Management (SWIM) Programme called WADIS-MAR that has just finished in June 2016 (Ghiglieri et al, 2016).

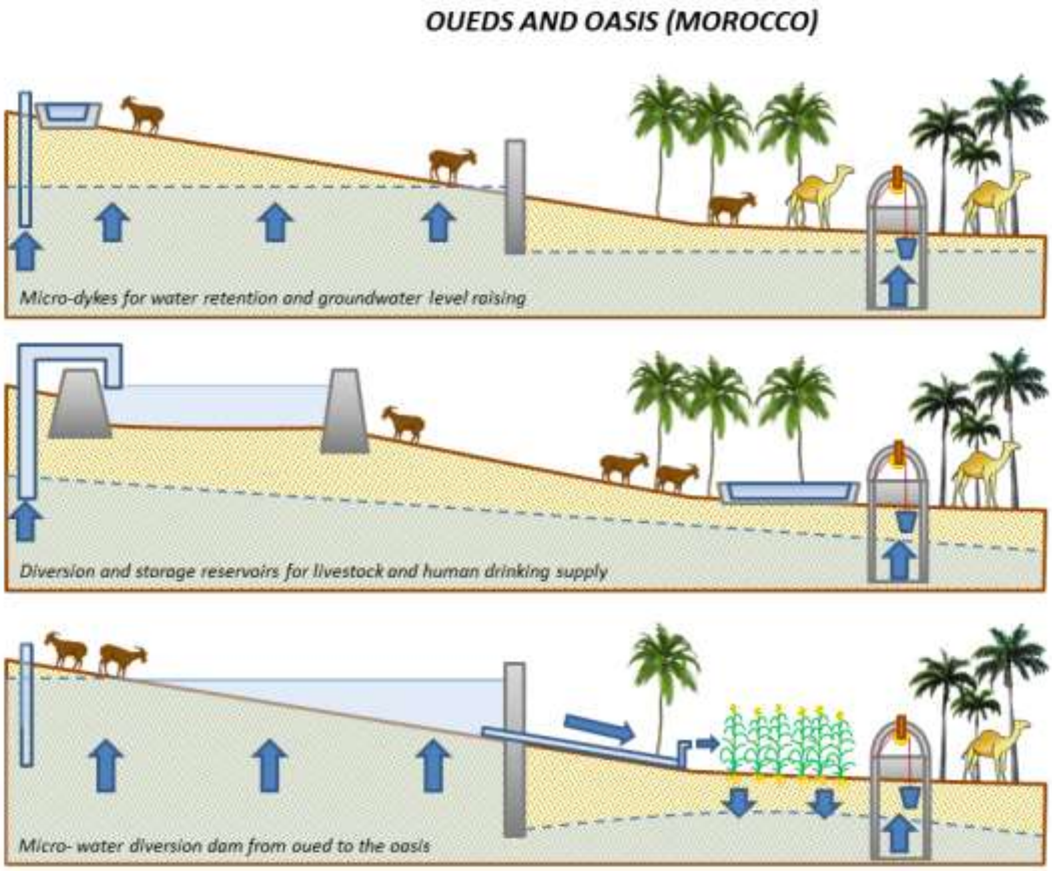


Figure 4-27: Dam examples in oasis management and MAR in Mauritania and Morocco experiences (AECID-Tragsatec, 2017, in print, based on TENMIYA, 2009 and others).

4.2.7 Permeable dams and gavions

As for the previous case, dams perform an important retention and lamination action to increase the volume of water infiltrated into the aquifer. A technical solution applied in areas where floods are often is to build dams with loose materials, either cemented with any mortar, or retained by means of a wire holding system (gavions). This sort of dams is typical of semi-arid and arid regions. There are not important design differences with the previous cases. The selection of the dam body is adapted to the materials availability in the area and the need to reduce the energy impact on the structure.

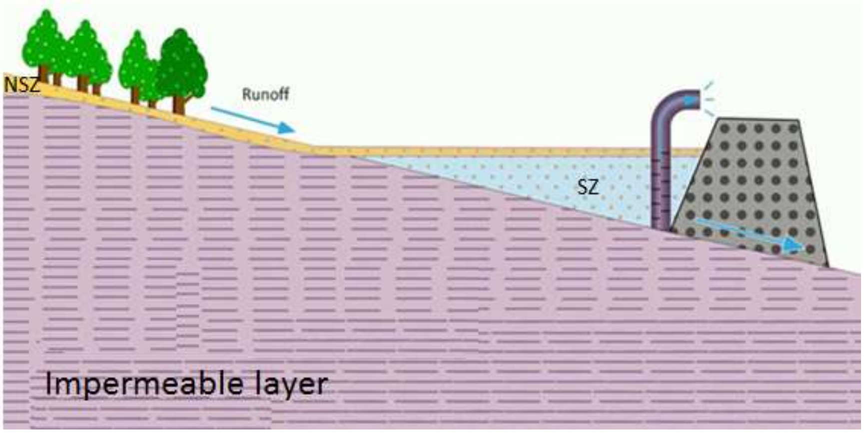


Figure 4-28: Permeable dam's scheme, check dams and gavions.


Figures 4-29: Gavions block reservoir dam in Las Palmas, Canary Islands (Spain) and check dam near Zarzis (Tunisia).

4.2.8 Drilled dams

Specific sort of reservoir dam which is endowed with a punching drill across the body, with a double function: as an energy dissipation measure and/or for cases where direct collection of water is advisable.

It is also usual in Mediterranean areas where the river bed is rather embedded in the bedrock. In cases of a high confining pressure, there is a spillway to a certain height to alleviate the lateral stress.

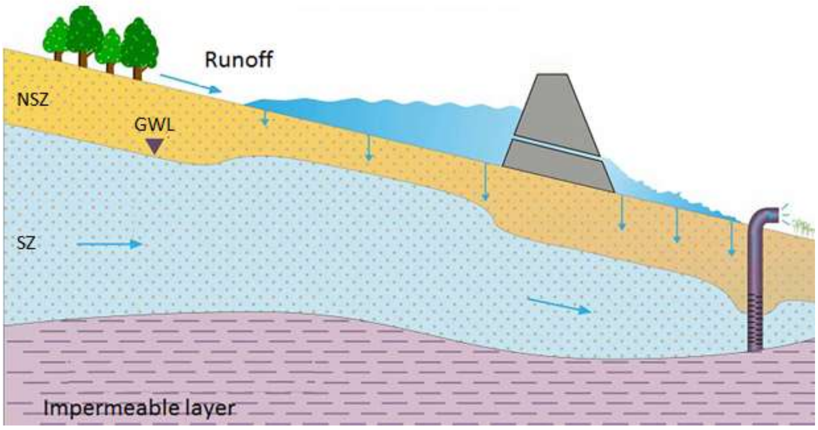


Figure 4-30: Drilled dam scheme.



Figures 4-31: Perforated lamination and protection dam in a stream header to enhance the recharge in the aquifer and equipped with a tap for direct water collection. Tarragona, Spain.

4.2.9 River bed scarification 

This technique consists in scarifying the bottom of the riverbed in order to increase the infiltration rate across the alluvial formations. It is practised in Catalonia since decades with the following criteria: the tractor is equipped with a rake and moves in the direction of the river flow but the velocity is slower than the current. So, the mud mobilized from the bottom is transported by the current downwards.


Figure 4-32: Riverbed scarification in Barcelona (Spain).

This practice has eventual ecologist's opposition and must be done with a certain guarantee of minimum impact on the riverbed fauna.

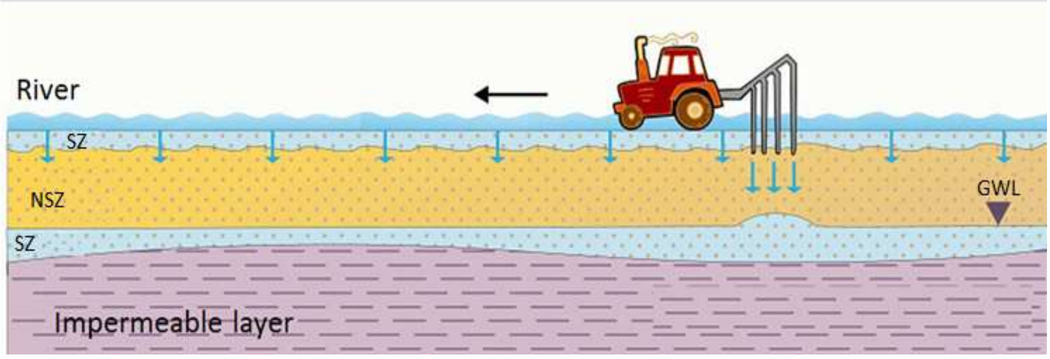
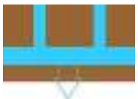


Figure 4-33: Riverbed scarification scheme.

4.2.10 Qanats (underground galleries)



The system called Qanat (which means "dig" in Persian) was invented in Iran thousands of years ago. Because of its simplicity and effectiveness it was easily extended to other regions of the Middle East, China or the Mediterranean, being currently present in the five continents. It is originally a system to collect rainwater for latter uses, and depending on the groundwater table position can be used for artificial recharge, even change the usage along the year.

The main function of this system is to drive the water from the aquifers located in the foothills upper parts and valleys bottoms by means of gravity. There are also qanats that exploit alluvial or even groundwater aquifers situated at sea level.

The system consists of a main tunnel or “mother” that runs with a slight inclination from aquifers to lower areas. Along the main tunnel there are a series of vertical wells or shafts whose functions were to provide ventilation, allow access for repairs and excavated material removal.

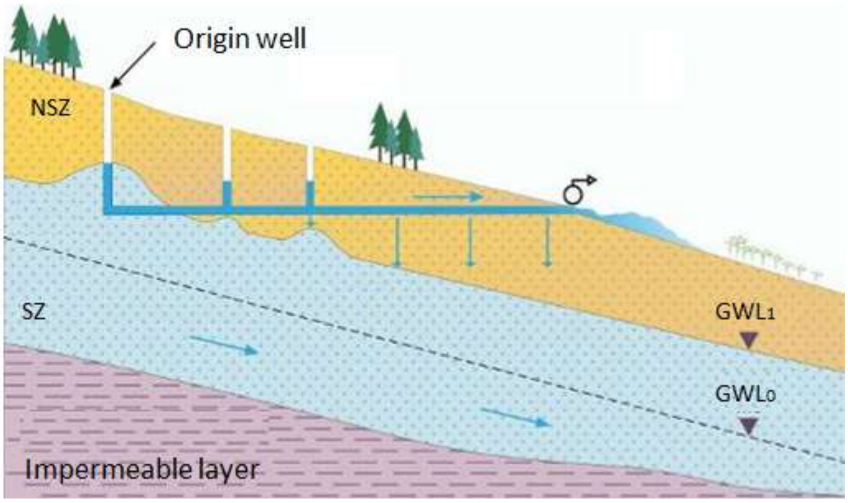


Figure 4-34: Qanat scheme.

This device presents three advantages in particular:

1. Distribution channels are underground; this fact significantly reduces evaporation losses in regions where the temperatures in summer can be really high.
2. Pumps or wells for water extraction are not necessary since the movement of water into channels is performed only by gravity. Eventually shafts are used as wells.

3. The water volume provided by these devices is controlled by the groundwater level. The qanats flow varies directly with the proportion of available water in the aquifers, which makes qanats a sustainable system in the long term. This last point is also its main disadvantage with respect to other MAR devices, since it has an important self-limitation in terms of performance and functionality.

Qanats are often dug into the mountain sides where there is a permeable formation such as an alluvial fan at the base. A previous study should be conducted prior construction, to locate the most appropriate way for the tunnels excavation. A common design criterion is the main tunnel´s slope, which should not exceed 5%.

Construction begins by digging a ventilation shaft at the future qanat output. The well is dug to find the potential aquifer. Then, the aquifer hydraulic conductivity is calculated. If the aquifer is suitable for the qanat construction, it continues with the excavation of the main tunnel to the upper parts of the mountain. A slight inclination must be maintained so as to allow the water movement by gravity avoiding washing processes to take place and undermine the tunnel bottom.

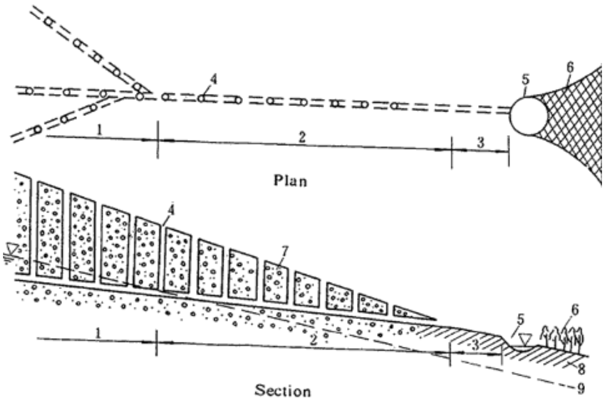


Figure 4-35: General outline of a qanat (Taken from www.waterhistory.org/histories/qanats/).

As the main tunnel construction progresses, ventilation shafts are dug, also to remove the excavated material. In areas where the ground is not consolidated or unstable, landslides and subsidence effect may take place in the tunnel, with risks for constructors, thus, these areas are often reinforced with baked clay tiles.

EXAMPLES: UNDERGROUND GALLERIES IN SPAIN

The inventory of draining shafts in Spain sums up more than 8,000 devices (Sanchis-Ibor et al. 2014). The qanat gallery in *Public Mine of Aigües de Terrassa* serves to supply the water demand of Terrasa city (Barcelona). This underground gallery has an approximate flow of 3,000 m^3/day (which represents 5% of the total demand). The total length is 14,429 m and 226 shafts are present allowing the ventilation and maintenance issues. It has walls formed with ceramic bricks, the same materials used in the ventilation shafts. In some gallery sections, the base is formed by a basement coated with a 20 cm quicklime layer.

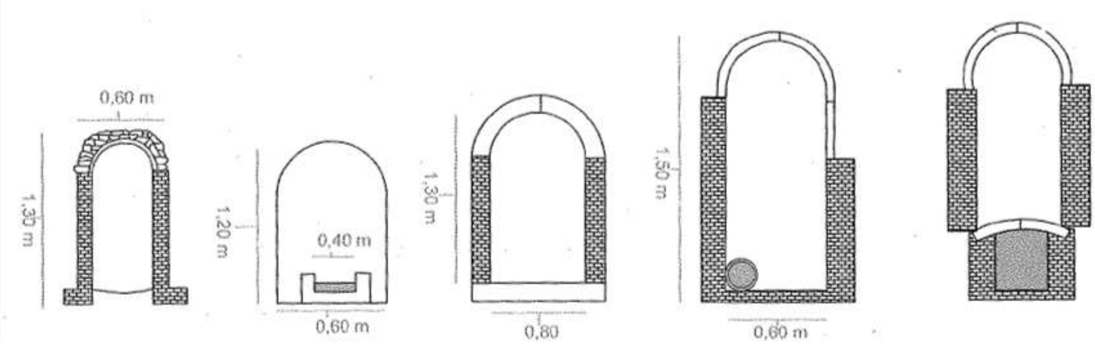


Figure 4-36: Public mine of Aigües de Terrassa. Qanat, Terrassa. Barcelona (Extracted from las Galerías drenantes en España: análisis y selección de Qanat(s) 2008).

Another example is the qanat of Fuente de la Tosca (Alicante, Spain). It has a length of 79 m. The inner structure varies in width and materials since stone walls and concrete blocks in the ceiling (1 in the figure 4-37), to excavated-rock sections (2-5) or reinforced natural caves (3-4 and 6).

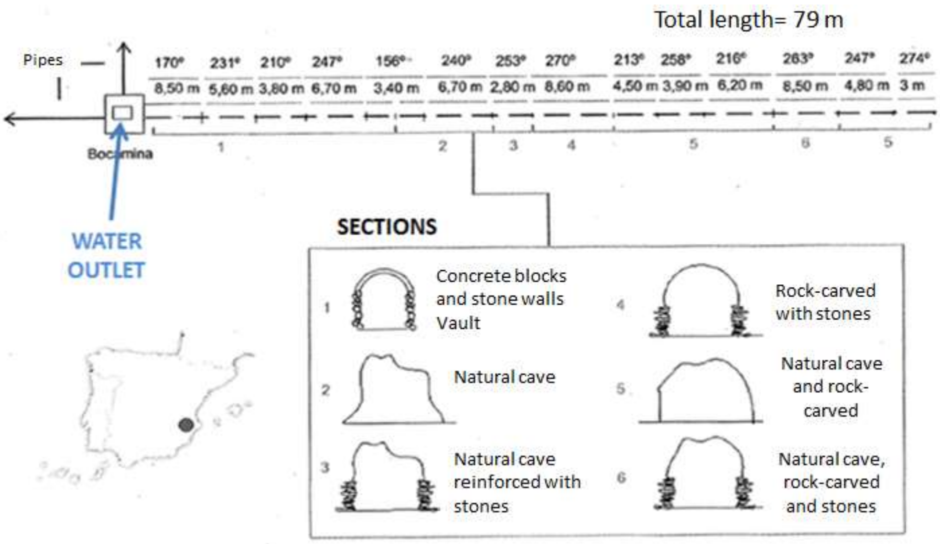


Figure 4-37: Font de la Tosca. Qanat. Relleu, Alicante. Extracted from las Galerías drenantes en España: análisis y selección de Qanat(s) 2008.

Depending on the depth and the aquifer characteristics, the qanat length can vary from a mile (1.61 km in Central Spain qanats) to even 18 km long (Southern Iran). The performance also varies widely, for example in the plains of Varamin, South-east of Tehran, where there is a system of 200 qanats whose performance reaches a 270 L/s flow, while others qanats only contribute 0.9 L/s depending on site conditions, size of device etc.

4.2.11 Open infiltration wells

These devices are useful in areas where either the aquifer is overlain by less permeable strata or soil infiltration rates may be low. Also, when it is not possible to construct dispersion facilities, open infiltration wells require a reduced land surface area being in occasions a singular point.

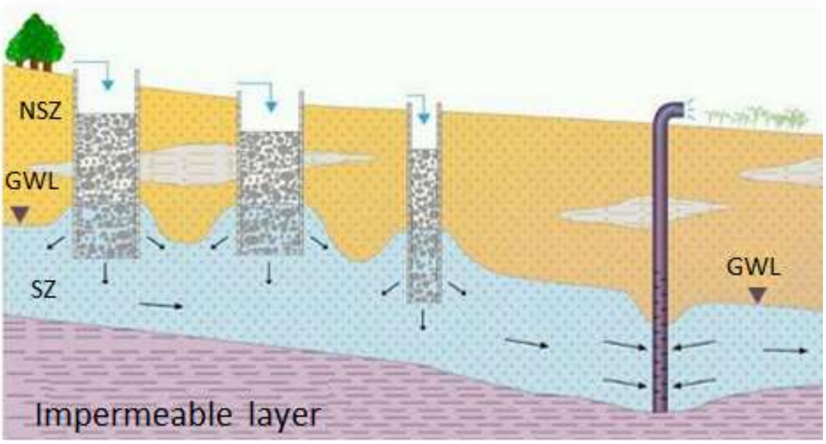


Figure 4-38: Open infiltration wells scheme. Different versions exist; this scheme depicts injection wells into the saturated zone.

Open infiltration wells consist of one or more "large diameter" and shallow wells, approximately 5 to 15 m deep (Bouwer, 1996). Both side walls and bottom should be as narrower as possible to encourage maximum infiltration. It is advisable to fill the well with gravel and a coarse sand filter layer, so they promote infiltration and reduce maintenance costs in case of obstruction (filters must be periodically removed and cleaned). Induced recharge water is injected or poured from the surface avoiding any cascading effect and dissolved air to enter the aquifer. It is advisable to protect the well top from sunlight and accidents with animals or people.

If the aquifer is highly permeable, such as a karstic limestone, large volumes of recharge water can be recharged rapidly and effectively.

The reuse of existing structures to recharge the aquifer, such as disused or abandoned mines or wells reduces significantly the work costs. Their use is usually limited to suitable cases or structures already available, such as, abandoned quarries, gravel pits, etc. This fact has brought up an inner MARSOL slogan: ***"Do not close a well, reuse it"***.

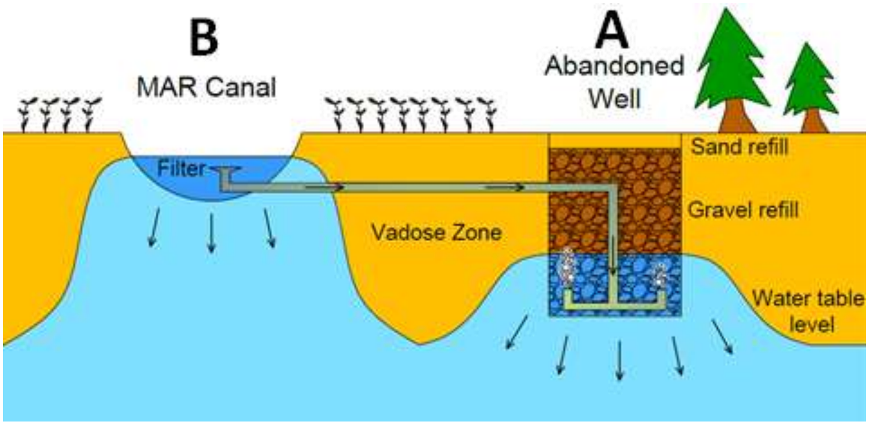


Figure 4-39: Old abandoned well reused for MAR scheme. Recharge water is conducted avoiding cascading effect.

Figure 4-40: Old well filled with sand and gravel (A) and in pipe connection next to a MAR canal (B). Invisible recharge at Los Arenales demo-site, Spain.

Although open infiltration wells are more effective in some cases than dispersion techniques, they may suffer contamination problems and clogging overdevelopment depending on the recharge water quality, because of suspended solids, bacteria, or pesticides filtration. Thus, a very crucial aspect to consider is the recharge water quality, specially suspended solids proportion and other pure clogging elements, such as vegetal content. Nonetheless, another possible water source is reclaimed water, taking into account the amendments that this source can cause in local waters.

Definitely, water pre-treatment is perhaps the most effective measure to carry out MAR techniques in these devices with the maximum performance, together with mixtures and combinations of different quality waters.

These wells should not be used in places where supply wells are less than 10 m deep, where the distance between injection and extraction wells is much reduced or where the subsoil is composed of calcareous formations or fractured rocks, to prevent groundwater contamination processes.

MARSOL EXAMPLE: OPEN INFILTRATION WELLS IN MENASHE DEMO-SITE (ISRAEL)

A good example has been developed in Menashe demo-site by Mekorot Company. The free water fall is avoided by means of a closed pipeline with a SAT design; water is poured below the groundwater table, avoiding shaking and cascading effects (figure 4-41).

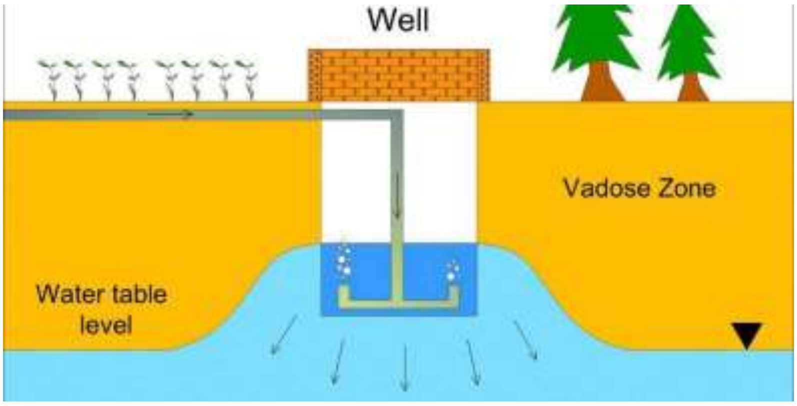


Figure 4-41: Medium-deep recharge well scheme.

Figures 4-42 a & b: Medium deep well example in Menashe demo-site (Israel).

4.2.12 Deep wells and well-boreholes

These devices present similar requirements and characteristics to open infiltration wells. The main difference is the depth, which depends on the permeability and especially on the low permeability strata thickness. The rest of the features in terms of coating, filling/refilling, maintenance, recharge water quality, etc., are very nearly the same. The difference lies in constructive design criteria; smaller diameter, different casing and rendered materials, etc.

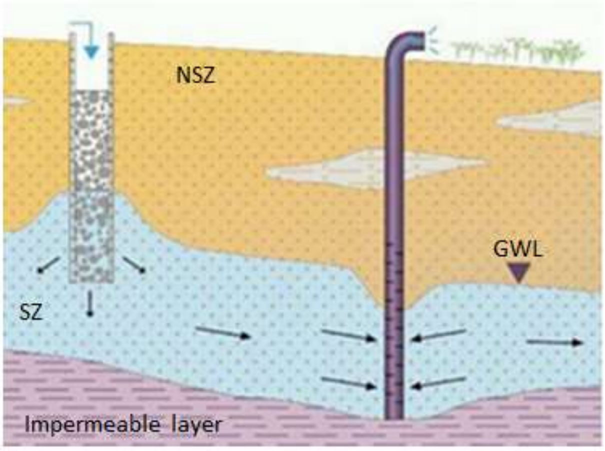


Figure 4-43: Deep well scheme.

Regarding well-boreholes (combination of a high-diameter well and a borehole from a determined depth, figure 4-45), they are usually installed in detrital fine-grained, free or semi-confined and shallow aquifers. This type of boreholes presents very similar characteristics to regular boreholes, but they are usually less than 30 m deep.

EXAMPLE: WELLS BATTERY IN GUADIANA´S CANAL FOR MAR, CIUDAD REAL (SPAIN)

Figures 4-44 a to c: Deep well for MAR next to Guadiana River´s canal (Spain).

This nearby MAR canal battery of wells is composed of 25 units between 60 and 100 m of depth along a channel starting at Peñarroya dam. These artificial recharge wells collect water directly from the river through a concrete pipe with diameter of 0.80 m, which is protected with riprap and a metal grid filter. Subsequently, the water passes through a gate to the decanter and is filtered during its passage through a casket sandy/gravel filter. Finally, the water is introduced into the well, trying to keep the dynamic level constant so as to avoid cascading effect and subsequent hyper-oxidizing conditions.

Each well consists of precast concrete elements with a 1.00/1.25 m Ø. The metal slotted casing has a variable diameter between of 0.40 m to 0.50 m in the second stretch and between 0.32 and 0.5 m for the third one, when it exists. The deeper borehole depth varies from 40 to 90 m. Figure 4-45 shows the constructive cross-section for a MAR well-borehole combination.

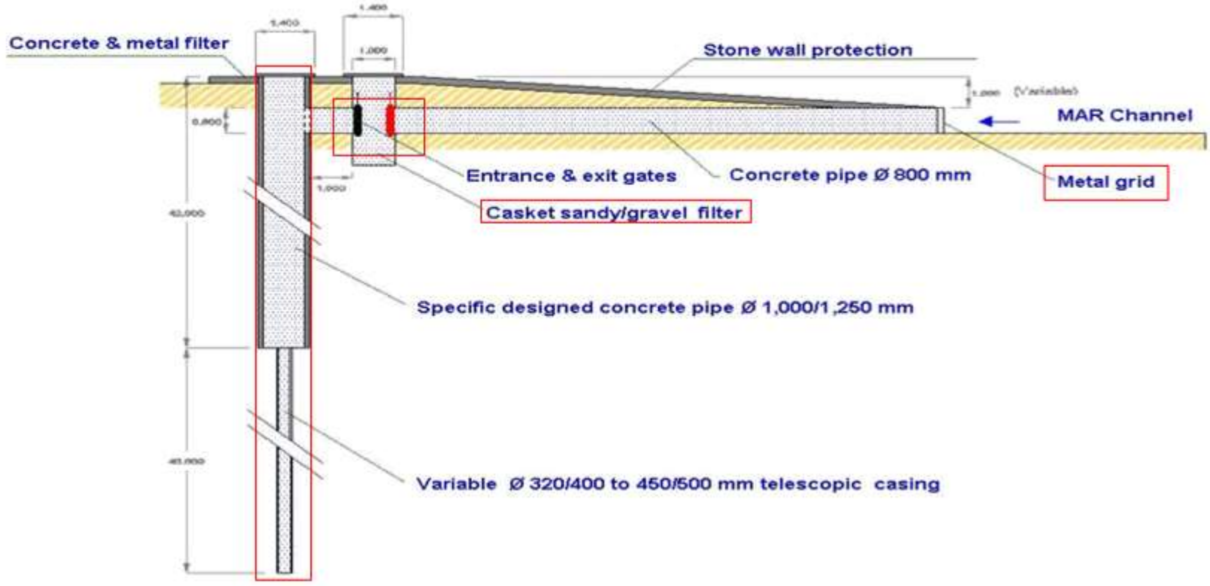


Figure 4-45: Example of a constructive scheme of a deep well for artificial recharge (Courtesy of CHG, 2010).

The wells present some key elements for a successful design:

1. Water pre-treatment by a metal grid + gravel/grit filter + sand filter.
2. Specific wells have a telescopic design with 2 or 3 stretches.
3. Combined well casing concrete-metal.
4. Valves for manual operation to maintain a constant dynamic level.
5. Gates to isolate the portal from the surface and a proper fence in those more crowded areas.

4.2.13 Boreholes

Unlike open infiltration wells or deep wells where most of the infiltration is passive by simple gravity, in boreholes treated surface water is either inserted passively or pumped under pressure (injection) directly into the aquifer

These devices are more appropriate for confined aquifers or for those cases in which aquifer hydrogeological parameters are lower in terms of transmissivity or storage coefficient and require the introduction of pressurized water to achieve viable and profitable recharge rates. It is essential that water is treated before injection to avoid regular clogging of the well-aquifer interface with sediment or bio-fouling.

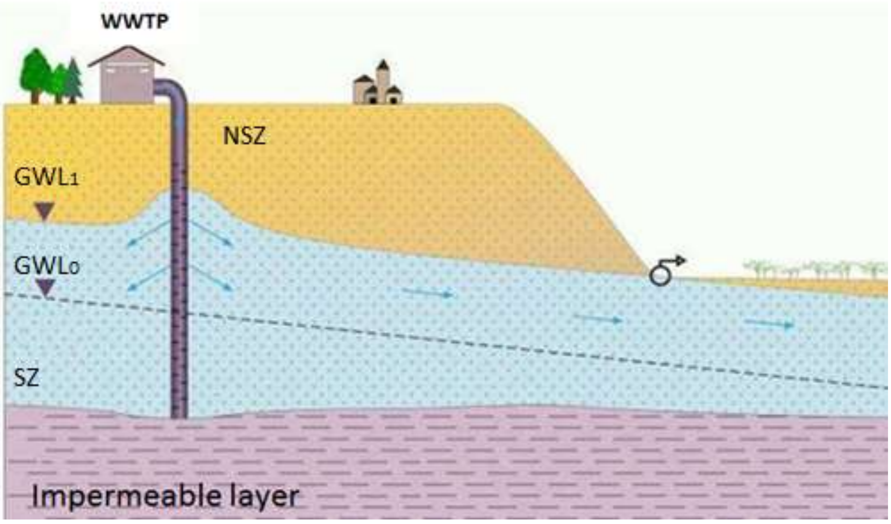


Figure 4-46: MAR borehole scheme.

In the case of injection boreholes, water is pumped into the aquifer and it flows naturally following the hydraulic gradient until be recovered with other wells or natural springs. They can also be designed to increase the water sheet in ponds and streams. This type of devices can be used as a technique of artificial recharge and recovery natural resources taking advantage of other water surpluses from other parts of the basin and its later usage in wetland recovery, swamps or dried areas due to the excessive extraction.



Figures 4-47: Deep boreholes in a karst aquifer (Majorca Island, Spain).

EXAMPLE: HYDRAULIC BARRIER OF LLOBREGAT (BARCELONA)

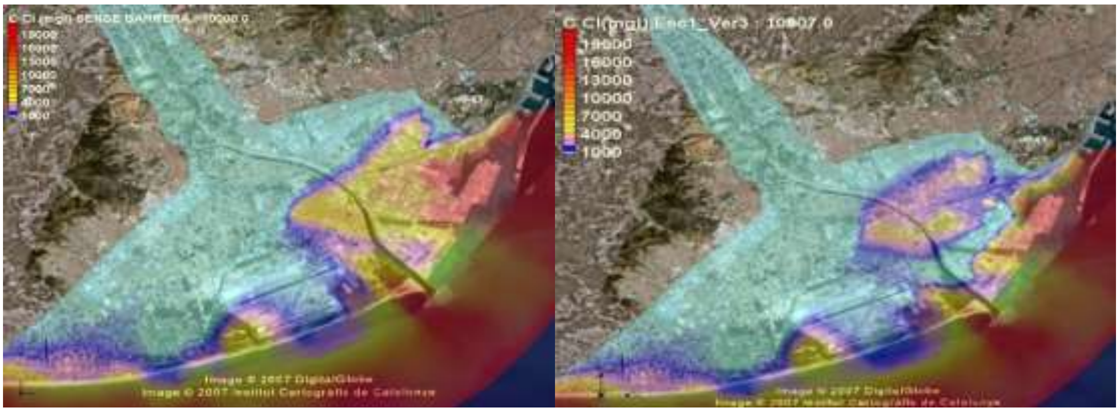
The first phase set of boreholes of the hydraulic barrier against seawater intrusion in Llobregat consisted of five boreholes distant from each other about 300 m. They have a drilling diameter of 610 mm. It is a positive barrier by means of reclaimed injection and treated water.

The boreholes are cased with stainless steel 350 mm reaching up to 70 m depth and the filter sections are die-cast 6 m in length alternating with blank pipe stretches of similar length in the main aquifer area.

The main infrastructure includes flowmeters, automatic injection control valves, level sensor and sampling ports. All boreholes have watertight head.

In any sea water intrusion plan a compromise between the quality of the water used for recharge and the quality of the water that you want to protect. There is always a belt near the coast whose wells should be sacrificed to pump fresh or reclaimed water to maintain the sea out. The width of that corridor will depend on the characteristics of the rate and depth of intrusion.

- Model for chlorides concentration evolution in the aquifer:



WITHOUT HYDRAULIC BARRIER	WITH HYDRAULIC BARRIER

Figures 4-48: Hydraulic barrier in Llobregat.

4.2.14 ASR

ASR method consists in injecting water during off-peak months through a borehole and the subsequent recovery during peak months through the same borehole. These devices are suitable in areas where low permeability strata overlaying the aquifer are present and when land availability does not recommend the use of dispersion techniques. As well, it requires higher quality of recharge water because it is directly injected into the aquifer and this entails energy expenditure. May also include cost saving because of using the same device for injection and extraction

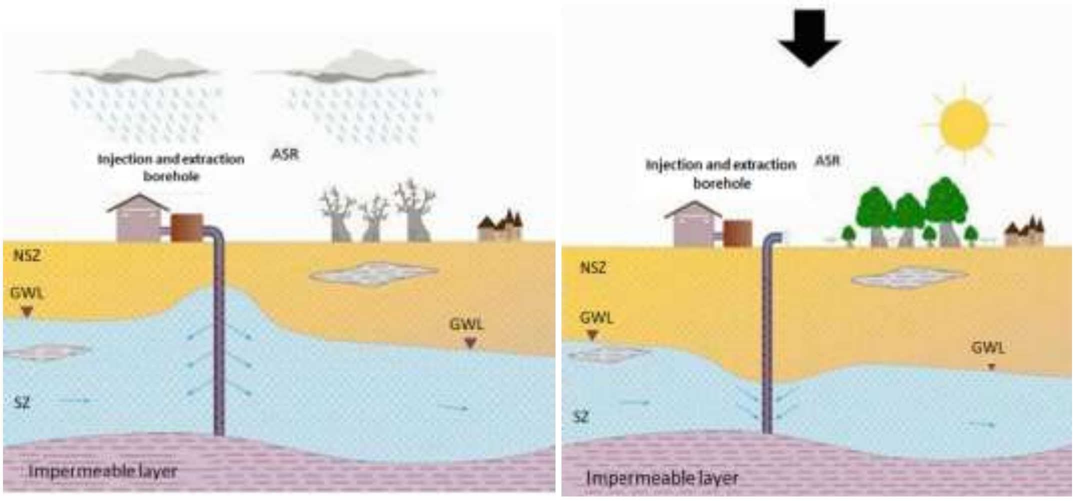


Figure 4-49: ASR mock-up.

The main difference with ASTR "Aquifer Storage Transfer and Recovery" is that water is injected and recovered through a single borehole in ASR; while in ASTR, water is injected in a borehole and recovered through another or other ones which are located at a prudential distance, sometimes several kilometres.

ASR technique can be used in different types of aquifers; the most suitable are consolidated aquifers where geological formations provide a competent level and do not make necessary the use of slotted-screens and gravel packing (Dillon and Molloy, 2006). In the case of fractured aquifers (hard rocks) whose porosity is due to the fractured rock massif, ASR method is successful even for lower flows (Murray and Tredoux, 2002). Tertiary and alluvial aquifers consisting of coarse detrital materials are also suitable for the use of this technique. However, fine-grained unconsolidated aquifers present more problems and require higher water injection quality. The organic matter and suspended solids contents must be low in order to prevent reductions in the ASR performance. Finally, carbonated aquifers can successfully meet obstruction effects. Some further problems may occur due to water mixture of native and recharge water (Herczeg et al, 2004).

Figures 4-50: ASR experience in Cobre Las Cruces Mine, Gerena (Seville, Spain).

The ASR method presents some advantages compared to surface systems, such as, low land requirements, lower evaporation rates and its potential use in low permeability layers or multilayer aquifers.

Some of the most common problems in terms of usage are the formation of an interface whose morphology varies depending on water´s characteristics, due to the injected water mixture with native water, the use of incorrect injection pressures which can alter the network fracture, demand of very high water quality, so, chemical pre-treatment is necessary and even chlorination or other disinfection techniques to prevent microbial growth may be applied.

Finally, obstruction of ASR wells is perhaps the most important impact because of clogging development, including air intake. These effects can be significantly reduced by simple settling and filtering mechanical treatments.

ASR wells are less susceptible to clogging than ASTR wells, thanks to their imperative reversal flow (back-washing).

Considerations about ASR design

The first question to ask in ASR systems design is the final purpose of the construction, e.g. water storage (seasonal, long term or emergency) or the improvement of water quality to a certain extent. It is paramount to consider the different objectives and prioritize them because treatments on the target aquifer and water depend on them. The demand of water and the guarantee of supply are also decisive in the design.

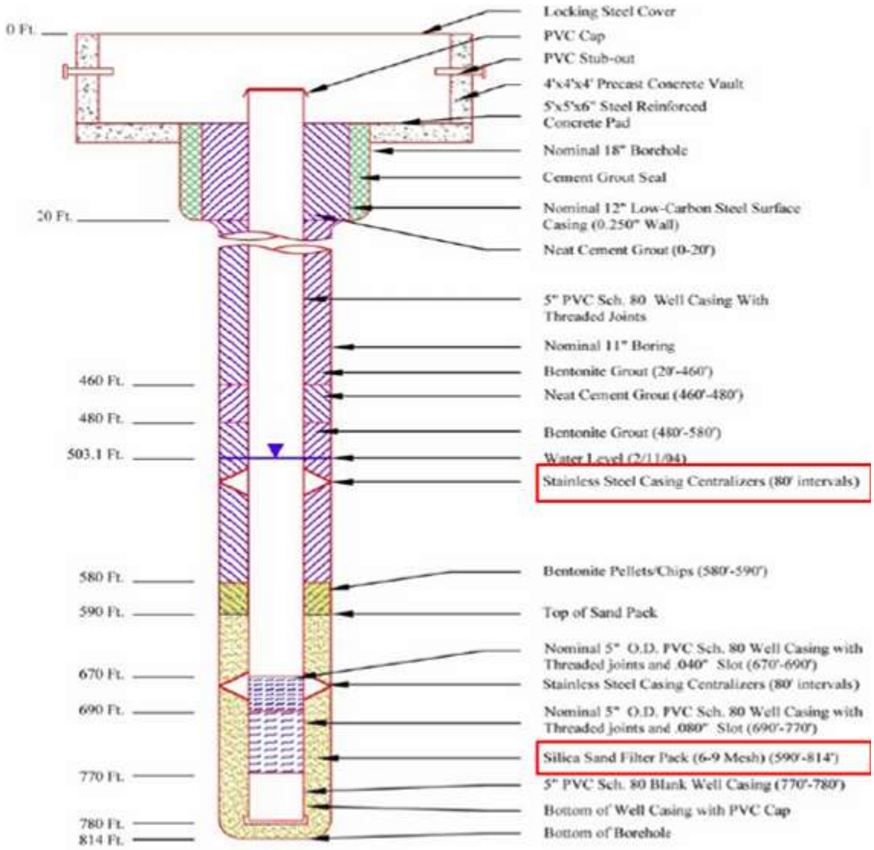
All ASR projects require a deep knowledge about hydrogeological conditions in the area, including lithology, structural elements (fractures, bedding, joints…), thickness, depth and extent, its geochemical composition and impermeable layers presence.

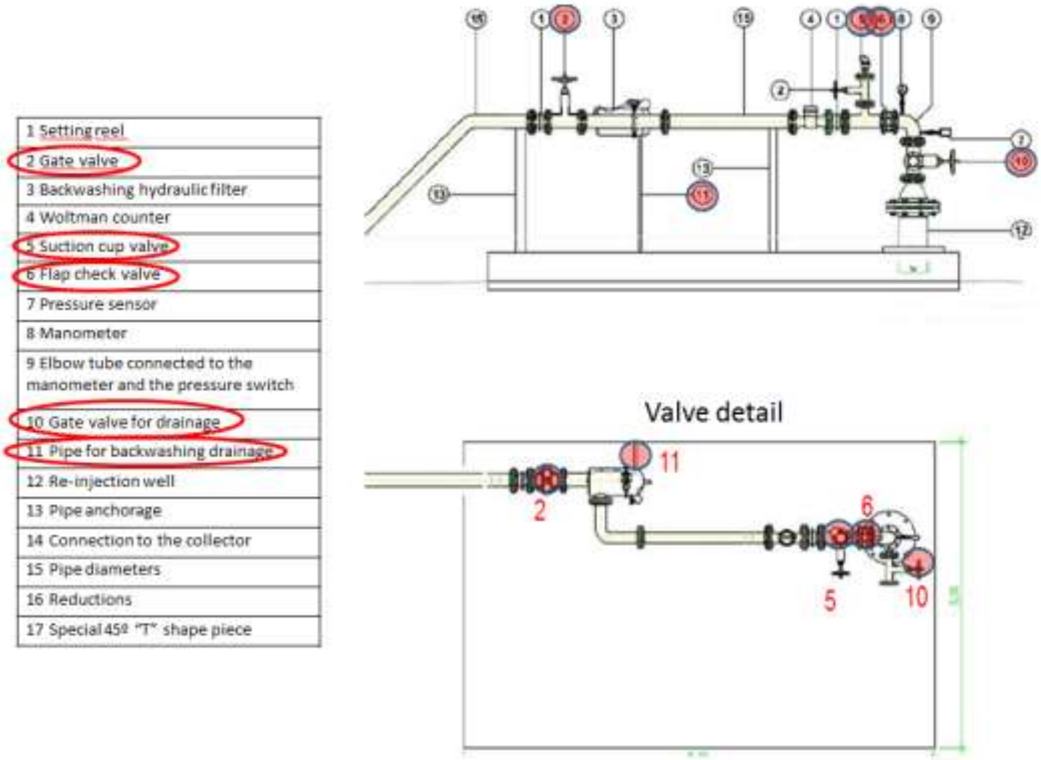
When designing an ASR system, financial and environmental feasibility are matters of great importance, in order to avoid future problems and to assure a successful investment.

EXAMPLE: CANAL ISABEL II ASR SYSTEM IN MADRID (SPAIN)

This ASR system has a unique design and is only employed in water scarcity emergency situations. Characteristics:

- 5 ASR/ASTR boreholes.
- Dual boreholes.
- Backwashing.
- Advanced sensor system.
- Specific design (tailor made). Successful key elements, such as, stainless steel casing centralisers (80´ intervals), silica sand filter pack (6-9 mm), appropriate casing dimensions (690´- 780´) and specific valves/equipment selection. Some of the most outstanding elements are underlined in the figures 4-51 a and c.





Figures 4-51 a to c: Mock-up for an ASR system in Madrid (Spain) (a), general aspect (b) and scheme where specific key elements have been remarked, in special centralizers and valves, (c).

Detailed and comprehensive information regarding ASR wells design, wellheads and well-fields, considering different materials of construction, drilling methods, corrosion control, yield strengths, casing collapse pressures... can be found in *Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells, (*Pyne, 2005). It includes also information about technical issues, geochemistry or selected case studies and the future directions that this technique might take.

There is also a useful web-site related to this technique where scientific publications and latest information are available. http://www.asrforum.com/What-is-Aquifer-Storage-Recovery.html

4.2.15 ASTR ASTR

Aquifer Storage, Transfer and Recovery (ASTR) is a system integrated by separate wells for injection and recovery. The flow rate of injection and recovery usually differs (Stuyfzand *et al*., 2012).

The use of separate wells may improve the system operation (*i.e.* greater recovery efficiencies). Better system performances can be obtained at sites where an ASTR facility may experiences problems with bubble drift as a consequence of regional flow.

The filtering during its transit through the aquifer will vary depending on the hydrogeological characteristics of the aquifer (dwell time, texture and aquifer composition, hydraulic gradient, etc.).

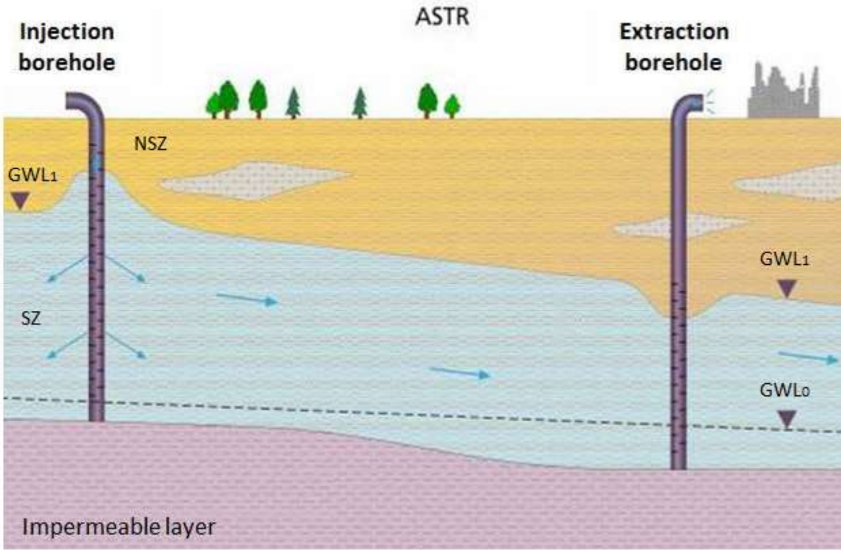


Figure 4-52: ASTR scheme.

Considerations about the design

The success of an installed ASTR system is mainly dependent on the aquifer characteristics (especially density stratification and lateral movement) and the quality of the injected water.

Operational experiences and related research have demonstrated that pathogenic microorganisms' elimination through natural filtering by the aquifer requires a certain transport distance and residence time in the aquifer. Hydrological calculations should be made to provide insights about the minimum time required in the infiltrating process.

Models of flow and hydrogeochemistry are necessary to predict aquifer response over the time, simulate reactions and processes in groundwater and determine clogging impact, among others. Modeling becomes again a tool for Decision Support System in ASTR plants.

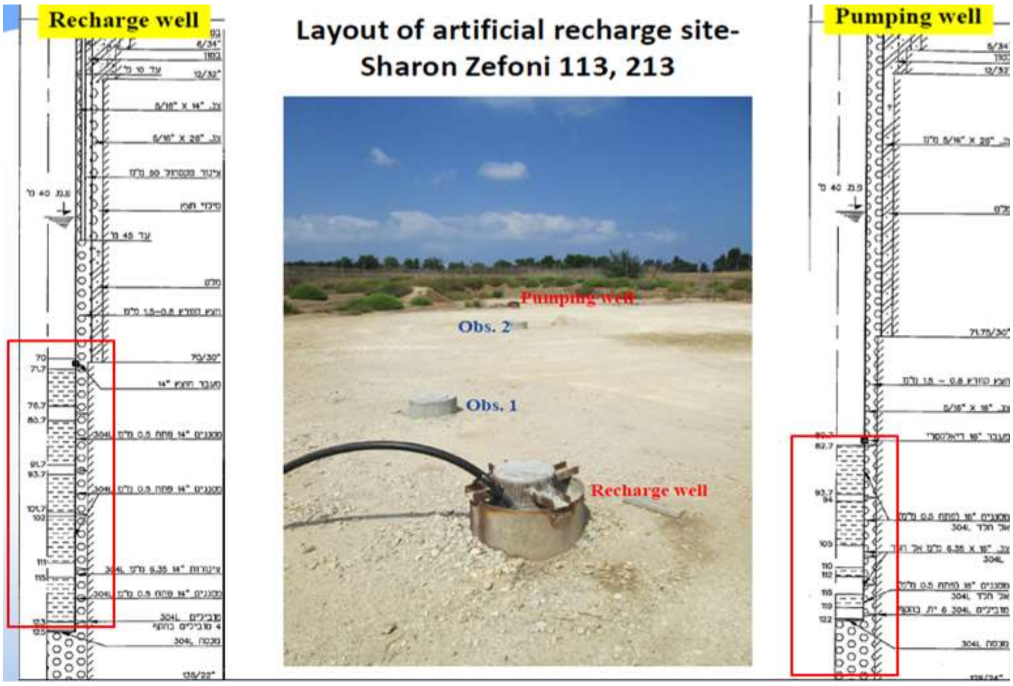
When freshwater is infiltrated into a brackish or saline aquifer the density differences between both types of liquid cause the lighter freshwater to float up (upward bubble drift). In an ASTR or ASR system this fact can decrease the recovery efficiency. In such situation it is usual the injection and extraction of fresh water at different depths of the aquifer, especially in multilayer cases.

MARSOL EXAMPLE: ASTR SYSTEM FOR INJECTING SURPLUS DESALINATED WATER INTO THE AQUIFER IN MENASHE DEMO-SITE (ISRAEL)

Israel National Water Company (Mekorot) is developing a new concept of injection wells to insert surplus desalinated water into the aquifer. Most of the old injection wells suffered from clogging problems prompting new designs. The old MAR experiences carried out during the 70´s and 80´s revealed that the water source (The Sea of Galilee) contained a high concentration of organic matter. The clogging was mainly caused by bacteria and fine sand. During the injection the yield was reduced (in comparison to the initial conditions) by 30-60% in the sandy aquifer and by 10-20% in the karst aquifer, forcing the partners to address new guidelines (MARSOL, deliverable 9-4, 2016).

Mekorot proposal: Guidelines for the design of new artificial recharge wells.

- The best construction has a drill diameter (26"-30") and casing / screen of 14-16" diameter. It is advisable a Johnson stainless steel casing or glass-fibre-reinforced plastic (GRP).
- Drilling with natural fluid (water) or biodegradable mud.
- Several piezometers to monitor the changes in the water level during the recharge process, assisting the clogging rate and operational protocol studies and activities.
- The water level should be maintained constant during injection to minimize air entrainment.
- The injection pipe should be full of water removing any air by means of pressure valves.
- The injection water should be clean and turbidity at demanding levels of about 0.1 NTU.



Figures 4-53: Example for an ASTR design aspect in Sharon Zefoni, Menashe demo-site. Column for the injection and extraction wells. Taken from Mekorot, 2015.

Mekorot considers using GRP pipe or Johnson stainless steel in the new injection wells. According to the literature, the development of biofouling and biological clogging on GRP is lower than in other pipe materials. The subsequent problem is the low percentage of the open space slots in comparison to Johnson stainless steel screen (figures 4-54).

Figures 4-54: GRP materials used in Menashe demo-site (Israel).

Mekorot has also provided advices about clogging and maintenance:

- The right rehabilitation method should be determined for each well in relation to the sort of clogging and related phenomena (iron and manganese precipitations…).
- The desalinated water in Israel has very low suspended solids and organic matters contents. Clogging may proceed from air bubbles during the injection (air entrapment clogging).
- Periodic backwashing (re-pumping) of the recharge wells at specific times of volumes recharged. The frequency will be determined during the pilot use.
- A unique hydraulic instrument has been found to both, inject and pump, and it is the Baski flow control valve-FCV.
- Mekorot is advancing in solutions to study the air clogging problem and improving their own pumping/ injection system.

Figures 4-55: Air entrainment pilot in Menashe demo-site (Israel). Courtesy of Mekorot. co.

4.2.16 River bank filtration (RBF) RBF

The River Bank Filtration method (RBF) consists of a well gallery or abstraction wells drilled or dug in the river banks, or other surface water body above materials which can behave as a filter.

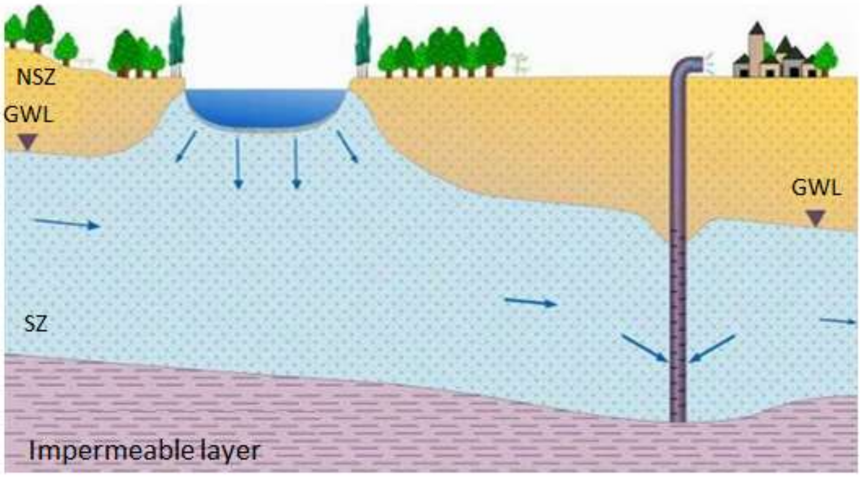


Figure 4-56: River Bank Filtration scheme.

The abstraction from the wells brings the adjacent water table down, and induces river water to enter in the aquifer system (by *"call effect").* This action poses a purification of the surface water during the transfer along the river bank. The direct consequence is the improvement of the water quality in comparison to the direct abstraction from the same river (Gale, 2005).

The main factors to consider for a maximum effectiveness of these "MAR devices" are:

- Reliable water source availability.
- Recharge water quality must be acceptable.
- Lake/river bed must have a high permeability alluvium beneath.
- Unconfined and shallow underlying aquifer.
- High transmissivity and permeability of the aquifer.

To ensure satisfactory infiltrated water purification into the aquifer it is advisable that the travel time through the ground and unsaturated area exceeds 30-60 days (Huisman & Olsthoorn, 1983), although legal restriction maybe more restricting than this. Therefore, the distance between wells lines and the shallow water body should be sufficient to ensure this transit time.

Due to the agitation experienced by these waters, they have a considerable amount of suspended material and dissolved air. When this water is infiltrated, suspended solids form a thin layer at the bottom of the river or lake, leading to a better water quality but a lower infiltration rate. If clogging becomes excessive, scarifying or other cleaning and maintenance options will be necessary.

One of the main advantages regarding direct water extraction from rivers/lakes is the minimal treatment required to purify the extracted water, becoming possible its use for higher quality requirements, such as drink supply.

As a matter of fact it is not a pure "MAR system" by itself, but the regular use of water for aquifer recharge in a vast amount of facilities has caused it has been included within the category of induced recharge.

MARSOL EXAMPLE: RBF SYSTEM IN SERCHIO DEMO-SITE (ITALY)

The Induced River Bank Filtration (IRBF) scheme along the Serchio River in Sant'Alessio-Lucca (Italy) allows abstraction of an overall amount of about 0,5 m^3/s groundwater, providing drinking water for about 300,000 people on the Tuscany coastal area (Lucca, Pisa and Livorno cities (Rossetto and Bockelmann, 2007)).

In this system, water is pumped by ten vertical wells (the next figure displays eight of them) inducing its filtration across the riverbank, achieving transmissivity values up to 10^{-2} m^2/s for this sand and gravel aquifer with 15 to 20 m thickness in this area. The system includes a down-stream weir to raise river head about 1.5 m above natural conditions, what enhances the water storage by both banks.

These 25 m-deep wells are used to abstract the water for supply demand. The total withdraw is about 600 L/s as an average.

Figure 4-57: Aerial view of the Sant Alessio RBF and wells field (Italy).

A battery integrated by 6 piezometers and a Wireless Sensor Network (WSN) was installed in order to monitor the RBF activity in terms of quantity and quality.


Figures 4-58: Piezometers network at Serchio river demo-site (Italy).

Figures 4-59: River bank Filtration system in Serchio, Italy, and weirs to raise the water flow level.

Figures 4-60: Sant Alessio´s control station. Groundwater from 10 wells is sent to a single pipe.

4.2.17 Inter-dune filtration

Inter-dune filtration is a MAR device very similar to RBF in the sense that apart from recharging the aquifer, it also improves the water quality.

It is a typical but not exclusive device of coastal areas, very useful to combat marine intrusion because it increases water quantity disposal and its quality in coastal aquifers. This device is very important in semi-arid areas because water reserves in the dunes do not usually represent large volumes, but poses important environmental functions. Due to the usual low rainfall that they receive and its medium to high permeability (about 20 m/day according to Davis, 1969), drainage is rapidly favoured.

Water is diverted by gravity from a river, canal or other water source (rarely pumped) to the depressions between the chains of dunes. From that point, the water infiltrates also by gravity and moves through the soil and the aquifer to lower areas. The dunes act as a natural filter removing organic matter residues, nitrogen, pathogens, etc.

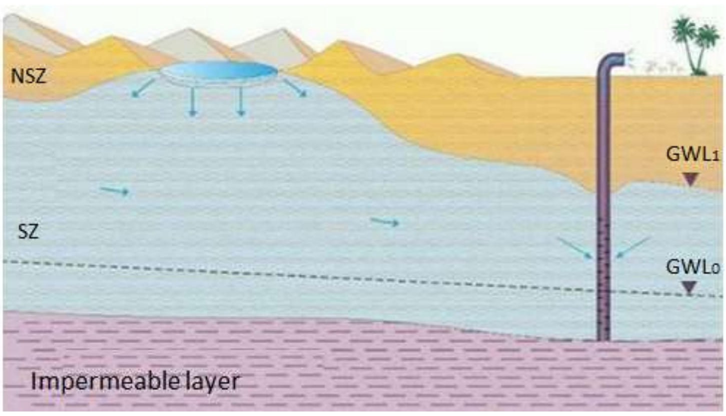


Figure 4-61: Interdune filtration diagram.

Figure 4-62: Interdune filtration in Carracillo, Los Arenales Aquifer, Segovia. (MARSOL Demo-site 3).

A key objective of these types of arid or semi-arid schemes is to improve the quality of the often scarce and poor quality water. Several research actions have been undertaken to understand and optimise the suspended and dissolved solids attenuation, including organic compounds, using physical, chemical and biological processes (Gale, 2005).

The dune system preservation depends on its resistance to destructive geodynamic processes. Any action of preservation must have an adequate forestation or reforestation, as well as a successful coastline dune design, especially regarding their “stopping height”, slope and orientation, to fulfil their ecological functions.

The “stopping height” is the height at which no erosion occurs (the height above the average aerodynamic surface in which the wind speed is equivalent to zero). The determination of this point is essential for the dune system stabilization. It can be obtained by physical methods (simulating environmental conditions in "wind tunnels" in the laboratory) or by means of an approximately calculation, which is the most frequent method. The calculation of the “stopping height” requires a thorough knowledge of certain factors such as the boundary conditions, accurate determination of the extrinsic factors (meteorological and climate), texture characterization of the material forming the dune (grain size, roundness index), its humidity, structural factors (debris spatial arrangement after transport and sedimentation), sand behavior after dynamic efforts, substrate roughness and, finally, the existing vegetation.

EXAMPLE: INTERDUNE FILTRATION SYSTEM IN AMSTERDAM (THE NETHERLANDS)

In the case of Amsterdam, the aquifer recharge of the dune system is done through canals and drains of 1 m deep and 20 m length, achieving an infiltration rate of 20 cm/day as an average. The highest infiltration rate occurs in the middle trench (Olsthoorn & Mosch, 2002).

4.2.18 Underground irrigation

It is a system of irrigation with buried pipelines and impulsion mechanisms to avoid evapotranspiration or to minimize it. Buried pipes and droppers drive irrigation water straight to the radicular area of the plants, causing a direct interaction between the water and the soil.

Some experiences have been carried out to over-irrigate the crops so as to enhance a direct recharge on the aquifer, avoiding some specific permits and requirements to be done in case the activity is declared as a “recharge plant”. The agrochemical products must be carefully managed to avoid direct leaching into the groundwater.

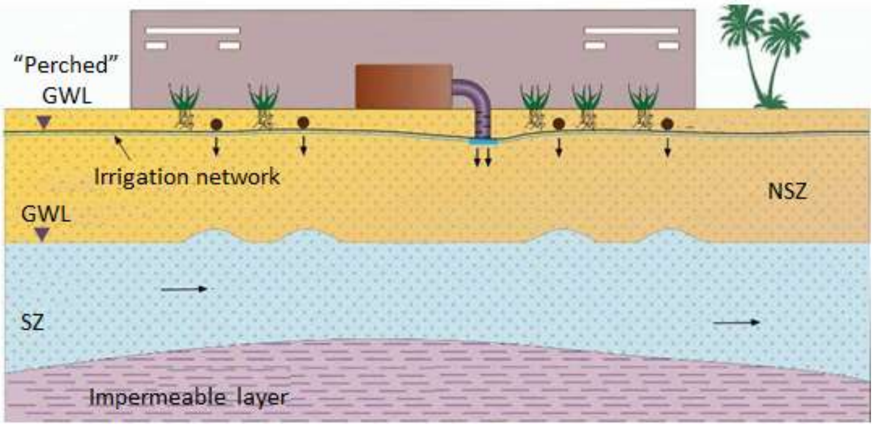


Figure 4-63: Underground irrigation scheme in a green house.

4.2.19 Rainwater harvesting in unproductive

A rainwater recovery system enables sustainable utilisation of part of the rain water when it becomes runoff on the soil surface. Moreover, it is also a method of erosion and flood control. In response to the present water shortage, there is a growing interest in urban drainage systems and alternative water sources among scientists, policy-makers and water managers.

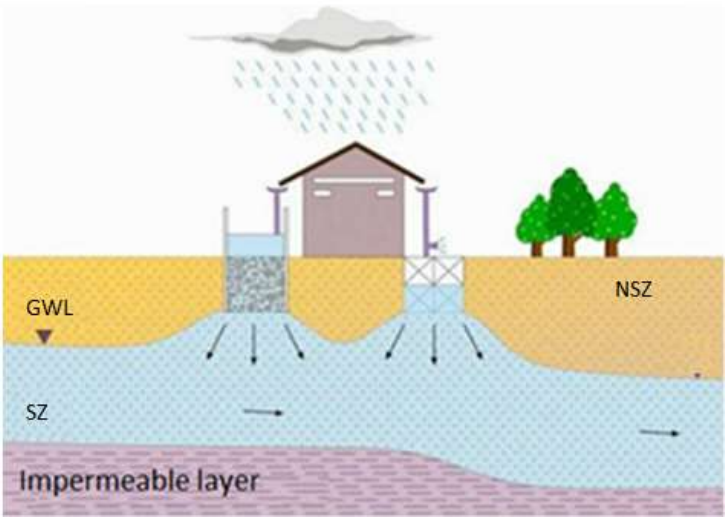


Figure 4-64: Rainwater harvesting in unproductive scheme.

Large rainwater volumes are lost through surface runoff along roads, paths, steep slopes, etc. Surface runoff catchment systems involve the conduction of the water through little channels by gravity towards areas more suitable for storage and infiltration.

The rainwater catchment systems design and dimensions are directly linked to the total recovered water volume. There is a vast diversity of this sort of systems, for example, retaining stone walls, live fences and barriers, terrace farming, individual terraces, etc.

There are also a large number of collection systems which can be constructed in urban areas, such as the rainwater capture traps in urban impervious surfaces, asphalt, roofs of houses, etc. Building envelopes and paving receive the main impact of rainwater drops, therefore, paving plays an important role in the way runoff behaves in an urban setting.

GREEN ROOFS

Collecting rainwater from roofs can take advantage of rainwater for household direct consumption and aquifer recharge. This method involves connecting the outlet ducts of the roof drain system to divert rainwater into existing wells or storage tanks. Drain pipes, roof surfaces and storage tanks should be constructed from chemically inert materials, such as plastic, aluminium, galvanized steel or fiberglass to avoid rainwater contamination and to allow biochemical reactions reducing potential contaminations.

EXAMPLE: GREEN ROOF PARC BIT BUILDING, MAJORCA ISLAND (SPAIN)

The example concerns 1,992 square meters of green roof in the *Complejo Balear de Investigacion, Desarrollo e Innovacion*, a 10,142 m^2 building designed by Tragsatec in 2010 and currently under construction (2016). It is located in the *Parc d'Innovacio Tecnologica (Parc Bit),* in the municipality of Palma de Mallorca.

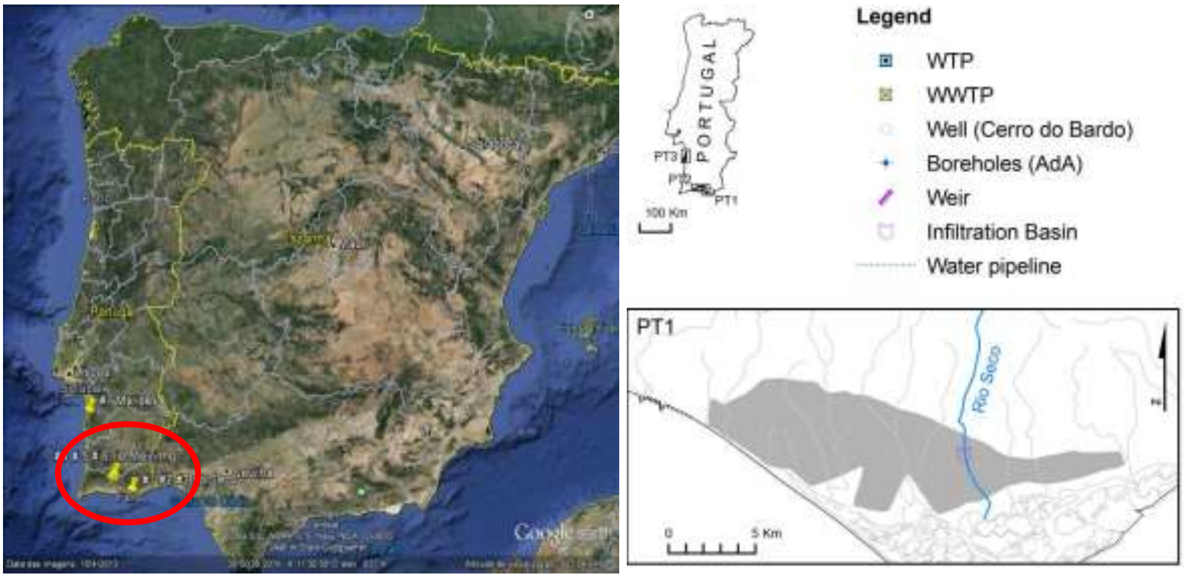
The construction proposed consists of an inverted ecological roof made of:

- A **10 cm** thickness of dry expanded clay layer on the slope.
- A **2 cm** layer of cement mortar and river sand, 1/6 trowelled.
- A separator membrane made of geotextile.
- A root barrier waterproof rubber membrane measuring **1.14** mm in thickness.
- Joints using the quick-fit or adhesive bonded joint process.
- A thermal insulation layer of extruded polystyrene **5 cm** thick.
- A drainage and moisture retention sheet.
- A compound substrate of topsoil from the excavation and a high porosity, stable, non-flammable and high drainage capacity substrate made of recycled products in equal proportions.
- Sedum-type cover plants with a density of 15 units per square meter.

Figures 4-65: Model and construction process of the green roof of the Parc Bit building, Palma de Mallorca (Spain).

MARSOL EXAMPLE: GREEN HOUSE FOR WATER HARVESTING IN EL ALGARVE SITE

Campina de Faro aquifer system is part of a declared "Vulnerable Zone" by nitrates (since 1997, enlarged in 2004) due to the applications of the Nitrates Directive 91/676/CE in El Algarve demo-site (Portugal). High nitrate concentrations in the upper aquifer system, caused by agricultural practices, resulted in a MAR plant. Its main objective was to demonstrate that the groundwater quality can be improved applying MAR through infiltration basins constructed in the *rio Seco* river bed, as well as rainwater harvesting system connected to large diameter infiltration wells.



Figures 4-66: Campina de Faro aquifer, Algarve demo site (Río Seco), Portugal.

The aquifer area is 86 km^2 and the average annual rainfall is estimated in 570 mm. The rainwater harvesting system is a complex composed of greenhouses whose size is 2.74 km^2, connected to large-diameter wells (called *Noras*). The area is flat and is characterised by low recharge rates. In these conditions, drainage is a serious problem in this area. The potential rainfall harvesting is calculated in 1.63 hm^3/year, approximately a 20% of the average water balance (8.3 hm^3/year).

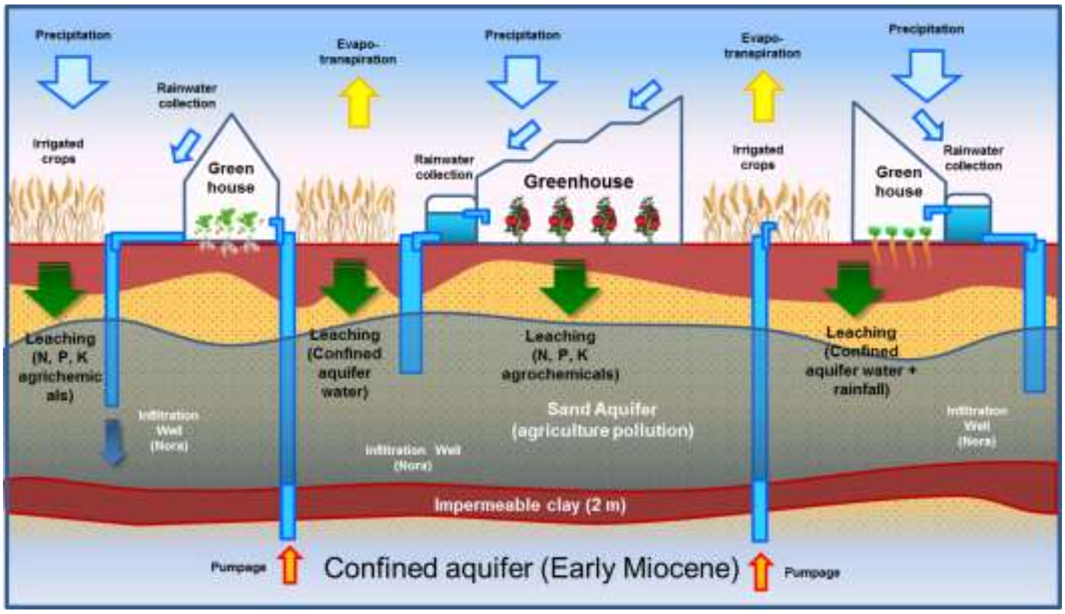
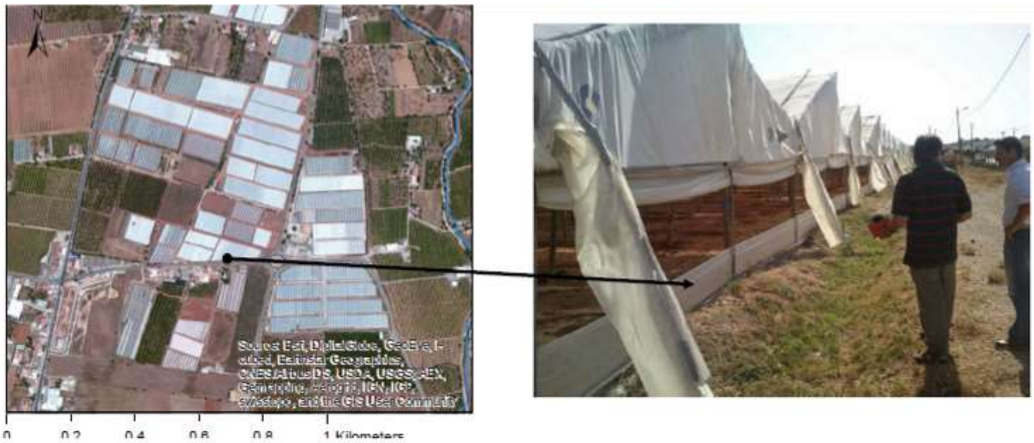


Figure 4-67: Campina de Faro Greenhouses system profile, Algarve demo-site, Portugal.



Figures 4-68 a and b: Aerial view of a greenhouse complex (a) and picture showing the actual drainage system (b).

There are about 60 "*noras*" in the intervention area. These facilities have diameters and depths varying from 2 to 5 m and from 20 to 30 m, respectively. The infiltration capacity of the "*noras"* is very high and was estimated between 50 and 180 m^3/day · m^2.

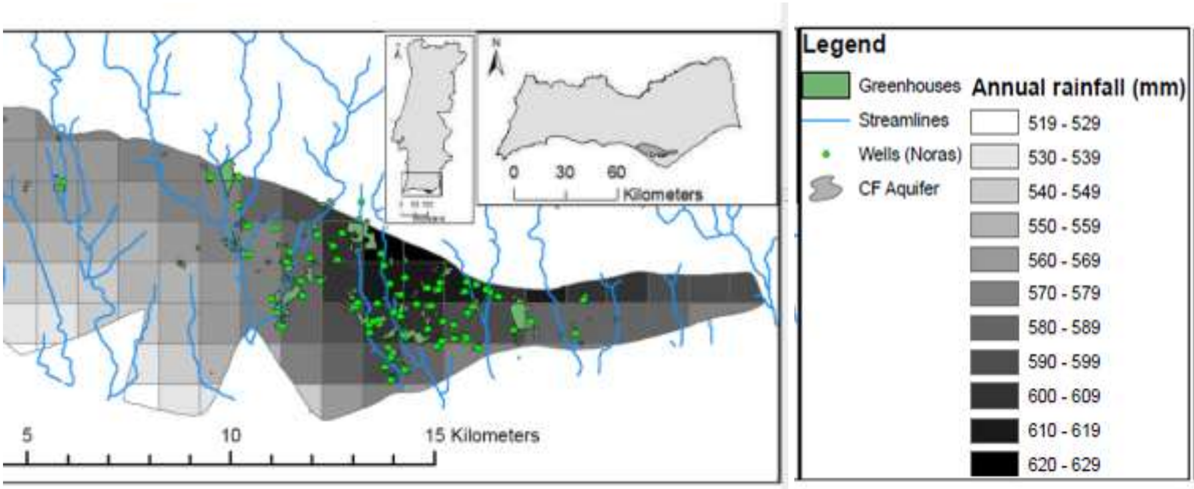


Figure 4-69: Location of green houses and large-diameter wells (Noras).

Figures 4-70 a and b: Large-diameter wells (Noras).

Greenhouse impervious roof drainage appears to be an opportunity for MAR, as harvested rainwater was identified as a main potential source for aquifer recharge.

It is worth mentioning that there is a recycling effect in this system, due to the fact that, at the same time the water collected from the roofs of these rural areas serves to improve water quantity and quality in the aquifer and subsequently this groundwater is used by farmers to irrigate their crops.

4.2.20 Sustainable Urban Drainage Systems (SUDS) 

Set of solutions on urban hydrogeology to enhance the infiltration rate below cities by means of different urban and architectonic designs. They are based on the principle of “concave edification” or tendency to surface structures willing to avoid any runoff. It is such a big collection of techniques that it is unfeasible to describe all the different sketches. It is advisable to consult specific references. A MARSOL partner has recently published a full book on SUDS with a vast number of examples and application procedures (GIAE, 2015).

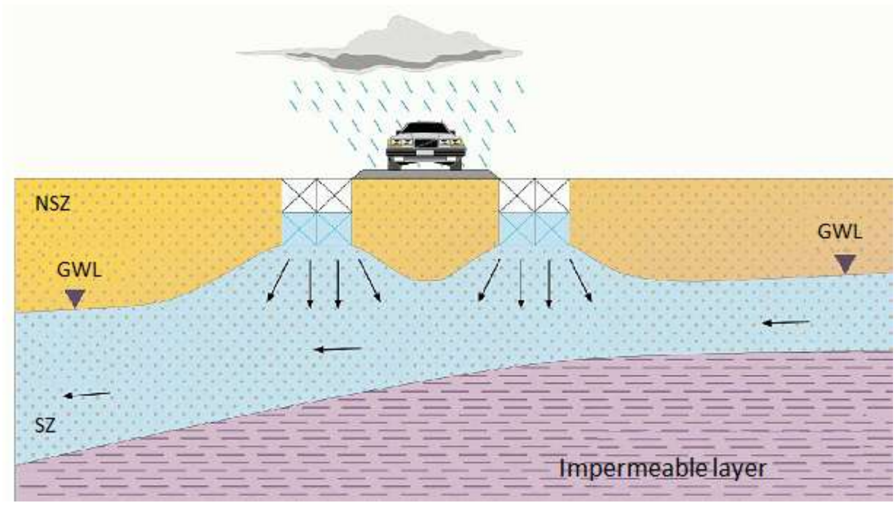


Figure 4-71: Example for a Sustainable Urban Drainage System (SUDS).

The recommendations on new designs are an important line of action under permanent development. It is important to pay great attention on technological watching activities so as to learn from other project´s expertise in order to make same mistakes or error again.

The increasing interest of Public Authorities on increasing urban permeability (Shuster et al. 2005) and building storm tanks (Andrés-Domenech et al., 2010) are connected to this kind of MAR. Once again a potential spill or sewage can be changed into a new source of water.

PAVEMENT

Pervious paving is generally used to manage storm water runoff for flood control. The major advantage of permeable paving is that it does not require any drainage or water collection and storage systems, as it permits rainfall to pass through it, assuming that the soil/strata below has adequate infiltration capacity.

Two variants are suggested (GIAE, 2015)

1. Permeable surface with collection of subsurface water and a 2% transversal slope directed towards the bio-retention strips. Open junctions concrete slabs are recommended as a top off on a bed of 5 to 10 cm thick graded sand on compacted soil, a geotextile sheet and a slotted or porous drainage pipe which permits water infiltration during its drainage.

2. The permeable surface drainages runoff by means of an integrated linear grid and a 2% transversal slope directed towards the grid. The ideal top off would be 8 cm thick open jointed concrete cobble with a "T"-shaped inverted frame to capture and transport the excess of water. The paving is set on a bed of sand between 5 and 10 cm thick approximately and a geotextile layer on the compacted ground. The grid pours into a polypropylene perforated channel which infiltrates a portion of its drainage into the soil.

Figure 4-72: Discontinuous permeable paving.

Figure 4-73: Detail of the cross section and plan for an average width street. Extracted from GIAE (The Comprehensive Management of Rainwater in Built-up Areas), Tragsa Group, 2015.

4.3 Recommendations for management and maintenance obtained from the experience in MARSOL demo-sites

The different demo-sites have an important remarkable advantage, which is the broad variety of time since the first plant was implemented (Menashe, 1966) until the last one (Malta South, 2012). So, there is a vast range of processes affecting the structures in different time steps.

It is also remarkable that despite being Mediterranean demo-sites, there are important differences in the environmental conditions, especially regarding the hydrogeological background.

Within this context, some *Tech Sols* are exclusively applicable to specific demo-sites whilst others can be used in several sites.

The rest of the chapter exposed the technical solutions applied in any specific demo-site, and a brief explanation about why it has been done or what resources have been applied to combat any specific impact, always within a problem-solution binomial assessment.

This information has been organized and exposed by means of tables, in the same order applied in the previous chapter 3-2:

1. Applied to water from its original source (quantity).
2. Applied to water from its original source (quality).
3. Applied to the receiving medium (in both soil and aquifer).
4. Applied to management parameters plus cleaning and maintenance operations.

This information is also enlarged in annex 1, where are briefly explained the different solutions applied in each demo-site, specifying where and how. Also annex 2 provides further details according to four groups of requirements (the best environmental conditions for each MAR type of construction, the advantages, disadvantages and environmental aspects.

4.3.1 Applied to water from its original source (quantity).

Tables 4-2: Main Tech sols grouped according to a set of four stablished categories.

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Manage/avoid operations during specific events/periods e.g. freezing weather, heat waves…	LOS ARENALES	MANUAL CONTROL AVOIDING FREEZING AND MUDDY RIVER WATER EPISODES (DECREASE IN INFILTRATION RATE)
Security structures for overflow events, run-off tramps, spillways, etc.	ALGARVE	HOOSE SPILLWAY

4.3.2 Applied to water from its original source (quality).

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Pre-treating of water for MAR in the heading of the structure: Filtering beds, decantation/stagnation structures, deairation, etc.	BRENTA	SINGLE CHAMBER FOR DECANTATION
Treatment structures intercalated along the construction for surface facilities, e.g. control of pH by means of mudstone gravel filters (specify)	LLOBREGAT	USE OF ORGANIC REACTIVE LAYER IN THE INFILTRATION POND. COMPOSITION: VEGETABLE COMPOST + SAND + MINOR AMOUNTS OF CLAY AND IRON OXIDE FUNCTIONS: MAXIMIZE INFILTRATION AND IMPROVE WATER QUALITY
Pre-treating by Disinfection By Products (DBPs), e.g. Cl, I, O_3, H_2O_2, UV rays, etc.	MENASHE	CHLORINATION IS THE MOST COMMON DISINFECTION PROCESS USED WITH DESALINATED WATER (HYPOCHLORITE 0.3-0.5mg/L; NOT THM FOUND)
Design and preservation of slope (rubble works, gabions...)	LOS ARENALES	GABIONS PROTECTION
Deairation techniques: piezometers, increase distance between injection-extraction points…	MENASHE	DEAREATION SYSTEM PATENTED BY MEKOROT.CO "AIR ENTRAINMENT PILOT"
Isolation from atmosphere/sunlight structures	SERCHIO	PIPELINE CLOSED CIRCUIT

4.3.3 Applied to the receiving medium (in both soil and aquifer).

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Changes in the receiving medium design. Furrows in the bottom, width, shape.	LOS ARENALES	FURROWS PLOUGHING IN THE BOTTOM OF INFILTRATION PONDS SPACED AT 80 CM PERFORM THE BEST INFILTRATION RESULTS
Use of jet type cleaning techniques	LAVRION	EMPLOYMENT IN ALLUVIAL PIEZOMETERS
Operations in the bottom: Algae drying, natural bed drying, cryotreating, cracking	LLOBREGAT	ALGAE REMOVAL
Mechanical cleaning (scarification or silting zones and cleaning /replacement)	LOS ARENALES	SCARIFICATION OF CHANNEL BEDS
Alternate normal and inverse pumping and frequency	LAVRION	IN PIEZOMETERS

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Use of dual systems allowing cleaning of one of them whilst the other is operating	SERCHIO	MULTIPLE WELLS SYSTEM
Cleaning of the vegetation in the MAR facilities	ALMOST ALL	FROM YEARLY TO EVERY THREE YEARS (NO CONSENSUS)
Cleaning techniques frequency	ALMOST ALL	FROM YEARLY TO EVERY THREE YEARS. SIMULTANEOUS TO VEGETATION CLEANING
Use of Basic Cleaning Vehicles (BCV)	LOS ARENALES	YEARLY IN THE SUMMER TIME

4.3.4 Applied to management parameters.

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Management parameters and ex-situ techniques related to water management, governance...	BRENTA	BASED ON DOWNSTREAM PIEZOMETERS MONITORING
Alternative sources of MAR water and management	LOS ARENALES	USE OF DIFFERENT SOURCES OF MAR WATER: WWTP + RUNOFF CHANNEL
Monitoring chemical properties of MAR water during recharge cycles	LOS ARENALES	TRIPLET SCHEMES: STUDY OF EVOLUTION OF WATER PARAMENTERS: TDO, EC, pH, TURBIDITY…
Promote participation of farmers or other social agents or stakeholders in water management	ALGARVE	FARMERS AND STAKEHOLDERS ONGOING DIALOGUE INCREASE MAR EFFECTIVITY
Design and adoption of a proper Watching and Control Program	SERCHIO	DECISION SUPPORTING SYSTEM DESIGN THAT INCLUDES ALERT AND REPORTING SYSTEMS
Specific Control Protocol	MENASHE	SPECIFIC GUIDELINES DESIGN IN ORDER TO PREVENT CLOGGING (AIR ENTRAINMENT IS THE MAIN CLOGGING PROBLEM IN RECHARGE WELLS)
Use of sensors to monitor evolution of aquifer response	MALTA	A COMBINATION OF PRESSURE AND FLOAT OPERATED SENSORS MEASURE THE PIEZOMETRIC LEVEL OF THE AQUIFER AND MONITORING THE FRESHWATER AND SEAWATER INTERFACE OF THE AQUIFER SYSTEM
Reuse of existing structures	ALGARVE	REUSE OF WELLS “NORAS” FOR WATER INJECTION OBTAINED FROM RAINWATER HARVESTING IN GREENHOUSES. INCREASE THE EFFECTIVITY OF THE SYSTEM AND DECREASING NITRATES CONCENTRACION
Use of Innovative technology for modelling and simulate quantitative and qualitative process of the aquifer	BRENTA	TIME DOMAIN REFLECTOMETRY (TDR) SENSORS AND MOSAIC MONITORING EQUIPMENT DEVELOPED BY *ICCS AND UFZ.*
To carry out cost-benefit Analysis	BRENTA	COST-BENEFIT ANALYSIS ENSURES THE SUCCESS AND VIABILITY OF A MAR SCHEME.

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Dissemination actions of MAR activities	ALMOST ALL	TO SET UP A ITALIAN NETWORK ON MAR, FOCUS GROUP FOR POLICY MAKERS AND GROUP OF CITIZENS, TRAINING ACTIVITIES FOR PROFESSIONALS AND RECIPROCAL COMMUNICATION WITH STAKEHOLDERS

4.3.5 Applied to maintenance programs and cleaning operations.

TECHNICAL SOLUTION	MARSOL demo-site example	EXPLANATION
Clogging prevention. removing the components that cause clogging, pre-sedimentation, activated carbon filtration and disinfection with chlorine	ALMOST ALL	FOR SURFACE INFILTRATION SYSTEMS, CLOGGING IS CONTROLLED BY PERIODICAL CLOGGING REMOVAL
Use of dual systems allowing cleaning of one of them whilst the other is operating	ALGARVE SERCHIO	DUPLICATION OF SOME FACILITIES ALLOWS SOME OPERATIVE OR MANAGEMENT POSSIBILITIES
Periodical cleaning of the vegetation in the MAR facilities*	ALGARVE BRENTA SERCHIO MENASHE LOS ARENALES	FOR SURFACE FACILITIES IT IS A COMMON ARGUES TO ALLOW THE GROWTH OF VEGETATION OR TO CLEAN VEGETATION PERIODICALLY. THE EXPERIENCE IN THE DEMO-SITES IS NOT CONCLUSIVE YET
Plantation of appropriate species at the bottom of MAR canals and infiltration ponds	LOS ARENALES	ROOTS PREPARE THE SOIL FOR A HIGHER INFILTRATION RATE. SELECTIVE CLEANING ALONG THE MAR CANALS
Use of Basic Cleaning Vehicles (BCVs)	LOS ARENALES	ABSOLUTELY RECOMMENDED THE PERIODIC CLEANING OF THE CLOGGING BED. SUGGESTED DESIGN AND CONSTRUCTION OF A SPECIFIC AND ADAPTED BCV

*Common with operations in the receiving medium

5. CONCLUSIVE REMARKS

- Environmental Impact Assessment approach shows the double face of MAR as a human activity. The assorted techniques are mainly used to solve problems while they also provoke others. Fortunately most of the possible impacts can be mitigated by choosing options provided by the same MAR methodology.
- All the MARSOL Demo sites count with abundant, diverse and successful examples of MAR implementation and management. As not all the existing facilities are encountered in the group of sites, it is necessary to design SMARTS (Sustainable Managed Aquifer Recharge Technical Solutions) including the expertise of the partners obtained in other experiences.
- Most of the designs and suggestion to carry out new facilities try to cover knowledge gaps and to increase cost savings, and are based on empirical experiences in a permanent process in which every deployment improves a previous implementation. Same applies for the SAT techniques adopted and/or applied cycle after cycle.
- There are remarkable instances of water management and energy efficiency improvements by means of MAR technique, but every solution is willing to be more and more improved. Some of the suggested SMARTS are pure lines of action.
- The future target is linked to the supply guarantee without climate dependence. In this context, reclaimed water must be more and more integrated, as it is the unique source with a 24/7 guarantee of supply.
- The best designs must be complemented by good planning, management, cleaning and maintenance activities and a wise operation. There are plenty of good cases of water management conducted by end-users upon technical advice.
- MAR techniques have a great capacity to reuse old infrastructures (quarries, mines, sand pits, old ditches…) so they can be transformed not only into recharging facilities but most of the times into new ecological hot-spots (artificial wetlands).
- One of the biggest impacts is clogging and an important goal will be to reduce the gas clogging concentration in MAR water and bubbles trapped in the aquifer by preventive means.
- It is important to carry out activities on the receiving medium to increase the infiltration rate and to lengthen the life-span of the facilities.
- The most important operation regarding water quality is the water pre-treatment. The bigger the quality of the source water is, the better the results are.
- As in other aspects of life, in general, it is also imperative to listen to specialists and strengthen relations among technicians / farmers / regulators as well as to keep alert on new publications and achievements in other parts of the world.
- The profits overcome the inconveniences as a general rule. That is the main reason why successful schemes should be exported to equivalent areas, prompting a “domino effect”.
- It is important to disseminate encouraging examples and successful cases from other experiences around the world among those stakeholders, who provide real help in the MAR facilities design, construction criteria and management. It is also important to pay attention on technological watching techniques in order to receive punctual information when new outcomes are achieved.
- Although some of these devices have been used for years, most of them are being object of intense research, in order to establish parameters of design, inspection and maintenance that will facilitate its use widely.

- Although some MAR devices deployment can be a complex process and present some problems during the construction and operation stage, the majority of these problems can be avoided or reduced conducting previous detailed technical studies.
- The design changes and management parameters must be created “a la carte”, depending on the climate and characteristics of each system.
- The process is opened. Each improvement suddenly becomes a new element to improve.

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7. ANNEXES

7.1 ANNEX I: Technical-solution binomials. Summarizing tables

Table 7-1: Technical solutions at each MARSOL demo site, (1st type, quantity).

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Recharge water (quantity)	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
WATER QUANTITY ASPECTS	*1-Preselecting: selective criteria for the origin of recharge water when several sources are available*	only WWTP		Water diversion from Voltoya and Eresma Rivers, Sewage (WWTP) and Irrigation return flow	I	Single	Single	X (rain, WWTP, desalination)	only WWTP
	2-Temporary storage of MAR water in surface reservoirs	X tanks, lagoon	F (Cerro do Bardo)	X				X (settlement)	X agriculture plant
	3-Control of the flow velocity of MAR Water (stopping devices…)			X		X heading gate		X (gates, valves…)	
	4-Manage/avoid operations during specific events/periods e.g. freezing weather, heat waves…	X		X	x	use during irrigation period		according to rainfall	Subject to high demand
	5-Security structures for overflow events, run-off tramps, spillways, etc.		X (hose spillway in Cerro do Bardo and Rio Seco)	X	x			spillway	

Table 7-2: Recharge water (quality) technical solutions at each MARSOL demo site.

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Recharge water (quality)	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
PRETREATMENT-TREATMENT	*6- Pre-treating of water for MAR in origin: (WWTP, membranes, mud lines, filters, packets…) (specify)*	X (WWTP)	X (SB Messines WWTP)	X pipeline filter				X	X
	7-Pretreating of water for MAR in the heading of the structure: Filtering beds, decantation/stagnation structures, deairation, etc.		X (Campina de Faro - Noras, Cerro do Bardo and SB Messines)	X stagnation structure	x	single chamber for decantation		X (only according to turbidity measures)	X
	8-Pretreating of MAR water using unsaturated zone as a pre-treatment natural filter		X (Cerro do Bardo and Rio Seco)	S					
	9-Treatment structures intercalated along the construction for surface facilities, e.g. control of pH by means of mudstone gravel filters (specify)			X gravel canal beds	x (organic reactive layer)			filters in the concrete channel	
	10-Pretreating by Disinfection By Products (DBPs), e.g. Cl, I, O3, H2O2, UV rays, etc. (specify)			S			hypochlorite	hypochlorite, H2O2	H2O2
	11-Chemical additives to eliminate clogging layers (specify)							hypochlorite	

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Recharge water (quality)	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
	12-Combination of different MAR facilities to improve the MAR water quality, e.g. a "triplet scheme" (WWTP, green biofilter, artificial wetland)?		X (SB Messines)	X	x			X	
SURFACE FACILITIES	*13-Design and preservation of slope (rubble works, gabions...) (specify)*		X (Rio Seco) - filling with gravel	X gabions in stopping devices and passes	x			concrete	
SURFACE FACILITIES	*14-Limitation/control of the water layer thickness*	X 50 cm	S	x (140 cm)	x			X	
SURFACE FACILITIES	*15-Denitrification additives (e.g. anammox)*								No needed
SURFACE FACILITIES	*16-Mechanisms to force the mixture of the different layers of MAR water, e.g. for canals let the water jump over or below stopping devices alternatively*			X (water flows up and down consecutive stopping gates					
DEEP INJECTION FACILITIES	*17-Employ of anticorrosion materials in the MAR devices*	X						X	X
DEEP INJECTION FACILITIES	*18-Changes in the depth of the pump for wells/boreholes*					Fixed 50 m		surface pumping	

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Recharge water (quality)	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
	19-Induced changes in water quality for irrigation. Fertilizers… (specify)	F (regulated)	X (Campina de Faro has specific regulations (Vuln Zone)	F (proposal for regulation)					
RECEIVING MEDIUM	*20-Avoid aeration on AR waters: communicating vessels, open/buried structures, velocity control (specify)*			X (avoid cascading and flow speed control)		laminar flow		laminar flow	Laminar flow. Closed circuit
RECEIVING MEDIUM	*21-Deaeration techniques: piezometers, increase distance between injection-extraction points… (specify)*			S (wells)				specific own system (patented)	
RECEIVING MEDIUM	*22-Isolation from atmosphere/sunlight structures (specify)*	X		only in the pipeline		X initial chamber protected	pipeline circuit		
RECEIVING MEDIUM	*23-Avoid natural salinization: Induced recharge, e.g. barriers in salty areas (specify)*			X (natural barriers)				X	X
RECEIVING MEDIUM	*24-Recycling effect of water in the MAR system (describe)*								
OTHERS	*25-Specific fishes/exotic species introduced to reduce clogging (e.g. medaka)*								

Table 7-3: Receiving medium (soil and aquifer) technical solutions at each MARSOL demo site.

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Receiving medium (soil and aquifer)	1- LAVRION	2- ALGARVE	3- LOS ARENALES	4- LLOBREGAT	5- BRENTA	6- SERCHIO	7- MENASHE	8- MALTA
PREVIOUS STUDIES	*26-The knowledge of the environmental conditions for the receiving medium might be considered sufficient? (describe)*		X (geological hydraulic & chemical knowledge)	X	x (saturated and unsaturated media monitored)			S	
	27-Regarding the selection of the site, are there "natural fences" to avoid water to leave the system?			X				S	
SURFACE FACILITIES	*28-Changes in the receiving medium design. Furrows in the bottom, width, shape... (describe)*		X furrows	X (furrows, slope control)		Earth canal. Slope preservation	river slope preservation		
	29-Changes in the receiving medium design. Geofrabrics in the bottom/slopes (specify)		F (WWTP of SBM)	S					
	30-Inverse pumping in wells pits close to a MAR canal or pond			X				X	
	31-Backwashing in geo fabrics, membranes and filters								
	32-Use of jet type cleaning techniques	X alluvial piezometers						X	
	33-Chemical cleaning (use of chemical additives) (describe)							hypochlorite	
	34-Operations in the bottom: Algae drying, natural bed drying, cryotreating, cracking (cake) (specify)			X cryotreatment, cracking, bed drying	x (algae removal)				
	35-Mechanical cleaning (scarification or silting zones and cleaning /replacement) (specify)		X (Seco river)	X scarification /replacement	x (scarification of the surface after	X		X	F

	SORT OF TECHNICAL SOLUTION	DEMO SITE							
	Receiving medium (soil and aquifer)	1- LAVRION	2- ALGARVE	3- LOS ARENALES	4- LLOBREGAT	5- BRENTA	6- SERCHIO	7- MENASHE	8- MALTA
					period of activity)				
INJECTION FACILITIES AND PIEZOMETERS	*36-Alternate normal and inverse pumping and frequency*	X alluvial piezometers						x	
	37-Mechanical cleaning (wall brushing, scratching...)	X piezometers					X	x	
	38-Chemical cleaning (use of chemical additives) techniques for the regeneration of recharge wells						X	x	F
	39-Selection of casing materials for wells according to groundwater characteristics (quality, quantity, durability...)		x		X	X	X	x	
	40-Employ of water level control automatic systems (alarm systems, buoys...)			X (singular sites)			X	x	
	41-Employ of clogging preventive systems, e.g. cathodic protection...(specify)						X		
OPERATIVE ASPECTS	*42-Use of dual systems allowing cleaning of one of them whilst the other is operating*		X (WWTP of SBM)				multiple wells system		
	43-Cleaning of the vegetation in the MAR facilities (specify)		X (Rio Seco)	X (allowance of natural plants in the green biofilter)		X cleaned canals	cleaned river	X cleaned canals	
	44-Specific plantation during any season			S					
	45-Cleaning techniques frequency (specify)		on demand (annual)	X (biannual)	periodic	seasonal	yearly	3-4 years	periodic
	46-Use of Basic Cleaning Vehicles (BCVs) (describe)			F (under development)				Tractor	

Table 7-4: Management and operative parameters technical solutions at each MARSOL demo site.

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Management/good Practices/Use criteria and codes	1- LAVRION	2- ALGARVE	3- LOS ARENALES	4- LLOBREGAT	5- BRENTA	6- SERCHIO	7- MENASHE	8- MALTA S
OPERATION	*47-Management parameters and ex situ techniques related to water management, governance... (describe)*			X (irrigation community regulations)		based on downstream piezometers monitoring	X	5 m3/s for recharge Max 10 m3/s	
OPERATION	*48-Election of the most appropriate period and place to MAR water / obligation due to administrative concessions*		X	X conditioned by administrative concession		Internal organization (Brenta consortium)		Winter. Recharge all the year	X according to availability
OPERATION	*49-Initiate 'soft' MAR cycles (start gradually)*			X		X		According to runoff	
OPERATION	*50-Input flow and flow water speed control (automatic, manual) (specify)*	X manual	X manual	X Manual	X Manual	X Manual	X Automatic	manual - automatic gate	X Manual
OPERATION	*51-Dual systems: duplicated MAR facilities to alternatively manage MAR and cleaning activities*								
OPERATION	*52-Alternative sources of MAR water and management (describe)*			X river and WWTP (only at Santiuste)				X (see 1)	
OPERATION	*53-Monitoring chemical properties of MAR water during recharge cycles*	X	X	X only in Carracillo ZNS3 and Alcazarén WWTP	X	X		X	
MAINTENANCE	*54-Specific protocol for clogging control*		S	F					
MAINTENANCE	*55-Protocol for proper hydro-mechanical aspects in space and time. e.g. pressure inside a pipeline circuit (describe)*								F

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Management/good Practices/Use criteria and codes	1- LAVRION	2- ALGARVE	3- LOS ARENALES	4- LLOBREGAT	5- BRENTA	6- SERCHIO	7- MENASHE	8- MALTA S
	56- Specific cleaning and maintenance programs or decisions made "on the go"?	on demand	on demand (only once)	X (according to budget)	on demand and according to budget				
DECISION SUPPORT SYSTEMS	*57-Integrated system design: all elements are interconnected*	For monitoring, not for use		X		X	I	X	X
	58-Promote participation of farmers or other social agents or stakeholders in water management		X	X					
	59-Limit fertilizers use	X (regulation)	X (Campina de Faro has specific regulations (Vuln Zone)	F (proposal for regulation)		X (regulation)			
	60-Decrease untreated spilling in the area								no needed
	61-Protected perimeter around the MAR facilities			X	X	X Internal (Brenta cons.)	X	2 km	not allowed
	62-Use of protection devices for fauna and people in MAR facilities	Fence		wood fence		Fenced		Fenced	Fenced
	63-Public use regulation			Wetlands only			X	Not opened	F
MANAGEMENT	*64- Early adoption of the Best Available Techniques (to what extent new BATs are tested prior their application?)*			I				previous tests on new techniques are done	

SORT OF TECHNICAL SOLUTION		DEMO SITE							
	Management/good Practices/Use criteria and codes	1-LAVRION	2-ALGARVE	3-LOS ARENALES	4-LLOBREGAT	5-BRENTA	6-SERCHIO	7-MENASHE	8-MALTA S
	65-Design and adoption of a proper Watching and Control Program			C	X	X Internal (Brenta consortium)	X	X	stakeholders
	66-Construction of dams specifically designed for MAR		X (Cerro do Bardo Weir)	X			X (RBF)		
	67-Construction of WWTP specifically designed for MAR								x
	68-For those devices constructed due to a R&D specific project, is there any guaranteeing mechanism to operate the system after the end of the project	own activities		X donation to irrigation community	own activities			Mekorot	own activities
	69-Are there already specific operative guidelines? (specify)			C			I	F	
	70-Use of sensors to monitor turbidity, dissolved oxygen, temperature… either inlayers or installed in surface facilities	X	X (for temp. & cond.)	X (ZNS stations)		X	I	X	X Utility control
REUSE	*71- The wells used for MAR were specifically designed or previous wells/shafts were used (change of use)?*		X (reuse of Noras and Cerro do Bardo Well)	X (*Do not close a well, reuse it!*)					
	72-Use of existing natural previous elements to improve MAR efficiency, e.g. River Bank Filtration (RBF direct or inverse), use of dolines, sinkholes…		X (Cerro do Bardo)	X inverse RBF, wells in Santiuste			X (RBF)		
	73-Use of pre-existing artificial previous elements for MAR e.g. rivers dams, meander scarfs…			X Alcazarén dam			S		

X	Currently in operation
F	To be developed shortly
I	Intended to be deployed in the future
S	In study
C	Technical solution from references

7.2 ANNEX II: Some conditioning factors for each MAR facility

Conditioning factors to select the best mar device: (it is desirable, pros, cons and environmental aspects)

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
1	DISPERSION	INFILTRATION PONDS/ WETLANDS	IT IS DESIRABLE	High permeability receiving medium beneath ponds Lithology detrital, alluvial or karstic Suitable in irrigation areas with groundwater Slopes under 10 % or terraces Groundwater table close to the surface (max. 50 m depth) Suitable for areas with treatment by lagooning Sources of availability of water in less than 10 km Only for unconfined aquifers
			PROS	Efficient devices in unconfined aquifers as a general rule Reuse of existing structures, such as abandoned mines or quarries Low construction costs and maintenance Improvement of water quality during infiltration Long service life of the facilities Simple monitoring infiltration rates
			CONS	Surface land occupation Need fenced perimeter Stable slopes depending on each lithology Need for cleaning and maintenance in dry conditions Need access to medium-heavy machinery Flooding in alluvial by overflows problems In the case of very uneven quality of water, induction techniques should be used
			ENVIRONMENTAL ASPECTS	Possible use for water supply (forest fires...) Possible settlement of waterfowl Water regeneration ability of degraded wetlands
2		CHANNELS AND INFILTRATION DITCHES	IT IS DESIRABLE	Areas with surplus water treatment plants or fluvial origin Paths as straight as possible to prevent shores and landslides Slopes less than 20 % Dams and stopping devices are recommend in order to prevent the cascading effect Water must meet the regulated standard of quality Desirability of avoiding water oxygenation by shaking Convenience of interlayer bridges and pass devices Convenience of building a parallel service track for maintenance and cleaning It is advisable to design specific models of Basin Cleaning vehicles or BCV Check the water level in the channel so that the infiltration rate is as high as possible
			PROS	Possibility to bury sections through punched pipes on filtering trenches Suitable and usual system in mountainous urban areas Erosion prevention Distribution during infiltration
			CONS	Dependent on the morphology and lithology slope and stability problems Occupation of surface land Difficulty for the burial of the channel in certain areas Condition to some plant species to flood their root zone Excessive development of plant species at the bottom of the channel (-) Hardly appropriate in urban areas, except at mountainous sites
			ENVIRONMENTAL ASPECTS	Barrier effect for certain animal species and human transport Slope stability Rapid growth of vegetation (-)

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
3		RIDGES/ SOIL AND AQUIFER TREATMENT TECHNIQUES (SAT)	IT IS DESIRABLE	The distance between the ridges must be 80 cm in sandy aquifers At the bottom of sandy channels, geotextiles can be inserted in intervals up to 40-60 cm depth Avoid shaking of water
			PROS	Increase the infiltration rate twice in detrital regarding flat bottoms Simple cleaning operations compared to flat bottom. It is feasible to insert geofabrics half-buried to facilitate cleaning operations Appropriate in areas of watersheds and floodplains Improvement water quality (pre-treatment)
			CONS	High necessity of removing the clogging processes dump Possibility to replace clogging materials by others without clogging, difficulties to get rid of the clogged soil
			ENVIRONMENTAL ASPECTS	Additional positive impact due to improve old structures Promote the sustainability of water (pre-treated wastewater reuse)
4		INFILTRATION FIELDS (FLOOD AND CONTROLLED SPREADING)	IT IS DESIRABLE	Positioned in extensive flats and permeable plains (alluvial) Location close to river beds, wetlands or water treatment plants (2-3 km max.) Commonly associated to lagooning waste water treatment plants Areas with a high or a very high permeability Detrital, karst or alluvial lithology Slopes less than 10 % Usual in slightly embedded d floodplains Appropriate in coastal areas with height less than 5 m (marshes) Highest infiltration values in soils with vegetation
			PROS	Seasonal use Reduce overfloods damage Flooding large accumulations of sediment on the surface make the land profitable for agriculture
			CONS	Careful compatibility with infiltration canals or ponds by risk of over flooding the banks and subsequent clogging enhancement Maintenance needed in case of ploughing ridges It is inconsistent with the presence of other “structural” facilities at flooded areas Heterogeneity infiltration and lack of control of the actual volume of water absorbed
			ENVIRONMENTAL ASPECTS	High ecological value at coastal floodplains and marshes Temporarily wetland and simultaneous ecological functions such as habitat for wildlife, improving water quality and soil fertility
5		ACCIDENTAL RECHARGE BY IRRIGATION RETURN	IT IS DESIRABLE	Areas irrigated with surface water Surface irrigation systems: furrow irrigation is the best irrigation type for MAR Areas with very low or no risk of flooding Water with low or medium salinity In unconfined aquifers with a maximum groundwater depth of 75 m increasing the vadose water in deeper aquifers. Areas with any lithology of medium to high permeability
			PROS	No installation and maintenance costs (accidental recharge) Certain crops (rice) represent a significant volume of water for the recharge
			CONS	Salinization of the soil with low doses of washing Contamination of the recharge water due to the presence of different fertilizers and pesticides
			ENVIRONMENTAL ASPECTS	Uncontrolled irrigation with groundwater lead to negative impacts In urban areas, incidental returns are usually of low quality water Irrigation water quality problems: excess of Nitrogen and salinization Only inappropriate management systems allow this technique unless it is intentional, e.g. to avoid very demanding regulations...
6		BOFEDALES WETLANDS	IT IS DESIRABLE	Areas of gentle slope (10) With the level of the water shallow aquifers

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				Structure usually associated to mining areas
			PROS	Diverse geological formations Device frequently associated with mining spaces
			CONS	Space occupation
			ENVIRONMENTAL ASPECTS	Incidence in the hydrodynamic regime Possible effects on riparian vegetation Wetland function providing ecological functions (fauna, flora, landscape…)
7	CANALS	RESERVOIR DAMS AND DAMS	IT IS DESIRABLE	High permeability of outcrops Alluvial, karst, detritus, volcanic and intrusive lithology's (detrital aquifers must be excluded) Suitable for irrigation areas Appropriate in the vicinity of reservoirs and overexploited aquifers Suitable in areas with some risk of flooding for water management activities Appropriate in watersheds and forest areas Suitable even on high slopes (embedded valleys) e.g. *atochadas, boqueras* and other ancient mechanisms Dykes of hydrological correction involve accidental recharge Often in high altitude ranges Prone in crystalline massifs with triple porosity
			PROS	Use suitable for forest hydrological correction and artificial recharge They allow avenues lamination Retention of avalanches and gravitational movements in mountain areas Its location on high ground and very permeable vessels, allows not remain stagnant water for prolonged periods, reducing evaporation losses and proliferation of insects.
			CONS	Sediments retention Clogging impact Open water may change local climate and biology (fauna & flora)
			ENVIRONMENTAL ASPECTS	Certain negative visual impact Sediment retention In general, positive impacts outweigh the negatives Additional benefits related to flood control (laminar flow) and decreased erosion
8		PERMEABLE DAMS	IT IS DESIRABLE	Permeable outcrops Alluvial, karst, detritus, volcanic and intrusive types Suitable for irrigation areas Appropriate in the vicinity of reservoirs Suitable in areas with some risk of flooding Appropriate in watershed and forest areas Ideal in river valleys with any encasing Hydrological correction dykes involve accidental recharge High and medium altitude range Prone in crystalline massifs with triple porosity They are usually built with permeable materials such as gravel and blocks
			PROS	Suitable use for hydrological correction and artificial recharge in forests They allow avenues lamination
			CONS	Sediment retention Clogging problems Maintenance expenses Frequent geotechnical problems (breakage, loosening...)
			ENVIRONMENTAL ASPECTS	Certain negative visual impact Sediment retention and clogging problems are generated, reducing the effectiveness and efficiency of the device Positive impacts outweigh the negatives Additional benefits related to flood control (laminar flow) and decreased erosion
9		LEVEES	IT IS DESIRABLE	Typical device of the alluvial formations

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				Areas with high risk of flooding or medium Gentle slope areas (<10 %) Unconfined aquifers with shallow water level It is not optimal for urban area Inappropriate for high mountain areas and basins headwater It requires the completion of previous topographical and hydrological studies to confirm that the topography is flat and verify that there is a continuous flow of water into the lower parts Extensive maintenance should correct the possible changes taking place in the river bed
			PROS	Possibility of inserting artificial barriers (inflatable...) and floating structures This system allows the integration of all circulating flows in the river in the recharge (increasing the infiltration)
			CONS	Visual impact Increased impacts and risks in case of overflood Clogging problems
			ENVIRONMENTAL ASPECTS	Incidence in the hydrodynamic regime of the river Possible effects on riparian vegetation Yearly maintenance costs
10		**RIVERBED SCARIFICATION**	**IT IS DESIRABLE**	Typical device of alluvial formations Areas with high risk of flooding Precise shallow water conditions Good water quality Gentle slope areas (<10 %) Unconfined aquifers It is not optimal for urban areas Inappropriate for high mountain
			PROS	Increases infiltration Cheap technique No maintaining cost
			CONS	Condition of aquatic vegetation and fish species Some authors doubt the effectiveness of the method
			ENVIRONMENTAL ASPECTS	Incidence in the hydrodynamic regime of the river Possible negative impact on the vegetation and fluvial fauna
11		**SUB-SURFACE/ UNDERGROUND DAMS**	**IT IS DESIRABLE**	Alluvial, karst, detritus, volcanic and intrusive, not too compacted aquifers In regions with semi-arid and arid climates with problems of heavy losses by evaporation Suitable in areas with saline outcrops (impact on quality) Appropriate in the vicinity of reservoirs Suitable even on high slopes (embedded valleys) Hydrological correction dykes involve accidental recharge Possibility of structures protected out of the evaporation tank In areas where superficial dams and dykes are not allowed It is not recommended in high salinity soils
			PROS	Combined use suitable for forest hydrological correction and artificial recharge They allow the supply to small towns with filtration Similar to the RBF technique with induction It allows correct geotechnical problems in urban areas
			CONS	Sediment retention Clogging problems It requires some maintenance Eventual replacement of sand filters
			ENVIRONMENTAL ASPECTS	There is no visual impact Sediment retention Possible changes in groundwater flow directions Positive impacts outweigh the negatives Water quality improvement (references) as for other systems depending on retention time etc.
12		**DRILLED DAMS**	**IT IS DESIRABLE**	Permeable outcrops Alluvial, detritus, fractured volcanic and intrusive lithology's

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				Suitable in irrigation areas Appropriate in the vicinity of reservoirs Inappropriate in areas with high risk of flooding Appropriate in watershed, forest and mining areas Ideal in river valleys with any encasing Hydrological correction dykes involve accidental recharge High and medium altitude range These devices are often used in ephemeral rivers with rapid flow and a high content of suspended solids
			PROS	Combined suitable use for forest hydrological correction and artificial recharge Overflood lamination
			CONS	Sediment retention Clogging problems Maintenance of pipes Frequent geotechnical problems (breakage, loosening...) Further away from riverbeds than the permeable dykes Cleaning costs
			ENVIRONMENTAL ASPECTS	Certain negative visual impact Sediment retention
13	WELLS	QANATS (UNDERGROUND GALLERYS)	IT IS DESIRABLE	Appropriate in detrital, karstic and volcanic materials Typical of arid and semi-arid regions More suitable when close to reservoirs Possibility of conversion from abandoned mines In areas with steep slopes, especially volcanic Water level not more than 50 meters depth
			PROS	Suitable for arid areas to reduce evaporation Sustainable device, since qanats´s flow varies directly with the amount of available water in the aquifers Invisible structures No land occupation No need for pumps or wells for water extraction since the movement is by gravity
			CONS	Risk of changes in the water quality due to its configuration Possibility of landslides and collapses, especially after storm events Important self-limitation in terms of performance and functionality The presence of gases or oxygen deficient areas are highly dangerous, and so is the flooding of the tunnel by a sudden entry of water, especially in the heading of the device
			ENVIRONMENTAL ASPECTS	Low visual impact Protection of the accesses Promotion of vegetation in arid or semi-arid areas, even in times of severe drought
14		OPEN INFILTRATION WELLS	IT IS DESIRABLE	Suitable for all lithologies, including hard rocks Not suitable in areas with an over-flood risk Moderate or medium slopes (max 15%) Shallow or intermediate water level (less than 50 m) Not suitable for forest except isolated access Suitable in the vicinity of wastewater treatment plants and basins It is advisable to fill the hole with gravel and coarse sand to encourage infiltration and reduce maintenance costs in case of obstruction They should not be used in places where supply wells are less than 10 m deep or where the subsoil is composed of limestone formations or fractured rocks in order to prevent contamination of groundwater, also dependent on distance between wells
			PROS	Possibility of recycling dry wells for MAR The reuse of existing structures significantly lowers the construction works They allow the possibility of reuse of reclaimed water as a source of recharge water
			CONS	Risk of pollution (open access to the aquifer) depending on the

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				distance between well bottom/ screen and groundwater table Performing strict maintenance and control of the quality of groundwater
			ENVIRONMENTAL ASPECTS	They require adequate protection to prevent the fall of persons or wildlife
15		DEEP WELLS AND WELL-BOREHOLES	IT IS DESIRABLE	Suitable for all lithologies, including hard rocks Suitable for areas where available land is scarce Not suitable in flood areas Moderate or medium slopes Shallow or intermediate water level (about 50 m) Suitable for confined aquifers with greater thickness of the impermeable layers. This device reaches greater depths No suitable in forest
			PROS	Minimal evaporation losses They allow the possibility of reuse of reclaimed water as a source of recharge water They allow the possibility of reuse of reclaimed water with pre-treatment as a source of recharge water
			CONS	Risk of appreciable pollution Geotechnical problems in urban areas and buildings in some cases Oxygenation of the water and reducing of the infiltration rate if the water falls by gravity from the surface Demanding in terms of quality of recharge water as it is introduced directly into the aquifer
			ENVIRONMENTAL ASPECTS	They require adequate protection to prevent the fall of livestock and wildlife
16		BOREHOLES	IT IS DESIRABLE	Device suitable for lithologies detrital and karstic Not suitable in flooded areas On moderate slopes Intermediate or deep water level (over 50 m) Not suitable in forest Suitable in irrigation areas with groundwater Device suitable for detrital and karstic lithologies Suitable for those cases when hydrogeological parameters are not enough and they require the introduction of pressurized water to achieve viable and profitable recharge rates
			PROS	Possibility of deep and induced injection They allow the possibility of reuse of reclaimed water as a source of recharge water Minimal evaporation losses
			CONS	Risk of salinization in special due to recycling effect Not suitable in areas with risk of flooding except for extreme protection It requires electricity for injection Complex equipment system Expensive to build and maintain Demanding in terms of quality of recharge water as it is introduced directly into the aquifer
			ENVIRONMENTAL ASPECTS	Possibility of geotechnical problems (sinks, cracks...) Possibility of recovery of natural resources, taking advantage of existing water surpluses in other parts of the basin, such as the recovery of wetlands
17		SINKHOLES, COLLAPSES...	IT IS DESIRABLE	In karst areas Possibility to use abandoned mines It requires good water quality Not suitable for urban areas
			PROS	Use of pre-existing forms as dolines…
			CONS	Hiper-oxidation of specific minerals in the aquifer if the water falls by gravity Risk of salinization
			ENVIRONMENTAL ASPECTS	Accurate lines from socket sources (rivers, reservoirs and

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				treatment plants) Possibility of high geotechnical risks (new collapses)
18		**AQUIFER STORAGE & RECOVERY (ASR)**	**IT IS DESIRABLE**	Device mainly suitable for detrital lithologies On moderate slopes Deep water level (over 50 m) Not suitable in forest Suitable in irrigation areas with groundwater
			PROS	Possibility of deep and induced injection Inexpensive method for meeting water quality standards, appropriate for supply demand Minimal evaporation losses
			CONS	Risk of salinization Not suitable in areas with risk of flooding except if extreme protection It requires a high electricity consumption Complex equipment system Precise supplementary facilities
			ENVIRONMENTAL ASPECTS	Possibility of geotechnical problems (sinks, cracks...) Problems arising from the introduction of air into the aquifer
19		**AQUIFER STORAGE, TRANSFER & RECOVERY (ASTR)**	**IT IS DESIRABLE**	Device mainly suitable for detrital lithologies On moderate slopes Deep water level(over 50 m) Not suitable in forest Suitable in irrigation areas with groundwater It requires a high knowledge of the aquifer and the transit zone
			PROS	Possibility of deep and induced injection Inexpensive method for meeting water quality standards, appropriate for supply demand Minimal evaporation losses
			CONS	Risk of salinization as for ASR Not suitable in areas with risk of flooding except if extreme protection It requires high electricity costs for injection Complex valve and auxiliary gears and systems Precise supplementary facilities Shortages in its construction and maintenance
			ENVIRONMENTAL ASPECTS	Possibility of geotechnical problems (sinks, cracks...) Expected qualitative changes Problems arising from the introduction of air into the aquifer bigger than in ASR structures
20	**FILTRATION**	**RIVER BANK FILTRATION (RBF)**	**IT IS DESIRABLE**	Exclusively alluvial formations In the immediacy of reservoirs Areas of very low slope in general Acceptable water quality Areas with relatively shallow water level Suitable for free shallow underlying aquifer Aquifers with high transmissivity and permeability
			PROS	The technique allows the association of medium-sized and large treatment plants Suitable for supply of river-close cities This method provides water for high quality uses
			CONS	Certain substances are not reduced by the RBF technique Frequent clogging problems due to the agitation experienced by these waters Its location in flood areas requires a high protection of the catchments
			ENVIRONMENTAL ASPECTS	Many more advantages than disadvantages Requires pipelines and junctions connecting riverbank-city
21		**INTERDUNE FILTRATION**	**IT IS DESIRABLE**	Sandy areas They often are mapped as sand dunes In a short distance from the coast Arid zones in general

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
				Low altitude Medium and high salinity of recharge water
			PROS	They act as a natural filter removing residues of organic matter, nitrogen, pathogens, etc. hey usually have detailed maps Protected structures in some areas
			CONS	Difficulty in fossilized dunes Un-stability problems
			ENVIRONMENTAL ASPECTS	They tend to be very fragile areas from the point of view of ecosystems Difficulty to carry out actions with low impact (very fragile ecosystem)
22		UNDERGROUND IRRIGATION	IT IS DESIRABLE	Shallow water level In general incidental recharge Irrigated areas with water from any source excluding returns
			PROS	Technique of leakage management Excessive doses of washing of the soil use in irrigation
			CONS	If the dose of washing is suitable and high irrigation efficiency, recharge is negligible
			ENVIRONMENTAL ASPECTS	Only inappropriate management systems allow an excess of water unless it is intentional
23	RAIN	RAINWATER HARVESTING IN UNPRODUCTIVE	IT IS DESIRABLE	Suitable in urban areas It is also suitable in rural areas (greenhouses) Use in areas with water surpluses Areas with high infiltration capacity
			PROS	Good quality water after interacting with ground (excluding evaporitic terrains) Cartography of unproductive (paved surfaces) Prevent urban floods
			CONS	Water loads of harmful pollutants in urban areas (HC, fats...)
			ENVIRONMENTAL ASPECTS	Hydrological problems such as floods Drainage problems in urban areas
24	SUDS	ACCIDENTAL RECHARGE PIPES AND SEWER SYSTEM	IT IS DESIRABLE	Accidental recharge In urban areas High returns due to sewage leakage (accidental recharge)
			PROS	Invisible system
			CONS	Mosquitoes and unwanted wildlife Odours by standing water. Upkeep cleanliness and vegetation. Clogging problems Very few citizens are aware of the advantages Avoid pollution by dumping
			ENVIRONMENTAL ASPECTS	Element which allows to assess the leaks less adversely
25		SUSTAINABLE URBAN DRAINAGE SYSTEMS (SUDS)	IT IS DESIRABLE	Cast of elements of appropriate management of urban areas Different possibilities, such as, urban elements (pavement), car parks, land retention, roads, sport facilities, etc. allow the adaptability to any kind of environment
			PROS	Comprehensive utilization of water in urban areas Prevention of urban floods Different facilities allow the combination of the devices increasing the effectivity of the system Decontamination of urban waters Avoiding and preventing erosion (slow down the runoff) Improving the quality of the environment
			CONS	General problems of hydrological and qualitative nature (variable quality of recharge water). Impacts difficult to predict

N	S	SORT OF DEVICE	CONDITIONING FACTORS	
			ENVIRONMENTAL ASPECTS	The large variety of typologies require specific studies Reduce the heat island effect in cities, adapting to climate change Environmental benefits: aesthetic, friendly and ecological. Impacts difficult to be foreseen Carbon sink function in vegetated structures

This table is open for future additions