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Supplementary document

Annex to Deliverable #D2.1

Matrix of feasibility criteria for managed aquifer recharge

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Abstract

This document is an annex to AGREEMAR project deliverable D2.1 Matrix of feasibility criteria for managed aquifer recharge (free to download at the address: https://www.agreemar.inowas.com/deliverables). The report contains a hierarchical database with criteria proposed for the assessment of geospatial site feasibility for managed aquifer recharge (MAR). For details regarding the methodology used for data collection, management and validation see original deliverable D2.1.

This list of feasibility criteria is not exhaustive and it will be continuously updated during the entire project duration. The list is open for external contributions and we highly encourage the wider MAR community to provide feedback and recommendations for improving the list. For this, please use the online questionnaire (https://agreemar.inowas.com/feasibility-criteria/) or contact us at: https://agreemar.inowas.com/contact/.

To learn more about the AGREEMAR project (Adaptive agreements on benefits sharing for managed aquifer recharge in the Mediterranean region) feel free to visit our website: https://www.agreemar.inowas.com.

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Overview

A Intrinsic site suitability

The thematic area of **intrinsic site suitability** contains information regarding the hydrogeological characteristics of the regions considered for MAR implementation. This group is organized into three topics: surface area, vadose zone and aquifer. Each of these topics contains a set of categories, which are used during the process of criteria selection to rank and identify sites intrinsically suitable for MAR.

A.1 Aquifer

A.1.1 Aquifer characteristics

A.1.1.1	*Aquifer storage capacity*	Amount of water that can be (effectively) stored within the aquifer.	[Mm^3]
A.1.1.2	*Specific yield (storativity)*	Storativity (S) is the volume of water removed from a unit area of an aquifer for a unit drop in hydraulic head.	[m^3/m^3]
A.1.1.3	*Aquifer storage capacity*	Amount of water that can be (effectively) stored within the aquifer.	[Mm^3]
A.1.1.4	*Specific yield (storativity) of the aquifer*	Storativity (S) is the volume of water removed from a unit area of an aquifer for a unit drop in hydraulic head.	[m^3/m^3]
A.1.1.5	*Aquifer geochemistry*	Geochemical composition of the aquifer.	[mg/l]
A.1.1.6	*Aquifer microbiology*	Microbiological composition of the aquifer.	[CFU/ml]

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A.1.2 Groundwater flow characteristics

A.1.2.1	*Groundwater gradient (dh/dx) inside the aquifer*	Low slope allows sufficient time for infiltration and water quality improvement.	[m/m]
A.1.2.2	*Groundwater flow velocity*	Not very high so that a sufficient amount remains in the aquifer for beneficial purposes, not very slow so that water can be uniformly distributed within the aquifer, without the need to recharge at many locations.	[m/day]
A.1.2.3	*Hydraulic conductivity of the aquifer*	Hydraulic conductivity is a measure of how easily water can pass through soil or rock: high values indicate permeable material through which water can pass easily; low values indicate that the material is less permeable.	[m/s]
A.1.2.4	*Direction of groundwater motion*	Darcy's law can be used to determine the flux vector.	[-]
A.1.2.5	*Residence time inside the aquifer*	Related with the scale of the groundwater system and the MAR objectives (e.g., large residence times for treated water so that natural decay and bio-chemical processes become effective)[1].	[day]

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[1] Toth, A., Huysmans, M., Hartog, N., Stefan, C., Mádl-Szőnyi, J. (2022) The use of regional groundwater flow characteristics for optimized screening of MAR potential and application conditions. 11th International Symposium on Managed Aquifer Recharge, Long Beach, April 11-15, CA, USA.

A.1.3 Aquifer structure and physical boundaries

A.1.3.1	*Aquifer geometry*	Reduces the penetration of ground surface contaminants.	[m]
A.1.3.2	*Aquifer lithology*	Vertical geological barriers, permeable to sea/lake/river such as boundary conditions in models.	[type]
A.1.3.3	*Lateral connections with the aquifer*	Hydraulic connections between the aquifer and other water bodies.	[no./area]

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A.2 Vadose zone

A.2.1 Groundwater table

A.2.1.1	*Thickness of vadose zone*	Infiltration rates depend on the thickness of the unsaturated zone. It also influences the residence time of the flow, and affects the water quality improvement through biodegradation and sorption mechanisms.	[m]
A.2.1.2	*Fluctuations of groundwater table (intra-seasonal and inter-seasonal)*	Seasonality of groundwater levels can impact the composition of vadose zone.	[m/time unit]
A.2.1.3	*Infiltration capacity of the vadose zone*	Time needed for surface water to reach the aquifer-Influences the filtration / purification of the water.	[m/day]

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A.2.2 Geochemistry

A.2.2.1	*Geochemistry of vadose zone*	Chemical and mineral weathering of various rocks, development of secondary porosity, etc. are triggered by the dissolution kinetics of rocks and minerals in aqueous medium.	[mg/l]

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A.3 Surface

A.3.1 Geomorphology

A.3.1.1	*Land slope*	High slopes increase erosion risks and increase; Low slopes may reduce run-off.	[degrees; %]

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A.3.2 Hydrography

A.3.2.1	*Drainage density (abundance of rivers and streams)*	Drainage density is significant in that it plays an important role in surface-runoff processes, influencing the intensity of torrential floods, the concentration, the sediment load and even the water balance in a drainage basin.	[km/km^2]

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A.3.3 Land use / land cover

A.3.3.1	*Soil occupation*	Types of land use / land cover influence the surface runoff generation, infiltration rates, etc.	[land use type]
A.3.3.2	*Land surface area*	Spatial extent of the influence of the soil occupation	[km^2]

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A.3.4 Soil

A.3.4.1	*Top-soil texture*	Fractions among sand, clay, silt.	[%; mg/kg]
A.3.4.2	*Total organic carbon of top soil*	TOC which will give different adsorption and biodegradation conditions.	[%; mg/kg]
A.3.4.3	*Lineament density*	Abundance of preferential paths of water infiltration from surface to subsurface.	[km/km^2]

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A.3.5 Karst features[2]

A.3.5.1	*Epikarst development*	High epikarst thickness can be very favorable to slow, spread and diffuse water infiltration.	[m]
A.3.5.2	*Degree of karstification*	Water flow velocity is affected by the degree of karstification and influences the water availability for recovery.	[m/h]

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[2] Read more: Daher, W., Pistre, S., Kneppers, A., Bakalowicz, M., Najem, W. (2011) Karst and artificial recharge: Theoretical and practical problems: A preliminary approach to artificial recharge assessment. Journal of Hydrology, 408 (3–4): 189-202. https://doi.org/10.1016/j.jhydrol.2011.07.017.

B Availability of water for MAR

The thematic associated with the availability of water resources for MAR implementation is considered, which plays an essential role on determining the feasibility level of a potential MAR site. It considers both conventional and non-conventional water sources (e.g., wastewater, desalinated water), their qualitative composition (e.g., chemical pollutants, pathogens, turbidity, etc.), along with the impact of climate processes.

B.1 Climatic context

B.1.1 Hydrometeorology

B.1.1.1	*Precipitation*	Amount of water that can generate runoff and be allocated for infiltration at MAR sites.	[mm/month]
B.1.1.2	*Evapotranspiration*	Refers to the amount of water that is removed from the water budget (contribute negatively as a sink term to the water deficit).	[mm/month]
B.1.1.3	*Direct run-off*	Refers to the water available for MAR from the flow of rainwater, snowmelt, or spring flow over the land surface toward stream channels.	[m^3/day]

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B.2 Source water

B.2.1 Source water quality

B.2.1.1	*Pathogen concentration of recharge water*	The concentration of waterborne pathogenic organisms, such as bacteria, protozoan and viruses. *E. coli*.	[Number of pathogens per liter]
B.2.1.2	*Nutrients concentration of recharge water*	Although necessary for plants, high levels of nutrient (e.g., nitrates) can be harmful for peoples. Following Australian guidelines (2006)[3], this category also includes total nitrogen, total phosphorous and organic carbon.	[mg/kg; ppm]
B.2.1.3	*Salinity and sodicity concentrations of recharge water*	High concentrations of salinity indicators (EC, Cl etc.) might reduce ability of plants to uptake water, and have adverse effects on humans' health (blood pressure, kidney stones, rheumatism etc.).	[mg/l; mg/kg]
B.2.1.4	*Organic chemicals in recharge water (pesticides, pharmaceuticals, etc.)*	Pesticides, pharmaceutical, cosmetics, nanomaterials and others. Potential health hazards at high concentrations: pesticides might cause acute health effects such as chemical burns, nausea, or convulsions. Pharmaceuticals are associated with toxicity, teratogenicity and carcinogenicity.	[µg/kg]
B.2.1.5	*Turbidity and particulates of recharge water*	With respect to MAR, turbidity-related risks include: reduced disinfection performance, leading to increased risk from microbial pathogens; increased risk of transporting a range of contaminants that can sorb to particles; reduced permeability due to clogging (operational risk).	[NTU]
B.2.1.6	*Inorganic chemical concentrations of recharge water*	This category includes pH, EC, Sodium, Chloride, Boron, Bicarbonate, Arsenic, Fluoride, etc.	[mg/l; µS/cm…]
B.2.1.7	*Radionuclides in recharge water*	Radioactive isotopes or unstable forms of elements.	[Bq]
B.2.1.8	*Proximity to contamination sources (including the sea)*	Distance from contamination sources including seawater intrusion.	[km]
B.2.1.9	*Pathogen concentration of recharge water*	The concentration of waterborne pathogenic organisms, such as bacteria, protozoan and viruses, *E. coli.*	[number of pathogens per liter]

↑ Go to overview ↑

[3] Australian guidelines for water recycling - Managed aquifer recharge (Phase 2) (2009). Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra. Available online at https://www.waterquality.gov.au/guidelines/recycled-water.

B.2.2 Source water availability

B.2.2.1	*Natural water availability*	Refers to the amount of water that can be allocated to infiltration purposes (storms, rainfall, monsoons, lakes, rivers).	[m^3/day]
B.2.2.2	*Non-conventional water availability*	Refers to the amount of water that can be allocated to infiltration purposes (treated wastewater, industrial water).	[m^3/day]
B.2.2.3	*Proximity to origin of water sources (incl. conventional and non-conventional)*	Indication of the degree of availability: how easily the source water can be transferred to the recharge site (also related to costs).	[km]
B.2.2.4	*Water supply connection density*	Describes the pressure exerted on community drinking water supply sources, given as the ratio of active public water supply sources (e.g., number of public wells) to water supply connections (e.g., number of households). Communities that rely on a single public water supply are especially vulnerable to shortages and contamination. Hence, it can influence the water availability.	[-]
B.2.2.5	*Surface water conveyance infrastructure*	Water availability restriction due to the presence of endangered species in the source water.	[ordinal]

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C Water demand

The thematic of water demand is an essential component of integrated water management for achieving sustainable development. The classification was derived from the general approach of groundwater-dependent ecosystem services (ES) and included the main four ES clusters: provisioning, regulating, supporting and cultural. In brief: provisioning ecosystem services include human benefits that can be directly extracted from nature, such as food, drinking water, wood fuel etc. Regulating services includes ecosystem processes associated with the mitigation of natural phenomena, thus allowing ecosystems to remain clean, sustainable and resilient to climate changes. Cultural services contribute to the cultural advancement of the people, the building of knowledge and ideas through the interaction with nature and recreation. Lastly, supporting services are needed for producing and maintaining the other three ecosystem services. These services involve natural processes such as soil formation and retention, biomass production, production of atmospheric oxygen.

C.1 Provisioning needs

C.1.1 Domestic supply

C.1.1.1	*Non-satisfied domestic demand by the existing water resource*	Portion of water available from MAR that can cover all water demand per period of time.	[%]
C.1.1.2	*Annual growth rate of domestic water supply*	Trend of water amount demanded for domestic activities (time scale larger than consumption rate).	[m^3/month; Mm^3/year]
C.1.1.3	*Water price*	Price might impact the water consumption.	[€/m^3]

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C.1.2 Agricultural supply

C.1.2.1	*Crop pattern*	Depends on the crop type that is using irrigated water obtained from MAR facilities.	[crop type]
C.1.2.2	*Land covered/used*	Area allocated for agricultural purposes that uses water originating from MAR.	[km^2]
C.1.2.3	*Annual growth/decline rate of agricultural supply*	Temporal variations of the water collected from MAR sites for irrigated purposes.	[Mm^3/time]
C.1.2.4	*Irrigation efficiency*	Percentage of irrigated water that is actually used by the plant (e.g., low efficiency increases the water demanded by the agricultural workers).	[%]

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C.1.3 Industrial supply

C.1.3.1	*Consumption per unit area*	Amount of MAR-allocated water needed to fulfil the industrial needs.	[m^3/km^2]
C.1.3.2	*Industrial area extent*	Area where the water is consumed for industrial purposes (in case water consumption is expressed per unit of area.	[km^2]
C.1.3.3	*Annual growth/decline rate of industrial supply*	Temporal variations of the water collected from MAR sites for industrial purposes.	[Mm^3/time unit]

↑ Go to overview ↑

C.1.4 Geothermal energy

C.1.4.1	*Generated energy from geothermal water*	Extracting hot water and reinjecting it into the aquifer (ASR).	[kW/m^3]

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C.2 Regulatory needs

C.2.1 Buffering water quality

C.2.1.1	*Rate of aquifer salinization*	MAR can provide necessary water to ameliorate aquifer water quality.	[(S/m) per time unit], [(mg/l) per time unit]
C.2.1.2	*Decrease of groundwater levels (e.g., annual mean values, seasonal)*	MAR can change temperature of groundwater (cooling or heating).	[°C]

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C.2.2 Buffering water quantity

C.2.2.1	*Flood risk (flood water might be harvested and injected to the aquifer)*	Harvested stormwater can be injected into aquifer to reduce flooding and erosion effects.	[rainfall intensity in mm/h]
C.2.2.2	*Erosion risk (run-off water might be collected and injected to the aquifer)*	Water surplus of humid period could be stored in the aquifer and used later on during wet season.	[water deficit in mm]
C.2.2.3	*Natural groundwater recharge rate*	Low natural groundwater recharge rates lead to reduced water availability.	[mm/time unit]

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C.3 Supporting needs

C.3.1 Groundwater dependent ecosystems

C.3.1.1	*Required stream baseflow*	MAR can guarantee a minimum river stage able to be exploited.	[m^3]
C.3.1.2	*Required springs discharge*	MAR affects springs discharge.	[m^3]
C.3.1.3	*Required water to maintain wetlands and phreatophytes*	Needs for groundwater dependent ecosystems and river minimum discharges.	[number / variability of species]
C.3.1.4	*Required water to maintain hyporheic zone dynamics*	MAR affects the hyporheic zone dynamics.	[m^3]

↑ Go to overview ↑

C.3.2 Land surface stability

C.3.2.1	*Risk of land subsidence (MAR can reduce the risk of land subsidence)*	Land subsidence can occur in zones where phreatic aquifer is overexploited.	[subsidence risk classes]

↑ Go to overview ↑

C.4 Cultural needs

C.4.1 Hot springs

C.4.1.1	*Hot water abundance in hot springs*	Hot water abundance in hot springs.	[m^3]
C.4.1.2	*Number of visitors of hot springs*	Refers to the amount of water demanded from MAR schemes regarding hot springs.	[No. of visitors per month / season / year]

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C.4.2 Leisure and recreation

C.4.2.1	*Decrease of water volumes in water bodies*	Required water for leisure and recreation activities	[m^3]
C.4.2.2	*Number of site visitors for leisure and recreation*	Number of site visitors for leisure and recreation.	[no. of visitors per month / season / year]

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D Non-physical considerations

The fourth thematic includes all non-physical considerations that are nonetheless relevant for the success of MAR schemes, such as legal and socio-economic aspects.

D.1 Legal constraints

D.1.1 Legal constraints

D.1.1.1	*Legal constraints at European, National, International scale*	Legislation[4] (e.g., Natura 2000, health, EU Water Framework Directive, wellhead protection zones, maximum infiltration zones), transboundary transfer flows.	[ordinal]

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D.2 Governance constraints

D.2.1 Water rights

D.2.1.1	*Water rights for beneficiaries*	Clarity, acceptability, and efficient control to ensure that the water rights of the beneficiaries are satisfied.	[ordinal]
D.2.1.2	*Source water owner*	Clear legal framework regarding the benefits and responsibilities of the source water owner.	[ordinal]
D.2.1.3	*Land ownership*	Clear legal framework regarding the benefits and responsibilities of the land owner.	[ordinal]
D.2.1.4	*Acceptance of MAR owner by local stakeholders*	Acceptance of MAR owner by local stakeholders.	[ordinal]
D.2.1.5	*Level of accountability in terms of legislations and public*	Level of accountability in terms of legislations and public.	[ordinal]

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D.2.2 Trans-border issues

D.2.2.1	*Existence of transboundary flows*	Sharing of water among different countries might lead to further complications, leading to delays, extra costs etc.	[ordinal]
D.2.2.2	*Issues with downstream/upstream countries*		[ordinal]

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[4] See also: Fernández Escalante, E., Henao Casas, J. D., Vidal Medeiros, A. M., San Sebastiàn Sauto, J. (2020). Regulations and guidelines on water quality requirements for Managed Aquifer Recharge. International comparison. Acque Sotterranee - *Italian Journal of Groundwater*, 9(2). https://doi.org/10.7343/as-2020-462

D.2.3 Political stability

D.2.3.1	*Regional conflicts (in general)*	Increase risk for intentional damages (vandalism, sabotage etc.).	[ordinal]
D.2.3.2	*Corruption*	Refers to all stakeholders involved (from owners to users).	[ordinal]

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D.3 Social constraints

D.3.1 Awareness of MAR

D.3.1.1	*Awareness for MAR*	Level of knowledge regarding the benefits (and potential hazards) of MAR techniques.	[ordinal]
D.3.1.2	*MAR acceptance (e.g., religion constraints)*	Depends on factors such as the importance of MAR objective for the citizens, reliability of MAR operators etc.	[ordinal]
D.3.1.3	*Priority of water allocation*	Water allocation for other purposes can affect water availability for MAR.	[ordinal]

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D.3.2 Vulnerability to groundwater supply

D.3.2.1	*Poverty status*	Water price might lead to discriminations among different society classes.	[ordinal]
D.3.2.2	*Linguistic isolation*	Might impact awareness of people for MAR-related information.	[ordinal]
D.3.2.3	*Educational attainment*	Impacts the understanding of people on the technical and non-technical details related to MAR concept.	[ordinal]

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D.3.3 Health

D.3.3.1	*Possible impact of MAR facility on health*	Potential health risks associated with the water quality needs to be sufficiently monitored during all phases of the MAR project.	[ordinal]

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D.3.4 Social capital

D.3.4.1	*Social participation / involvement in MAR implementation*	Participation in local organizations and unions[5].	[ordinal]
D.3.4.2	*Social support for MAR enhancement*	Support from the authorities, family, acquaintances, neighbors.	[ordinal]

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D.4 Environmental constraints

D.4.1 On optical aesthetics during the construction stage

D.4.1.1	*Distance of MAR to other types of infrastructure, especially sensitive landscape*	For example, noise levels can impact the acceptance of MAR solutions from near-by residents.	[km]

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D.4.2 On emissions

D.4.2.1	*Emission during construction*	Dust and carbon emissions; Liquid wastes from paints and machinery during the construction period.	[l; mg/m^3]
D.4.2.2	*Risk of Insect proliferation*	Insects can transmit diseases, deteriorate the aesthetic of the area, influence the agricultural activities etc.	[%]

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D.4.3 Cultural heritage

D.4.3.1	*Risk of MAR on archeological sites/objects*	Probability of negative impacts caused by MAR on archeological sites/objects.	[%]

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[5] Hoa, L.T., Dinh, P.T., Chau, N.T.P., Thuy, N.T.T. (2022) Assessment of livelihood risks due to climate change and ecological resources in Can Gio mangrove biosphere reserve, Vietnam *IOP Conf. Ser.: Earth Environ. Sci.* 1028, 012001. https://doi.org/10.1088/1755-1315/1028/1/012001

D.5 Economic constraints

D.5.1 Investment costs

D.5.1.1	*Cost of preliminary studies*	All preliminary characterization studies of the recharge site (e.g., geological and hydrogeological characterization, technical-economic study, impact study, and preparation of the authorization file).	[€]
D.5.1.2	*Cost of water abstraction*	cost of civil engineering works for the pumping of water out of the river/canal. As well as pumping equipment.	[€]
D.5.1.3	*Cost of water transfer*	Construction of water transfer infrastructure including the supply pipeline.	[€]
D.5.1.4	*Cost of recharge water*	Refers to pre-treatment units, e.g., primary (intermediate settling and filtration basins, secondary and tertiary.	[€]
D.5.1.5	*Cost of land acquisition*	Cost of purchasing land for the construction of infiltration basins.	[€]
D.5.1.6	*Cost of Infiltration basins*	In general, this is the main investment. Includes the design (civil engineering) and construction of infiltration basins (injection wells in the case of direct recharge), as well as associated equipment.	[€]

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D.5.2 Operating costs

D.5.2.1	*Cost of water purchase during operating phase of MAR*	Purchase cost in the case of withdrawal from a water canal or network, as well as charges, levies, or other taxes.	[€/time unit]
D.5.2.2	*Cost of maintenance and uptake during operating phase of MAR*	Maintenance of the recharge water pumping system in the river.	[€/time unit]
D.5.2.3	*Cost of energy during operating phase of MAR*	Electricity consumption of the equipment and pumping system used to supply the recharge water to the recharge site. It will depend on the flow rate and the price of energy.	[€/time unit]
D.5.2.4	*Cost of pre-treatment operation during operating phase of MAR*	The operational and maintenance costs of the infrastructure for pre-treatment of groundwater (excluding investment). They include, for example, the cost of maintaining and cleaning settling tanks, the cost of chlorination products, etc.	[€/time unit]
D.5.2.5	*Cost of monitoring during operating phase of MAR*	All the costs related to the control and periodic monitoring of groundwater or recharge water quality (e.g., laboratory analysis cost) or the costs associated with checking the proper functioning of the device (essentially labor costs if an automated control system is not set up).	[€/time unit]
D.5.2.6	*Other annual expenses during operating phase of MAR*	Includes all financial expenses not mentioned above: administrative and personnel management expenses, financial expenses on investment and insurance loans etc.	[€/time unit]

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D.5.3 Levelized costs

D.5.3.1	*Levelized cost: maintenance cost-recharge*	Maintenance expenses over the life of a MAR project divided by the annual volume of recharge (or infiltration)[6]	[€/m^3]

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D.6 Infrastructural constraints

D.6.1 Accessibility

D.6.1.1	*Accessibility network to MAR facility*	Distance to main/secondary/gravel roads.	[km]

↑ Go to overview ↑

[6] Maréchal, J.-C.; Bouzit, M.; Rinaudo, J.-D.; Moiroux, F.; Desprats, J.-F.; Caballero, Y. Mapping Economic Feasibility of Managed Aquifer Recharge. Water 2020, 12, 680. https://doi.org/10.3390/w12030680

D.6.2 Communications

D.6.2.1	*Communication systems with and within MAR facility*	Sufficient Internet, mobile signals.	[ordinal]

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D.7 Safety

D.7.1 Safety of the workers and users

D.7.1.1	*Water level of the recharge ponds in relation to workers and users' safety*	Water levels must be below a certain threshold	[cm]
D.7.1.2	*Electricity contact with operating system in relation to workers and users' safety*	In case the voltages are high, then linkage of electric energy from the pumping system/recharge network might be dangerous.	[volt]

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