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Monitored and Intentional Recharge (MIR): A Model for Managed Aquifer Recharge (MAR) Guideline and Regulation Formulation

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Abstract: Guidelines and regulatory frameworks for conducting managed aquifer recharge (MAR) are scarce worldwide compared to the countries where MAR projects operate. At the same time, guidelines and regulations are crucial to implementing MAR activities safely, respecting human health and the environment, and guaranteeing the sustainability of the intentional recharge. The present study aims to provide a conceptual model comprising the minimum elements to consider when drafting guiding and normative MAR documents. To this end, aspects discussed in nine guidelines were evaluated through a score that allowed their significance to be assessed. The authors also reviewed 22 regulations, guidelines, or MAR site operation rules to construct the monitored and intentional recharge (MIR) conceptual model. This effort was enhanced by active participation in the real drafting of two national regulating documents for MAR. The evaluation of aspects in the documents showed the importance of water reuse and risk and impact assessment. The MIR conceptual model comprises nine blocks that summarize the most important aspects to consider. This conceptual model, which guides MAR regulations in two countries, has great potential for application in different sites under diverse contexts.

Keywords: monitored and intentional recharge (MIR); managed aquifer recharge (MAR); guidelines; regulations; monitoring; artificial recharge; formulation; maximum allowable concentrations (MACs)

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1. Introduction

Managed aquifer recharge (MAR) is a term that encapsulates a series of techniques to store water underground in aquifers for diverse purposes [1,2]. Although MAR has been practiced around the world for many centuries [3,4], it has experienced accelerated growth in recent years [5], particularly to adapt first to managing water resources in normal climate variability and later to the uncertainty of a warming world with more intense and frequent extreme climatic events (e.g., droughts, floods) [6–8].

Nonetheless, negligence and lack of experience while conducting MAR can result in collateral damage that sometimes outweighs the potential benefits. Inadequate consideration of source water quality and hydrochemical interactions between recharged water and the target porous medium may cause aquifer and groundwater contamination [9–13] and consequently costly and time-consuming remediation efforts [14]. Furthermore, the increasing identification of emergent pollutants in recycling wastewater schemes (including MAR) [15–17] poses a risk to environmental integrity and human health [18,19]. In settings with shallow water tables, MAR can induce water logging and consequently crop damage [20]. An inappropriate estimate of potential clogging development in MAR systems could significantly lower their efficiency and expected lifespan [21–23].

When dealing with MAR, careful attention should also be paid to the final use of water. About 60% of MAR systems around the world have been designed to increase drinking water availability [24,25]. Lack of concern for human health risks and social dynamics around MAR could negatively impact the population with access to MAR water [26].

Besides undesired MAR performance, the factors above can also be detrimental to the general perception of the technology and affect the confidence of the public and decision-makers in its implementation [27]. In this context, conducting MAR safely under clear guidelines and regulations is critical to avoiding harm to human health, the environment, and socioeconomic assets and ensure the system's proper functioning. Furthermore, the principle of "Do No Significant Harm" (DNSH) has been recently incorporated into the compulsory sustainability requirements to obtain funds for any project in the EU through regulations such as the Sustainable Finance Disclosure Regulation (SFDR), the taxonomy for sustainable activities, and the benchmark regulation [27]. These requirements, although many clarifications about their indicators are ongoing, should apply to any future MAR project, especially within European Union (EU) borders.

State of the Art and Cross-Pollination

Very few countries and organizations have moved forward with normative bodies concerning MAR directly or indirectly compared to the number of countries where MAR systems are already operating [28–32].

The first indirect pragmatic effort to regulate MAR was proposed in 1989 by the World Health Organization (WHO) with its guidelines for the safe use of wastewater and excreta in aquaculture and agriculture [33]. These guidelines explain the full range of practical and technical factors to consider when planning, designing, and operating systems for wastewater reuse. The WHO has also developed a framework for evaluating the socio-cultural, environmental, economic, and political aspects of MAR [34], and an assessment of the risk to health entailed by this technology [35].

At the multinational level, the EU has provided a comprehensive regulatory framework to ensure the good status of surface and groundwater through the Water Framework Directive (WFD) (2000/60/EC) [36], the Groundwater Directive (2006/118/EC) [37], and the catalog of priority substances of the Directive 2013/39/EC [38], among others. These normative bodies indirectly regulate MAR and consider this technology as a measure to achieve environmental objectives [30]. More recently, the Joint Research Group has formulated a directive on the minimum water quality requirements for water reuse in agricultural irrigation, which indirectly involves MAR [39]. Additionally, several authors and the Common Implementation Strategy for the WFD have been working towards a guiding document on MAR for the EU [28,29,40,41].

The most comprehensive and globally accepted guidelines on MAR are probably the Australian Guidelines for Water Recycling [42], which apply a scientific and risk-based approach focusing on identifying and managing risks. They acknowledge the importance of interactions between the source water and the aquifer as well as the attenuation of pollutants during residence time and consider all water sources and MAR types [5]. The Australian guidelines place a strong emphasis on monitoring to reduce any risk and assess system performance. They recommend four types of monitoring, namely baseline, validation, operational, and verification. Due to their comprehensive scope and international acceptance, the Australian Guidelines have served as a model for formulating MAR guiding documents in countries such as New Zealand [5] and India [43].

The USA implemented The Underground Injection Control Regulations And Safe Drinking Water Act Provisions [44]. This document regulates water injection into aquifers, setting rules for well permitting and technical specifications for their design and construction. Water pollution is prevented by setting maximum allowable concentrations (MACs) for a comprehensive list of contaminants [45,46]. Several USA states have proposed their own rules and guidelines for MAR, all of them more stringent than the national regulation. Some of these states are Arizona [47], California [48,49], Florida [50], and Washington [51].

The MAR regulatory body in the USA is complemented with technical guidance on MAR implementation by the ASCE [52].

Several countries have formulated their own regulations and guidelines addressing MAR with more limited impact at the international level, including China [5], New Zealand [5], Belgium [28], Namibia [30], South Africa [30], Brazil [53], Chile [54,55], India [56], Italy [57,58], Mexico [59,60], Portugal [61], Spain [62], The Netherlands [63], and Thailand [64]. Most of the guidelines share a common target, although their stage of development and detail is different. These ruling and guiding documents engage primarily with permitting and monitoring (e.g., Belgium, Chile), water pollution control through MACs of potential contaminants (e.g., the Netherlands, Mexico), and control of specific MAR applications, such as wastewater reuse (e.g., Spain, Belgium). In many cases, MAR is merely mentioned in national law with few documents devoted entirely to the subject. Most of these documents focus in an unbalanced way on quantitative or qualitative aspects.

The guidelines on MAR above have been classified according to their geographical scope, compliance severity (hard or soft), and type of document (Table 1). Three types of documents were differentiated based on previous works [30], namely guideline, regulation, and operator rules. The classification also includes the year of publication and whether MACs are specified for the source water employed for recharge (Table 1).

Table 1. Consulted MAR guidelines classified according to their approach, content, and severity (countries or states in alphabetical order). N: no; Y: yes.

Country	Scope	Severity	Type	Year	MACs [2]
Arizona (USA)	Regional	Hard	Guideline	1994	N
Australia	National	Soft	Guideline	2009	Y
Belgium (Torreele)	Local	Hard	Operator rule	2012	Y
Brazil	National	Soft	Regulation	2019	N
California (USA)	Regional	Hard	Guideline	2012	Y
Chile	National	Soft	Regulation	2013	N
China	National	Soft	Guideline draft	2014	N
Florida (USA)	Regional	Soft	Guidelines	1999	Y
India	National	Soft	Guidelines draft	2014	N
Italy	National	Hard	Regulation	2016	Y
Israel (Shafdan)	Local–National [1]	Hard	Operator rule	1966	Y
Mexico	National	Hard	Regulation	2003–2009	Y
Namibia (Windhoek)	National	-	Guidelines. Regulation proposal	2004	N
New Zealand	National	Soft	Technical guidance	2017	Y
Portugal	National	Hard	Regulation	2000	N
South Africa	National	Hard	Regulation draft	2004	N
Spain	National	Hard	Regulation	2007	Y
Thailand	National	Hard	Guideline	2022	?
The Netherlands	National	Hard	Regulation	1993	Y
USA (ASCE)	National	Soft	Regulation	1974–2019	Y
WFD (EU)	International	Soft	Regulation	2000	N
WHO	International	Soft	Guideline	2001	N

[1] Mekorot water supply Company applies Shafdan standards to national level. [2] Maximum allowable concentration.

Despite the current documents regulating MAR, there is no explicit guide on the minimum requirements to publish a sound regulatory framework and the essential aspects that it should address.

The main purpose of this work is to provide a conceptual model for developing modern MAR guidelines and regulatory documents. To this end, the available regulations and guidelines on MAR were critically reviewed in order to formulate a conceptual model with the minimum aspects to consider. The content of the reviewed documents was also classified and the most addressed aspects identified and qualitatively assessed, resulting in a list of the most relevant elements to consider when drafting MAR regulations or technical guidelines. This research effort should ease the global penetration of MAR safely and responsibly. As far as the authors are aware, this is the first work of its kind.

2. Methodology

2.1. The Monitored and Intentional Recharge (MIR) Conceptual Model

A model on the most relevant topics was elaborated based on the review of 22 documents on MAR involving regulations [30], guidelines, and MAR site operator rules. The model was also based on the experience of drafting MAR guidelines for Niger and Peru and the score assessment of key aspects explained below (Section 2.2).

The proposed term MIR was retained, despite the risk of creating some confusion with the acronym MAR, with the intention to create a synergy between both concepts. The MIR conceptual model was also developed from first-hand experience because the authors have contributed to formulating initial draft documents for Peru and Niger's MAR guidelines.

2.2. Review of Main Aspects in MAR Guiding and Regulating Documents

First, the MAR guiding and regulatory documents were scanned to identify the key aspects they address. Subsequently, the aspects were evaluated in each MAR document in terms of the level of detail in which they are discussed and scored from zero to four, where zero corresponds to "no mention" and four to a complete and detailed discussion (Table 2). The scores were added, and the key aspects were ranked based on their final score. The key aspects were also allocated to broader thematic categories, namely: (1) general context, (2) MAR planning, (3) social concerns, (4) receiving medium features, (5) financial issues, (6) risk and impact assessment, (7) operation questions, and (8) various aspects. For each category, the level of development for each studied document was evaluated. The MAR documents assessed were the WHO guidelines for water recycling [33–35], the Australian guidelines on MAR [42], the USA regulatory body on MAR [44,46], the ASCE MAR guidelines [52], the European guidelines on water reuse in agriculture [39], the European guidelines on integrating water reuse [40], and MAR guiding documents for Chile [56], India [43], and Mexico [53,54].

Table 2. Categories assigned to evaluate the level of development of each aspect.

Numerical Category	
0	No mention
1	The aspect is mentioned
2	The aspect is discussed
3	The aspect has its own section
4	The aspect has its own section and is comprehensively discussed

3. Results and Discussion

3.1. Review of Main Items in MAR Guiding and Regulating Documents

The most discussed aspect in the reviewed documents was wastewater reuse, with particular attention to water sources, final uses, and water quality (Table 3). This outcome

highlights the importance of water recycling, which is particularly relevant in the face of water scarcity and climate change. Likewise, other aspects well-addressed in the documents were related to the protection of health, groundwater sources feeding dependent ecosystems, and the importance of guaranteeing water supply for agriculture and food production, showing increasing awareness of water security and how to conduct MAR operations safely.

Table 3. Main aspects discussed in the reviewed documents and their corresponding score.

Group	Aspect	Score
General context	Wastewater reuse, including water sources and final uses	28
Risk and impact assessment	Health protection	27
MAR planning	Review of policy and legal framework	24
Operation aspects	Monitoring and pilot testing	24
Receiving medium	Groundwater source protection	22
Risk and impact assessment	Agriculture supply protection	22
Risk and impact assessment	Risk assessment	21
Risk and impact assessment	maximum allowable concentration (MACs) list	21
MAR planning	MAR system design and characteristics	20
General context	Definition of terms	19
Social aspects	Water management framework, including entities and their duties	19
Financial issues	Funding/financial issues/costs	18
Risk and impact assessment	Dependent ecosystems protection	18
Receiving medium	Recharged water—unsaturated zone interaction	17
Operation aspects	Operation and maintenance plan (O + M)	17
MAR planning	Administrative components	15
MAR planning	Planning activities and considerations	15
Risk and impact assessment	Sanitary and environmental risks assessment	15
General context	Successful MAR case studies	14

The most relevant operation aspect was monitoring and pilot testing. Maximum allowable concentrations (MACs) of potential contaminants (nitrates, phosphates, heavy metals, emergent pollutants) in recharge water comprise another relevant topic in terms of risk assessment. The main aspect of the aquifer developed in most of the documents concerns the interaction between the recharged water and the receiving medium, which is crucial in many schemes relying on reclaimed wastewater. Pertaining to MAR planning, the aspects with the highest assessment score were the review of the policy and legal framework and the MAR system design and characteristics, i.e., an evaluation of the available MAR technologies.

Generally, the technical guidelines for developing countries pay less attention to qualitative aspects and are more permissive in regard to MACs in recharge water (reducing the list of substances or rising the thresholds). They also pay more consideration to external financing issues than more developed countries´ guidelines, e.g., funds for development.

Social organization and governance are considerably unevenly distributed; therefore, the markers to relate social organization and the economic level for each country have driven into a vast range of cases, without a clear general trend. It is also perceived that *early MAR* countries (where MAR technology has been recently implemented) publish documents that pay more attention to successful MAR cases, either within their frontiers or even in the international context.

Overall, the aspects with major relevance are related to risk and impact assessments and wastewater reuse. Appendix A provides a detailed table of the results of the evaluation of relevant aspects through scoring and ranking (Figure A1, enlarging Table 3).

3.2. The Monitored and Intentional Recharge (MIR) Conceptual Model

Nine factors (so-called blocks) are proposed to draft any future comprehensive guideline or regulation on MAR. These blocks were grouped under the umbrella of the monitored and intentional recharge (MIR) conceptual model. The key aspects with high scores above (Section 3.1 and Table 3) were reordered logically and included in the nine blocks of the model. The Appendix A, (Figure A1) presents the score assessment in detail, the last column contains the MIR block/s in which the aspects were allocated.

The MIR blocks are (1) water source, (2) hydrogeological and environmental conditions, (3) MAR technology, (4) MAR sensors for data gathering, (5) monitoring guidelines, (6) final use of the intentionally recharged water, (7) analytical aspects, and (8) risk or impact assessment (Figures 1 and 2) [65]. An additional category was integrated, (9) others. It was infeasible to construct the blocks of the MIR conceptual model in parallel to the main aspects identified in MAR documents since the main aspects do not provide a sound logical framework to group regulatory and guiding key elements.

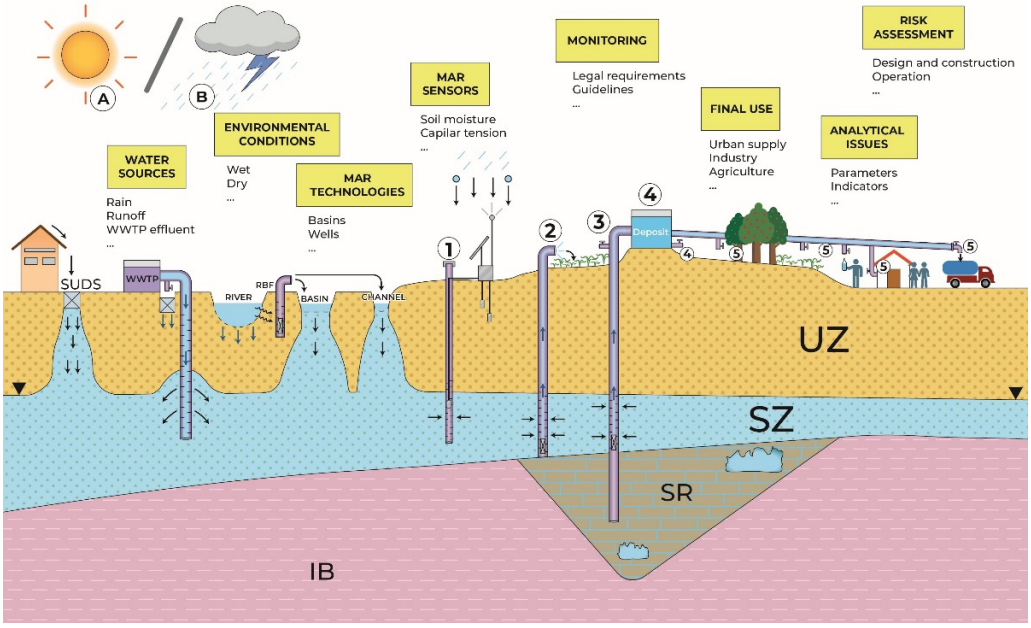


Figure 1. General scheme illustrating the main blocks comprising the monitored and intentional recharge (MIR) conceptual model. IB: impermeable bedrock; UZ: unsaturated zone; SZ: saturated zone; SR: strategic reservoir (geological formation for long term groundwater storage); WWTP: wastewater treatment plant; SUDS: sustainable urban drainage systems; RBF: riverbank filtration. A and B refer to the different climatic conditions in MAR site areas. Number (1) refers to the UZ and SZ monitoring from a piezometer (MIR block 5, monitoring). The rest of the numbers correspond to usual sampling points, either from the extraction borehole, out of the conduction option (2) or collected inside the pipeline (3); sampling point from any storage cell where any treatment takes place at different depths (4); and hydrant from irrigation or tap for urban water supply (5). Sampling points 2 to 5 relate to the MIR blocks 6 and 7 (final use and analytical issues).

Each block included as part of the MIR concept is discussed in greater detail below.

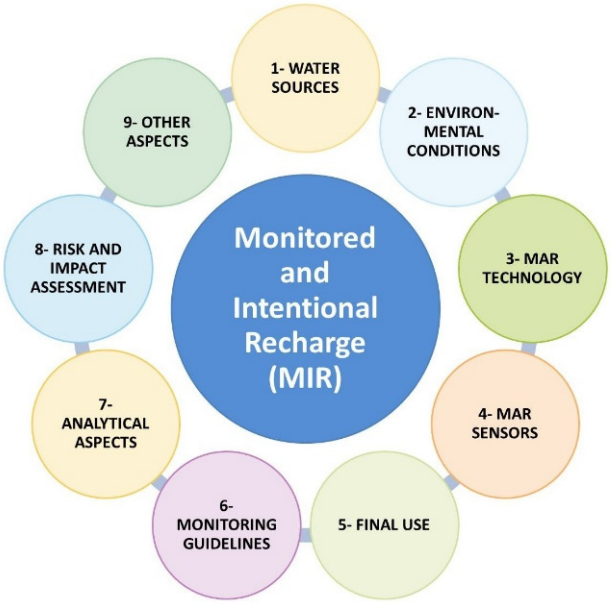


Figure 2. Components of the monitored and intentional recharge (MIR) conceptual model and proposed chapters (called blocks) for any managed aquifer recharge (MAR) system´s technical guidelines document.

3.2.1. Water Sources

The first element in conducting MAR is the availability of water sources in sufficient quantity and adequate quality. The most common water sources in MAR projects include rivers, rainwater, urban runoff, reclaimed wastewater [52,66], wetlands (e.g., Phoenix, ISMAR 6), inter-dune filtration, desalination plants, urban supply surpluses, irrigation returns, and drainage (Figure 3).

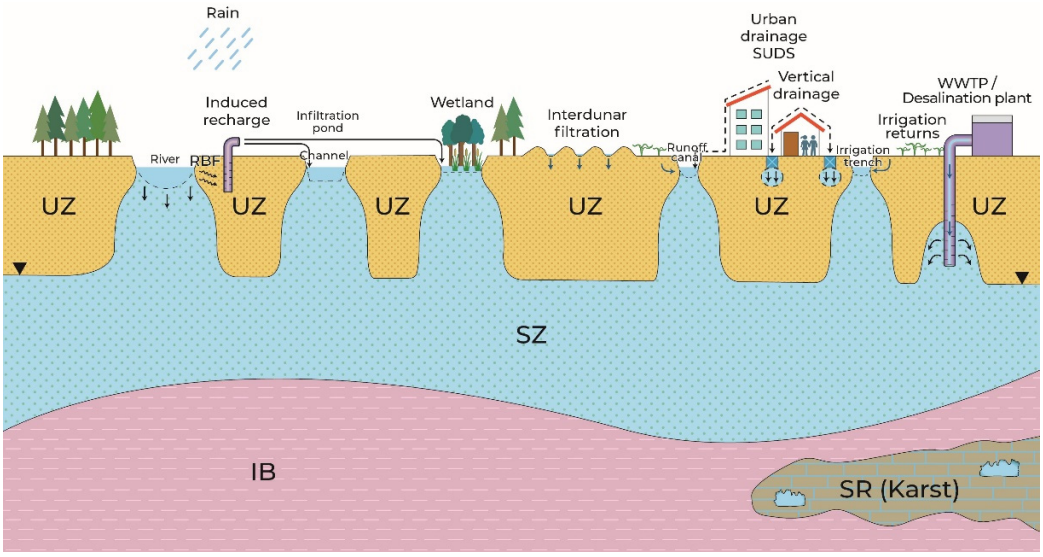


Figure 3. Main water sources for managed aquifer recharge (MAR) specifying the origin of the water for intentional recharge, as per the monitored and intentional recharge (MIR) concept, block 1. Abbreviations are specified in the legend of the Figure 1.

Desktop pre-feasibility studies must consider the availability of water resources for MAR, their temporal distribution, and the likely adverse impacts on the natural media, avoiding risk to ecosystems and confrontation with other water users [67].

The most common water sources for MAR are rivers and lakes. These sources are temporary or opportunistic, and their availability usually coincides with surface water

abundance [39,66]. Hence, it is worth emphasizing the convenience of aquifer storage (for weeks, months, or even years) through MAR for subsequent abstraction when necessary. In some cases, surplus water in stream courses with decent quality is lost to the sea. MAR projects could tap into these resources, helping to meet water demands in sectors such as agriculture [68].

A very promising water source for MAR is reclaimed wastewater. It assures year-round recharge and enables MAR in areas with over-allocated surface water rights and water allowances. Globally, reclaimed wastewater is employed in 17% of MAR projects [25]. However, due to its permanent character and exacerbating water scarcity and droughts in many regions, the use of reclaimed wastewater will likely increase, particularly for agriculture [39,69,70].

Urban runoff often has poor quality [71,72]. It requires a scheme with either pre-treatment, treatment, post-treatment, or a combination of them to reduce the risks of aquifer contamination and MAR system clogging.

3.2.2. Hydrogeological and Environmental Conditions

MAR operations depend largely on site-specific conditions, such as the nature of the target aquifer and the climatology, which are included in the MIR's block of environmental settings (Figure 4).

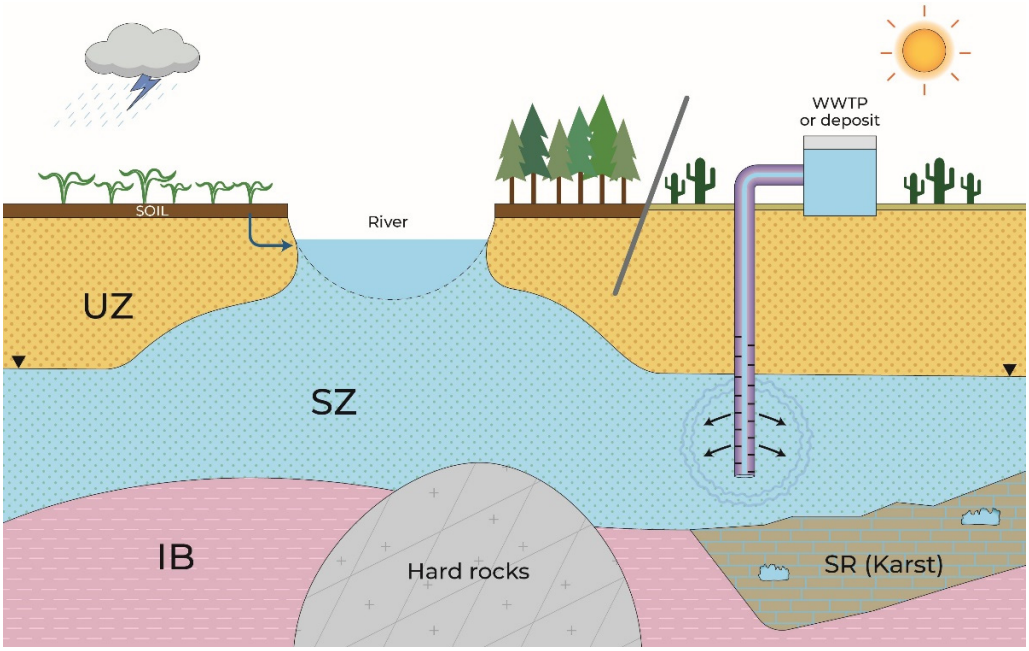


Figure 4. The MIR conceptual model considers the MAR system's hydrogeological, hydrological, and environmental conditions (block 2). Superficial and water spreading MAR systems are usually implemented for wet areas (**left**, humid areas), such as infiltration basins; in dry areas, punctual MAR systems are often used, such as boreholes, as they are more convenient (**right**, arid and semi-arid areas). Abbreviations specified in the caption of Figure 1.

Concerning climatic conditions, three broad types of climatic zones should be taken into account, namely arid, semi-arid, and humid. The type of climate zone involved in a MAR project critically influences the amount of recharge, not exclusively because of the changing character of the available water resources in terms of volume and distribution throughout the year but also due to factors such as the initial soil moisture content, which help to determine the water quantity infiltrated during the initial stages of the intentional recharge into unconfined aquifers.

The other factor in this block of MIR is the receiving medium, which initially differentiates the unsaturated and saturated zones.

When considering the unsaturated zone, essential parameters are related to local geomorphological and edaphological characteristics and include the thickness of the vadose zone, the vegetation cover, and the terrain slopes (e.g., to estimate the potential runoff).

Regarding the saturated zone of the aquifer, the first characteristic to ascertain is its nature, which can be porous, karstic, or fractured. Subsequently, additional information should be obtained with the aim of fully characterizing the saturated zone, including the permeability, aquifer behavior and degree of confinement, thickness, homogeneity, isotropy, hydraulic gradient, degree of consolidation, mineralogy, oxidation-reduction state of the native water, and differentiation between aerobic and anaerobic zones, among others.

Another element to bear in mind is the interaction between the recharged water and the target geological formation. Different hydrochemical processes prevail in different regions during transit through the saturated and unsaturated zones, as is often observed with wastewater flowing through aquifers [66,73]. Furthermore, depending on the characteristics of the aquifer and due to redox conditions changes and residence times, the receiving medium has the potential to remove pollutants through processes such as sorption, solution, precipitation, cation exchange, and diffusion [74–77]. This purifying capacity is usually restricted to the so-called attenuation zone, which is recognized in some of the most modern regulations, including the Australian Guidelines for MAR [42] and the Underground Injection Control Regulations and Safe Drinking Water Act Provisions from the USA [44,45], as a means of attaining groundwater quality objectives.

In case of injection through the borehole, if the depth of static water level is shallow (about 10–25 m depth), it is important to decide (based on pumping test interpretation) the permitted rising level to prevent any potential risk of soil subsidence or overflow. This term has been named "depth of alert" [66], and it is the minimum depth for the groundwater level after MAR activities to avoid compromising the activities taking place on the surface and within the soil.

Global warming and rapid socioeconomic changes have led to stress on aquifers and water resources worldwide. Hence, when assessing the environmental conditions for MAR, the potential effects of climate change should also be examined to avoid system malfunction. MAR sites relying on surface water might be negatively impacted by decreasing river flows. Given the impacts of climate change on water resources, MAR can also be considered under existing and new regulations as a buffer to deal with water scarcity and extreme climatic events such as drought [7,78], especially as a tool to store water during extreme precipitation events and as an interannual reservoir.

Another relevant environmental issue to consider in a MAR site design is the interrelation of MAR, groundwater, and dependent ecosystems. In a "give and take" process, some wetlands related to flooding episodes, or even very valuable species subjected to dry seasons, can suffer the negative consequences of a well-intended MAR system when the ecological key relations are not considered as part of the local water cycle. These issues are not commonly addressed in general guides through national laws or international directives enforcing habitat protection. A greener and more integrated procedure should be encouraged by water authorities for recharging processes in a delimited watershed.

3.2.3. MAR Technology

The third factor or block involved in the MIR concept is selecting the appropriate MAR technology. Different MAR systems are suited to different conditions. Hence, choosing the most convenient one for a particular site and purpose requires a detailed evaluation of the local characteristics and the pros and cons of the available technologies. It is also worth studying legal, environmental, and budgetary constraints.

Gale [79] summarized and classified the main MAR types, distinguishing five categories based on the main feature enabling infiltration or the source of water: (1) spreading methods; (2) in-channel modifications; (3) wells, shafts, and boreholes; (4) induced bank filtration; and (5) rainwater harvesting. Several authors have proposed new MAR

classification systems, usually entailing minor modifications to the original work by Gale [24,25,66,80].

DINA-MAR, TRAGSA, and Fernández Escalante et al. [66,81,82] proposed a MAR classification scheme that comprises equivalents to the categories proposed by Gale plus an additional category for the sources of accidental recharge (unmanaged), which strictly speaking is not MAR. The classification by DINA-MAR, TRAGSA, and Fernández Escalante et al. also includes 13 additional MAR systems and a relationship between MAR technology and spatial distribution (e.g., punctual for wells, linear for trenches or channels, and polygonal for infiltration basins). Table 4 summarizes this classification system, including the main categories and the specific MAR types. Appendix B contains an extended version of this scheme (Figure A2), including schematic illustrations and actual photographs.

Table 4. Summary of MAR categories and systems [66,81,82].

MAR Category	MAR Type
Water spreading	- Infiltration ponds/wetlands - Channels and infiltration ditches - Ridges/soil and aquifer treatment techniques - Infiltration fields (controlled flooding)
River channels	- Reservoir dams and dams - Permeable dams - Levees - Riverbed scarification - Sub-surface/underground dams - Drilled dams
Targeted recharge	- Qanats (underground galleries) - Open infiltration wells, shafts - Deep wells and boreholes - Boreholes - Sinkholes, collapses - Aquifer storage and recovery (ASR) - Aquifer storage, transfer, and recovery (ASTR)
Filtration	- Riverbank filtration (RBF) - Interdune filtration - Underground irrigation
Rain based systems	- Rainwater harvesting systems - Sustainable urban drainage systems (SUDS)
Accidental recharge	- Accidental recharge from pipes and sewer systems - Accidental recharge by irrigation return

The MIR model recommends that any guiding document on MAR must consider the MAR types. The final technological choice should be left to the petitioner during the implementation stage after carefully evaluating the local conditions.

3.2.4. MAR Sensors for Data Gathering

Sensors and monitoring are relevant components in the MIR concept, helping to characterize the climate and receiving medium and assess risk during operations.

MAR monitoring data can be collected remotely or on-site. Remote data collection usually involves data storage in data-loggers and remote data logging, often through modems and SIM cards. On-site monitoring entails recovering data from data-loggers in person and sampling water to determine water constituents in the laboratory following standard protocols and regulations, particularly when analyzing unstable parameters (e.g., nitrate).

A sampling frequency must be specified according to the intended use of the recovered water. This frequency can range from daily analyses for drinking water supply to quarterly sampling for environmental and research purposes [42] (Figure 5, upper right corner).

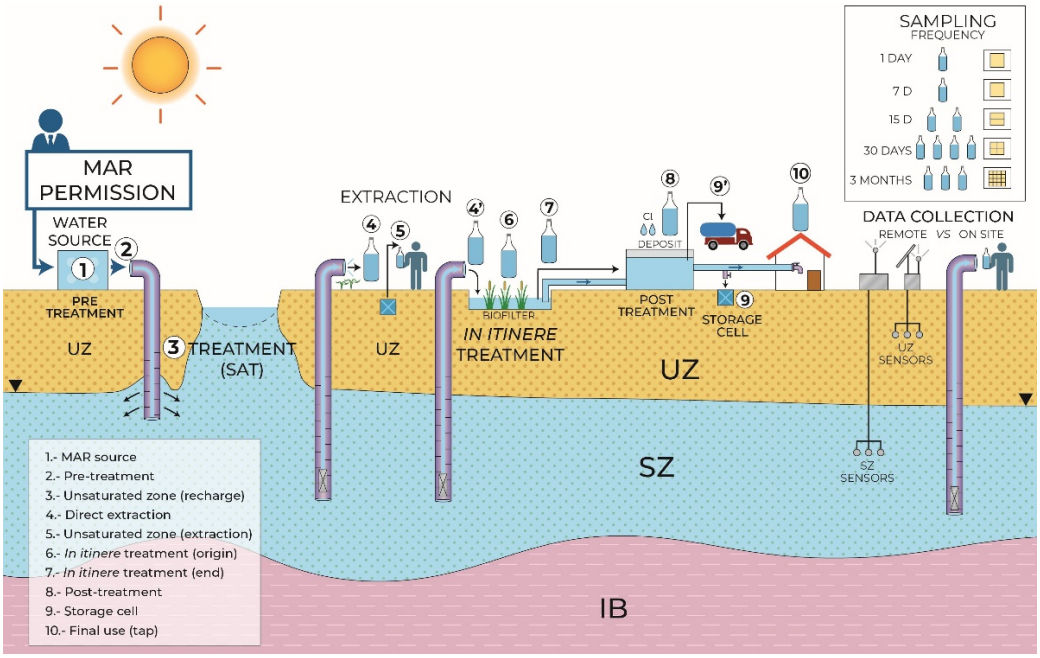


Figure 5. Up to 10 sampling locations for MAR monitoring are considered in the monitored and intentional recharge (MIR) conceptual model, blocks 4 and 5, including sampling frequency and data collection means (block 7). Abbreviations specified in the caption of Figure 1.

A survey on monitoring methods and devices was conducted among consortium members of the MARSoluT project (marsolut-itn.eu), which gathers 10 institutions conducting MAR research across Europe and the Mediterranean region [83]. This survey revealed that monitoring in MAR engages predominantly with the saturated zone (lithosphere), followed by the unsaturated zone (pedosphere) and, to a minor extent, the climatological conditions (atmosphere). The survey and an extensive literature review [81,84] also proved that MAR system monitoring deals primarily with water quantity, and that the most frequently measured properties are water levels, water temperature, soil temperature, and soil water content. Table 5 shows the most commonly measured properties in MAR system monitoring based on the survey. These properties are categorized by the realm or earth-sphere in which they are determined.

The survey also demonstrated significant heterogeneity in terms of data formats. At least 28 manufacturers produced the devices utilized by the institutions of the MARSoluT consortium. This considerable number of manufacturers implies that the data collected at the levels of a single project or a consortium usually come in diverse formats, requiring the utilization of programs or manual procedures to integrate monitoring information [83]. In the future, formulating standards for data gathering and exchanging involving active participation from end-users and manufacturers could considerably improve syntactic and semantic interoperability [84,85] in MAR systems and ease operation. To date, a standard in this direction has been formulated in the irrigation sector through the UNE 318002-3:2021 standard [86], which enhances interoperability considerably among irrigation systems in Spain, and has excellent potential to be applied beyond.

Table 5. Main monitored properties in MAR systems categorized by the realm in which they are observed [83].

Realm (Earth-Sphere)	Property
Environmental conditions (atmosphere and hydrosphere)	- Flow rates and discharge - Soil infiltration/seepage rates - Precipitation - Solar radiation - Wind speed and direction - Relative humidity - Other meteorological variables
Unsaturated zone (pedosphere)	- Volumetric water content (VWC) - Soil electrical properties (dielectric permittivity, resistivity, and conductivity) - Water potential - Vapor pressure - Conductivity - Temperature
Saturated zone (lithosphere)	- Water level - Temperature - Conductivity - pH - Oxidation-reduction potential (ORP) [83] - Turbidity - Total dissolved solids (TDS) - Total suspended solids (TSS) - Other physicochemical properties - Salinity - Hydrogeochemical parameters

3.2.5. Monitoring Guidelines

The MIR conceptual model addresses aspects related to monitoring, such as the cost of the hydrochemical analyses, the location of sampling (horizontally and vertically), and the data collection frequency and system (Figure 5). Since water quality is a vital aspect of ensuring the safety of human health and ecosystems, water sampling during MAR operations should be conducted at critical points. These points must be specified in the monitoring guidelines. The MIR conceptual model differentiates 10 sampling points along a MAR system (Figure 5): (1) water origin, (2) pre-treatment, (3) the unsaturated zone during recharge, (4) direct groundwater extraction, (5) the unsaturated zone during groundwater extraction, (6) treatment of water along the MAR system (the Latin term "in itinere", which means "on the road" or "on tour", was selected and comprises MAR system elements such as biofilters or vegetated channels), (7) endpoint of the in itinere segment when there is subsequent treatment, (8) post-treatment sampling spot, (9) storage node for recovered MAR water, and (10) final use (e.g., tap water). From these points, the most frequently sampled among MAR projects are either the direct abstraction (Figure 5, point 4) or the end point of *in itinere* treatment (Figure 5, point 7).

Drawing lessons from environmental laws governing surface water, aquifers should be zoned according to the main hydrochemical and hydraulic processes resulting from MAR. For example, guidelines should establish different water quality criteria for the zone in which the recharged water interacts with the native groundwater and the receiving medium (i.e., the water quality impact zone) and the sector of the aquifer in which only hydraulic impacts of MAR are observed (i.e., the hydraulic impact zone [27,42]). Thus, modern regulations should also discriminate between sampling aquifer zonation horizontally and vertically.

Any monitoring program must also comply with the legal requirements, consider the international context and specific regulations through technology watch, and acknowledge authorities´ requirements in cases of conditional allowances.

3.2.6. Final Use of the Intentionally Recharged Water

There are multiple final uses of the recharged water. The most common ones are irrigation, industrial supply, urban water supply, street sweeping and cleaning, reuse, storage in strategic reservoirs (SRs) for long-term availability (e.g., water storage for emergencies and future generations) [68], groundwater storage augmentation, (positive) hydraulic barriers, and short-term temporary storage (Figure 6). Other uses observed in MAR systems worldwide include water transfers and environmental restoration of high-ecological value assets, such as wetlands and springs. Mining is often included in the group of industrial uses.

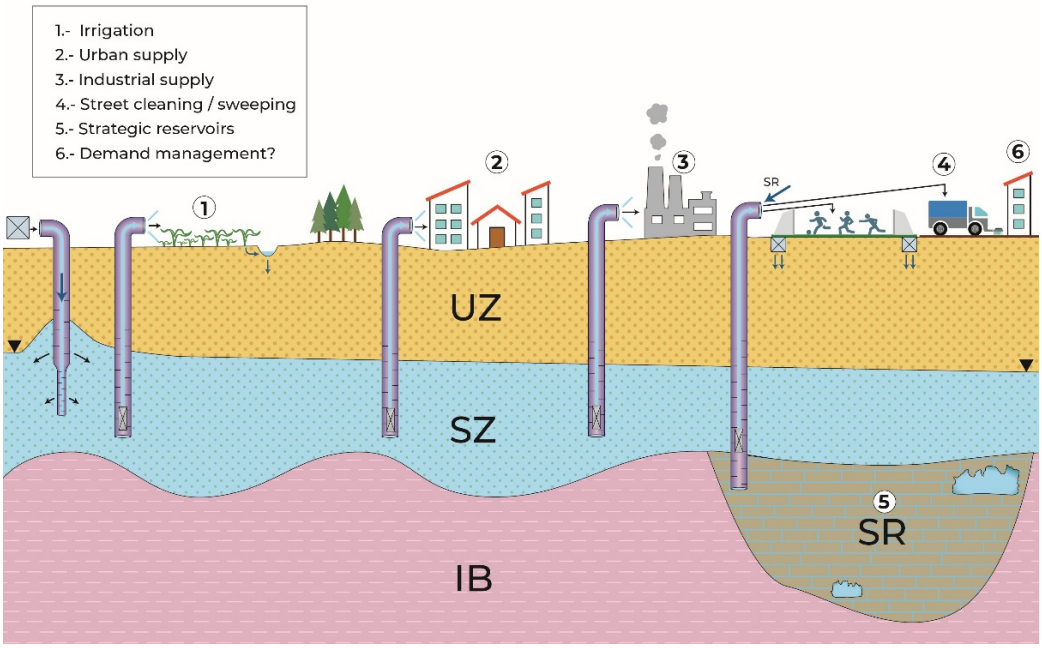


Figure 6. Most common end uses of MAR water summarized in the monitored and intentional recharge (MIR) conceptual model, block 6. Abbreviations specified in the caption of Figure 1.

MAR water end-users should be involved in water management and governance and involved when drafting MAR guiding documents [36]. This assures transparency in the regulatory process, enhances trust among stakeholders, improves water demand control, and can lead to the co-management of MAR systems (Co-MAR) [87]. End-user participation also opens the door to citizen science and a more rigorous control and surveillance of water resources and the related infrastructure.

3.2.7. Analytical Aspects

Based on a study of regulations, guidelines, and operational rules at the international level, Fernández Escalante et al. [30] found high variability in the number of regulated contaminants and parameters, ranging from just 6 in Spain to 149 in the USA. The same authors proposed a list of a minimum of 32 parameters to be analyzed when operating MAR systems, specifying that the list is wide open for each practitioner´s criteria. The list is based on the frequency with which the parameters were mentioned in the reviewed documents, their usefulness in hydrogeological and hydrochemical characterization, and economic and pragmatic criteria. Though the wide list of parameters depends on national legal frames, economical constraints still play a crucial role; therefore, these parameters must be chosen based on specific local issues under technical scrutiny. Authors consider that each technician adapts the "recipe" to their reality, especially from an economic standpoint.

These parameters require a review based on potential risks, depending on the particular MAR technology and its location, to optimize monitoring. These 32 parameters may be too many or too few, depending on the end use of the water. This choice may improve the selection of "critical sampling points", which serve the function of reducing specimens to key points, eliminating redundancies. This activity might be part of either the monitoring stage itself or the surveillance and control program.

One persistent challenge for the water management community is to improve scientific understanding and methods to enable risk management in the absence of advanced water quality monitoring, particularly in developing countries.

Other critical analytical aspects are the feature of a MAR system to which MACs apply and the spatial scale. Concerning the first aspect, different MACs are necessary for the source water, the aquifer, and the final use depending on the particular context. Regarding the spatial scale, setting MACs for broad administrative regions (e.g., countries or provinces within a country) might be short-sighted since they might lack consideration of the aquifer's particular characteristics and result in contamination or mobilization of undesired minerals and compounds [88]. Ideally, MACs and any multi-barrier and multi-level approach to ensure safe MAR operations should be based on scientific evidence, preferably at the aquifer or site-specific scale. Bacteriology is inseparable from each MAC proposal. Contemplating water sources, aquifers, and environmental conditions to establish a regulating document for MAR at the national scale may be challenging. Still, it is time for a worthwhile effort to ensure proper praxis of MAR [40].

Apart from the parameters in the saturated and unsaturated zones, MIR suggests taking into account additional aspects when defining the analytical monitoring of MAR projects, i.e., cost of the analyses, stakeholder involvement (including end-users of MAR water), the MAC for potential contaminants involved in the current regulation, and the sampling location and frequency (Figures 5 and 6).

A hazard of MAR schemes relying on wastewater to conduct recharge is the appearance of contaminants of emerging concern (CECs). They comprise a series of chemical compounds and their metabolites, usually of anthropic origin, which are present at low concentrations in one or several environmental compartments (e.g., soil and water) and pose a risk to human health and ecosystems [89]. They include pharmaceuticals, personal care products, pesticides, and industrial compounds. The reduction in the concentration of these contaminants during MAR, particularly in soil aquifer treatment (SAT) schemes, is highly variable and primarily mediated by biodegradation [90]. CEC removal ranges from 0 to more than 90% and depends on site characteristics and the barriers to improving water quality [16,90,91]. CECs warrant further research [5]. The MAR regulations and guidelines of Italy, Mexico, the USA, and the Netherlands set MACs for several CECs [30].

3.2.8. Risk or Impact Assessment

A safe routine for conducting MAR is adopting a risk management approach, which involves evaluating and controlling risk to acceptable levels [31,92]. The MIR conceptual model suggests monitoring a series of risks subdivided into two major groups, namely "design and construction" and "operation" (including management or joint management of the recharge storage (aquifer) and the water supply. In this sense, pumping and subsequent use of the recharge water create free storage for the next injection year or event). These clusters were further subdivided into technical and non-technical risks [93–96] (Table 6). Additional aspects can be included by answering the question, "is it important to you?" [94]. This approach can also help by reducing the need for redundant samples or parameters. Detection of critical spots in the system may be crucial to improve the efficiency and cost of monitoring.

Table 6. Important risks to consider when dealing with MAR as per the monitored and intentional recharge (MIR) conceptual model, block 8.

	Technical Aspects	"Non-Technical" Aspects [95,97]
Design and construction	- Legal constraints - Economic constraints - Lack of social acceptance - Weak water governance	- Availability of water source - Concessions or water rights constraints - Water scarcity - Hydrogeological assessment - Lack of infrastructure - Dependence of valuable habitats
Operation (and management)	- Legal constraints - Economic constraints - Lack of social acceptance - Weak water governance	- Structural damage - Water shortage and volume constraints at the source - Drought - Clogging - Unacceptable water quality in a sensitive location - Specific objectives - Distortion of local ecological relations

3.2.9. Other Aspects and General Recommendations

Public participation and stakeholder engagement (i.e., Co-MAR [88]) should be crosscutting issues during the construction of any normative document on MAR, including the views and knowledge of a broad audience, which results in robust and comprehensive regulations. When dealing with the economic aspects of MAR projects, it is advisable to analyze the cost recovery principle, which, following "the polluter pays principle", requires full recovery of all the costs incurred in producing water [36]. This principle should increase awareness of water use among consumers and help, in some cases, to control demand and preserve the environment. The assessment of the total economic value of a MAR project should also consider the "collateral" benefits of the scheme, and the synergies and trade-offs occasioned by the interaction between MAR and ecosystem services.

Other elements to be taken into consideration during MAR regulation drafting are standardization and interoperability. A clear definition of terms directly or indirectly related to MAR should be established from the beginning [98], along with formats to submit data to water authorities (common language) during the permission granting process for MAR operation and allowance renewal. These efforts should ease communication across all agents engaged in MAR projects.

A short summary of the nine blocks comprising the MIR conceptual model is presented in Figure 7. Appendix C contains an extended version (Figure A3).

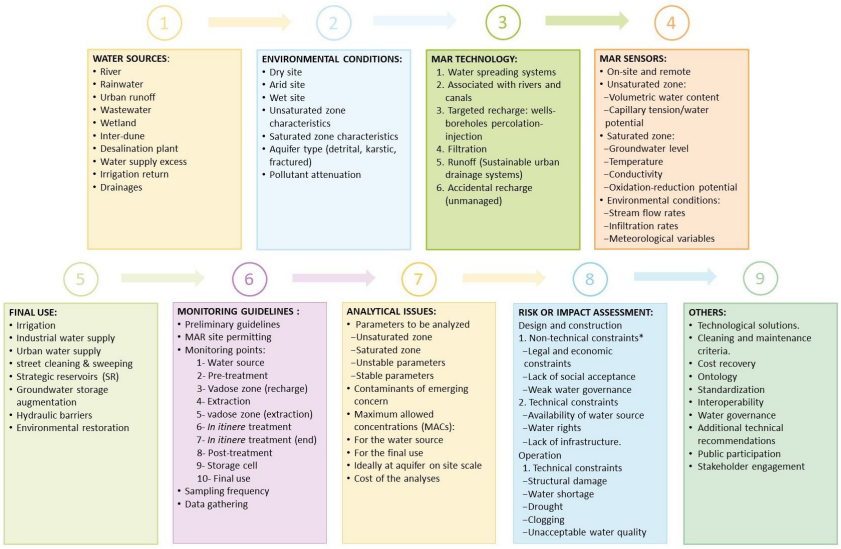


Figure 7. General summary of the nine essential blocks that constitute the monitored and intentional recharge (MIR) conceptual model.

4. Conclusions

The aspects discussed in specific guidelines and regulatory documents on MAR were analyzed and assessed through a score. These scores revealed that most of the documents focused on risk and impact assessment aspects and the reuse of water, stressing the importance of alternative water sources and increasing care for water quality, health protection, and ecosystem protection.

More than 22 guidelines or regulatory documents on managed aquifer recharge (MAR) were reviewed, resulting in the monitored and intentional recharge (MIR) conceptual model. This model comprises nine blocks summarizing the minimum elements to consider when drafting guidelines or norms on MAR. The elements in these blocks contribute to safeguarding the environmental quality and human health and ensuring the technical sustainability of MAR systems. MIR also elaborates on state-of-the-art issues in MAR research, such as pollutants of emerging concern, interoperability, and climate change.

The nine blocks that make up the MIR conceptual model are:

1. Water sources for MAR;
2. Environmental conditions in which MAR activities take place, including the climate, and aquifer type, geology, surface water basin, groundwater body, and depurative capacity;
3. MAR technology;
4. MAR sensors for data gathering, which can characterize the environmental conditions and monitoring the system;
5. Guidelines for monitoring water quantity and quality, which includes aspects on sampling frequency and points;
6. Final use of the recovered water, including irrigation, water supply, hydraulic barriers against seawater intrusion;
7. Analytical aspects, with recommendations on the scope and scale of the maximum al-lowed concentrations of potential pollutants;
8. Risk assessment, elaborating on some of the risks to assess when conducting MAR operations, considering dependent habitats;
9. Others, including relevant topics difficult to include in previous blocks as well as MIR broad blocks that need consideration, such as standardization and interoperability, contaminants of emerging concern, economic aspects, public participation, and active stakeholder engagement.

Even though the MIR conceptual model proposes a complete list of elements to study when drafting guidelines and regulations on MAR, it also encourages a tailored approach based on the specific context of the country or region. At present, Peru and Niger are preparing MAR normative bodies guided by the MIR conceptual model. In the future, this model could be applied in Europe and beyond.

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Appendix A

GROUP	ASPECTS	WHO	AUSTRALIA	USA	ASCE (USA)	MEXICO	CHILE	EUROPE (water reuse)	EUROPE (agricultural water	INDIA	ASSESSMENT SCORE	MIR BLOCK
GENERAL CONTEXT	Definition of terms	3	3	2	3	4		2		2	19	9
	Methodological aspects	2	3	3			4				12	6, 9
	Reuse aspects, including water sources and final uses	4	3	4	2	3	2	4	4	2	28	1, 5
	MAR case studies		3	4	3			1		3	14	9
	Assessment of adequate environmental conditions for MAR	2	3	3	2	2			2		14	8
	Report of general trends / records	3	2		3						8	6, 7, 8
MAR PLANNING	Detailed description of water treatment plants for water reuse	2	1	1	4		2			2	12	1, 3
	Detail description and assessment of surface water sources		2	2	4		2			2	12	1, 2
	Social, political, and economic viability assessment		1		2		1	2		3	9	8, 9
	Administrative components	3	4	2	3			3			15	9
	Planning activities and considerations		2	3	4		2	2		2	15	3, 5
	Review of policy and legal framework		4	4	3	3	3	4	3		24	6
	MAR system design and characteristics	2	4	2	4	2	4			2	20	3
	Preliminary site characterization	2	4	2	4		2				14	2, 8
	General construction procedures		1		4	1				2	8	3, 6
SOCIAL ASPECTS	Water management framework including entities and their duties		3	4	3	2	3	2	2		19	6, 8, 9
	Groundwater users and platforms for their interaction	3	2							3	8	6, 9
	Result dissemination to target groups		3		2			2			7	8, 9
	Public outreach	2	2	4				4			12	8, 9
	Stakeholders involvement / connection with	2	2					4			8	9
	Water governance		1		1			1		3	6	9
	Public participation	1	1					4		2	8	8, 9
RECEIVING MEDIUM	Groundwater source protection	2	3	4	4	2	3	2	2		22	1, 8
	Recharged water - unsaturated zone interaction	4	3	2	2	2	2			2	17	6, 7
	Assessment of groundwater storage evolution		3	3	4		2				12	6, 7, 8
	Pollutant migration and atenuation (saturated zone)		2	4					3		9	6, 7, 8
FINANCIAL ISSUES	Funding / Financial issues / costs	4	2	4			3	3		2	18	9
	Potential economic benefits of MAR		1	1			2	2			6	8, 9
	Social benefits of water reuse / MAR		2				1	3			6	8
	Water trading and banking		1	1	2			2		2	8	8, 9
RISK AND IMPACT ASSESSMENT	Dependent ecosystems protection	3	3	4	2		2	2	2		18	2, 8
	Agriculture supply protection	4	3	3	2			4	4	2	22	8
	Urban supply protection		2	3			2	2		2	11	8
	Health protection	4	4	4	3		3	3	3	3	27	8
	MAR for landscape protection		1	2			1	3	2		9	2, 8
	Sanitary and environmental risks assessment	4	4	4					3		15	8
	Identification of barriers for MAR implementation and operation		2	4		1			3	2	12	8, 9
	Preventive measures		2	2		1			4	3	12	3, 9
	Hazards identification								4	2	6	2, 8
	Risk assessment	3	4	3			2	3	3	3	21	8
	Impact assessment	2	4	3	2						11	8
	Maximum allowed concentration list (MACs)	2	3	2	3	4		3	3	1	21	6, 8
	Contaminants of emerging concern (CEC)			1				1	4		6	6, 7, 8
OPERATIVE ASPECTS	Contingency plan or program		2	1	1				3		7	8, 9
	Operation and maintenance plan (O+M)		2		4	3	3		3	2	17	4, 6, 8
	Reporting	2	2	2	2			?			8	6, 8, 9
	Data collection, analysis and interpretation		2		4						6	6
	Monitoring and pilot testing	3	4	2	4	2	4		3	2	24	6, 7, 8
	Identification of elements/parameters to monitor		4						3		7	6, 7
	Monitoring equipment				3	1	2		1		7	4, 6, 7
	Discussion of the different types of monitoring	1	4	1	1	1	1	1	1	2	13	4, 6
	Clogging prevention		2		4		3				9	6, 7, 8
	Water pretreatment	1	2	1	4						8	1, 5, 6
	Recovery aspects		2		4						6	4, 5
	Project´s life and closure		1	2	4	3					10	3, 8
	Site security and occupational safety		1	3	3					2	9	8
	Operational efficiency quantification		2		4		2		2		10	5, 6
	Spill management	4	3		1				2		10	8, 9
	Feedback and assessment to improve operations		4		2		2	4	2		14	6, 9
VARIOUS ASPECTS	Saline water intrusion / brackish protection		2				2			2	6	4, 5, 6
	Relevance of guaranteing monitoring in the long-term		3			3					6	6, 8
	Numerical modeling		1		3	2					6	6, 8
	Research neccesities		4	4				2			10	ALL
	Decission trees		3	4		2			3	3	15	6, 8, 9

Figure A1. (Enlargement of Table 3). List including the whole aspects discussed in the reviewed guideline documents, degree of development for each subject in each publication (from 1 to 4), assessment score according to the appearance and development of each topic, and corresponding MIR block/s containing each item.

Appendix B

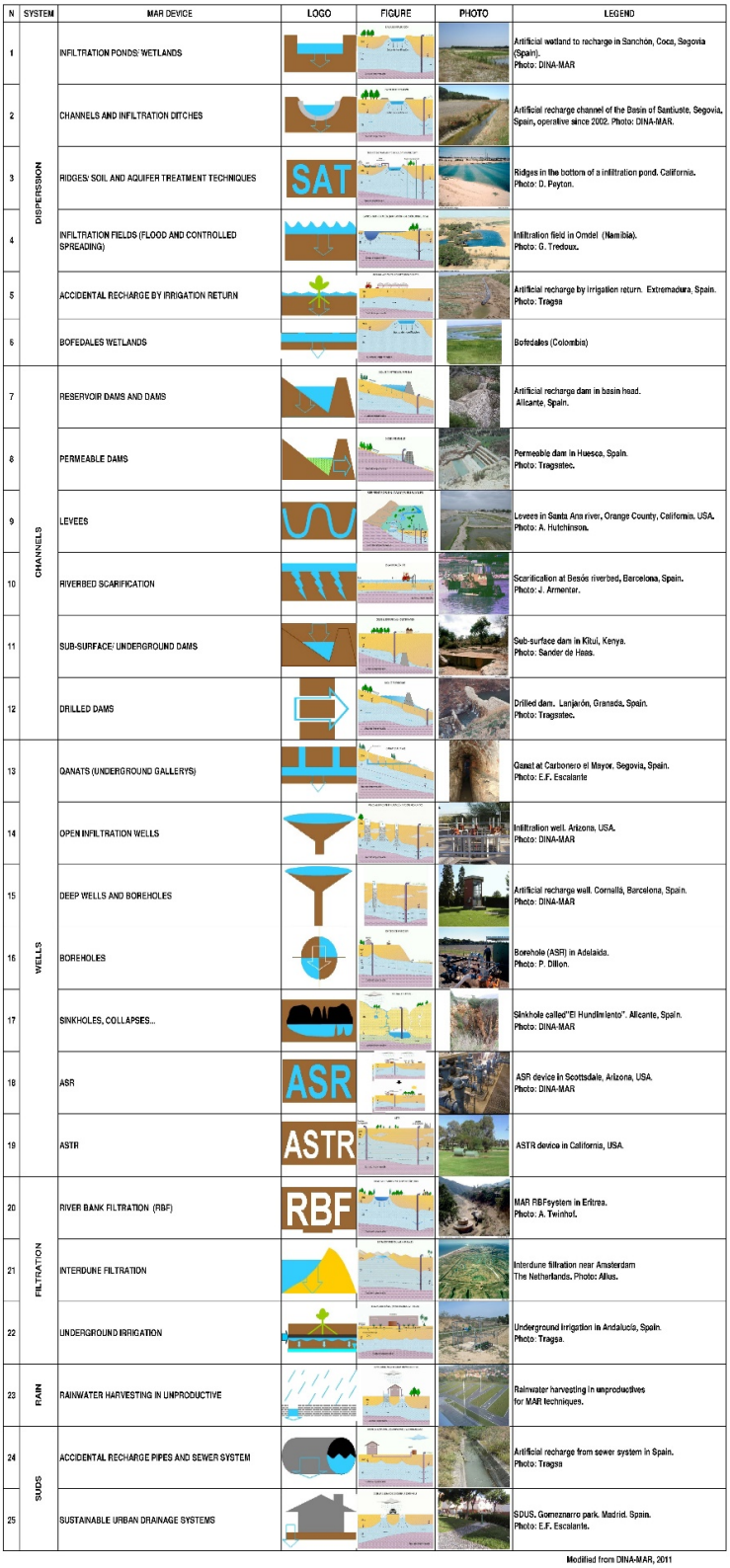


Figure A2. (Expansion of Table 4). MAR technology inventory. Systems and devices. Complete figure modified from [46] https://dinamar.tragsa.es/pdfs/poster-dispos%20V-3-en-b.jpg. (Accessed on 1 October 2022).

Appendix C

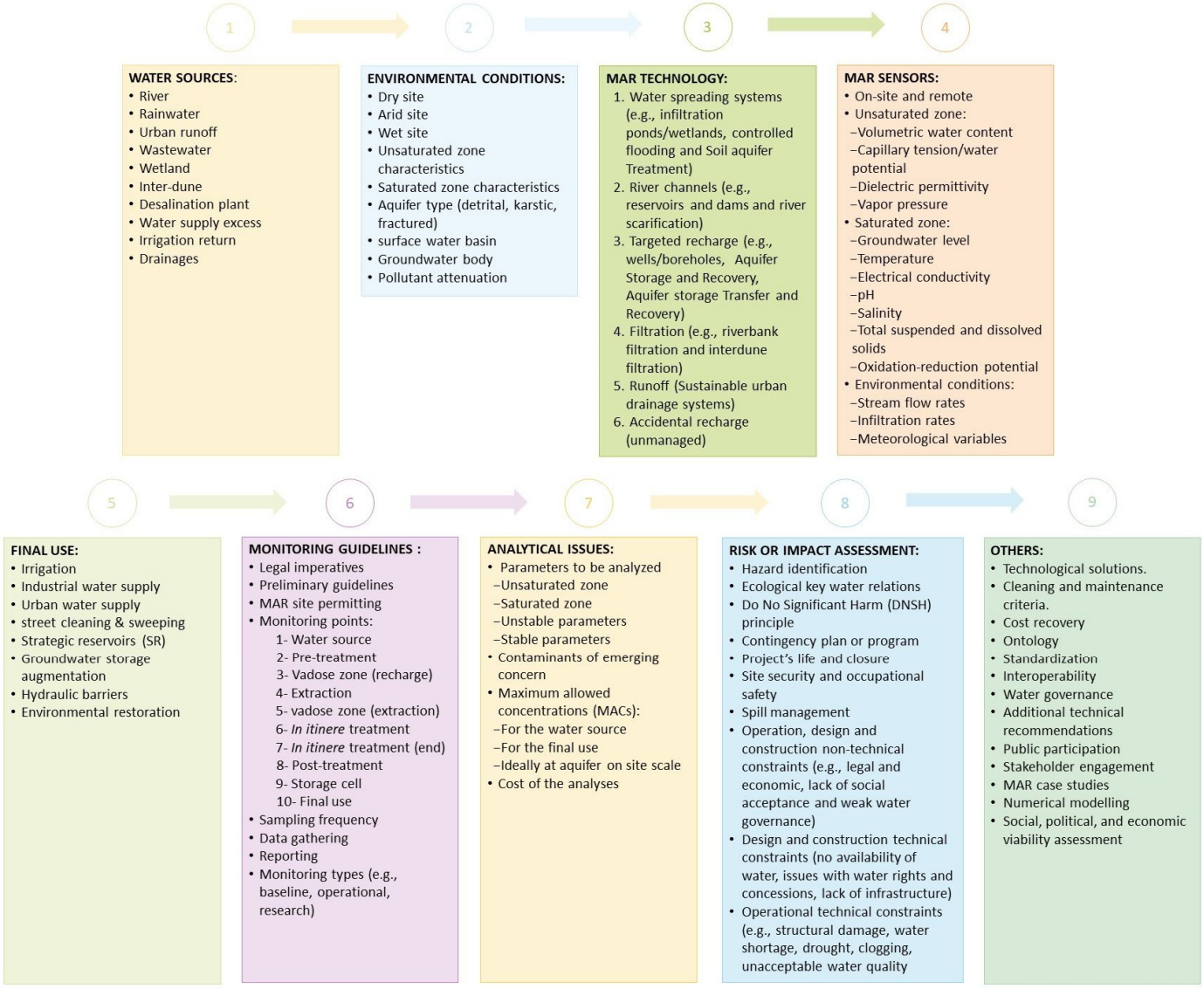


Figure A3. (Expansion of Figure 7). Blocks of the monitored and intentional recharge (MIR) conceptual model in detail.

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